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

Testbed Evaluation Plan

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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.

The primary purpose of this report is to document the evaluation plan for this project. The report expands on detailed testbed description including the geographic location, modes, operational conditions and cluster analysis details. In addition, the plan also provides details on the analysis scenarios, DMA/ATDM applications and strategies that are evaluated using the Testbed and the plan to answer DMA/ATDM-specific research questions. The analysis plan provides details on the evaluation approach used to answer specific research questions.

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Chapter 1. Introduction

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. Capable, 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. Therefore, instead of selecting a single testbed, a portfolio of AMS Testbeds were 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: San Mateo (US 101), Pasadena, Dallas, Phoenix, Chicago and San Diego Testbeds.

The primary purpose of this report is to document an evaluation plan that combines the testbed specific analysis plans to collectively address the key questions and hypotheses of the DMA and ATDM Programs. The evaluation plan concisely summarizes the full scope of analyses planned in the multiple testbeds and provides a synthesis of what the combined analyses are expected to reveal. The evaluation plan also states the research questions that will be directly, indirectly and not addressed by the overall analysis along with the corresponding test hypothesis and the operational scenarios that enabled the research. Specifically, the evaluation plan presents the plan for:

1. Evaluating the system-wide impacts of individual DMA applications, individual DMA bundles, and logical combinations of bundles and applications, and identifying conflicts and synergies for maximum benefit
2. Evaluating the system-wide impacts of ATDM strategies when implemented individually and in logical combinations, and identifying conflicts and synergies for maximum benefit
3. Evaluating the combined impacts of the DMA bundles and ATDM strategies when prediction and active management are coupled with data capture and communications technologies that can systematically capture motion and state of mobile entities, and enable active exchange of data with and between vehicles, travelers, roadside infrastructure, and system operators

1.1 Evaluation Plan Overview

As far as the layout of the report is concerned, it is organized into five chapters in the following order:

- Chapter 1 – Introduction: This chapter provides an introduction to the evaluation plan and identifies the purpose and overview of this document, and a brief description on the AMS Testbed Project.
- Chapter 2 – AMS Testbeds: This chapter provides a description on the 6 different AMS Testbeds that are being used for evaluation of the DMA applications and ATDM strategies. Chapter 2 includes details on the geographic and temporal scope of the analysis.
- Chapter 3 – Evaluation Plan for DMA Program: This chapter provides the evaluation plan for the DMA applications including hypotheses that will be tested, performance measures to be evaluated as well as application mapping.
- Chapter 4 – Evaluation Plan for ATDM Program: This chapter provides the evaluation plan for the different ATDM strategies including application mapping, scenarios that can answer research questions etc.
- Chapter 5 – Risks and Mitigation Approach: This chapter provides the approach to mitigate risks associated with the overall AMS project as well as individual testbeds.

Chapter 2. AMS Testbed Sites

This project primarily aims at evaluating DMA applications and ATDM strategies on virtual simulation-based test networks using Analysis, Modeling and Simulation. Six testbeds have been selected and represent six different geographic locations in the United States: San Mateo, CA, Pasadena, CA, Dallas, TX, Phoenix, AZ, Chicago, IL and San Diego, CA. Chicago (IL) and San Diego (CA) 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. This section presents a high level overview of these AMS Testbeds used to conduct analysis that will support the DMA and ATDM programs. In particular, the section describes:

1. Geographic and temporal scope of the analysis conducted across the different testbeds including the roadway or facility types, operational scope, etc.
2. Operational conditions that were selected for each testbed using a cluster analysis process.
3. Modes considered in each testbed.

Table 2-1 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 2-1 - Overview of Testbeds

Testbed	Geographic Details	Facility Type	Applications / Strategies
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.

Testbed	Geographic Details	Facility Type	Applications / 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

2.1 Geographic and Temporal Scope

Six simulation-based testbeds are used in the AMS project and define a range of geographic and operational characteristics as well as different levels of resolution and roadway types. The geographic and temporal scope of each of the six testbeds is discussed in this sub-section. Figure 2-1 shows the six testbeds extending over the United States.

Figure 2-1 - Testbeds Used for AMS Project [Source: Booz Allen]

Sections below provide an overview of each of the six Testbeds including specific geographic mapping of included facilities.

2.1.1 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 only non-holiday 5-hour PM peak period between 2:30PM and 7:30PM. Figure 2-2 shows the geographic overlay map of the Testbed.

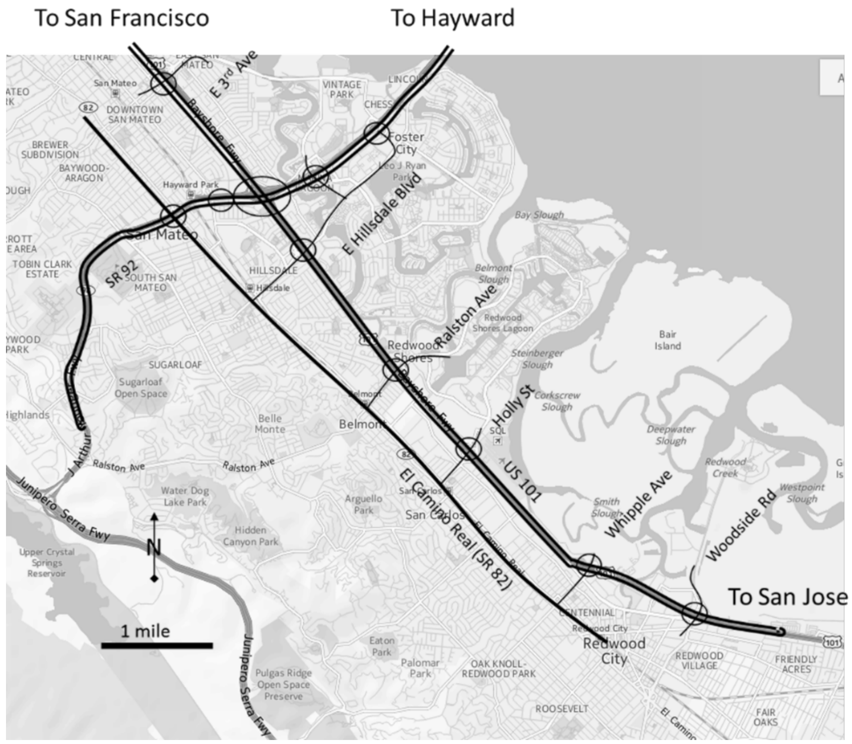

Figure 2-2 - San Mateo Testbed [Source: Booz Allen]

2.1.2 Pasadena

Primarily covering the City of Pasadena, the network also includes unincorporated area of Altadena to the north, part of the Cities of Arcadia to the east, Alhambra to the south and Glendale and Northeast Los Angles to the west. The total analysis area for the macroscopic model is 44.36 square miles and the microscopic model is 11 square miles. This model network includes four major freeway segments: I-210, I-710, CA-134 and CA-110, totaling to 17.7 centerline miles. The freeways also included about 10.5 miles of HOV lanes on I-210 and CA-134 for both directions. The network also covers a wide range of arterials and collectors that comprises a balanced roadway system. This Testbed takes both AM and PM peak periods into account. Figure 2-3 shows the geographic overlay map of the Testbed.

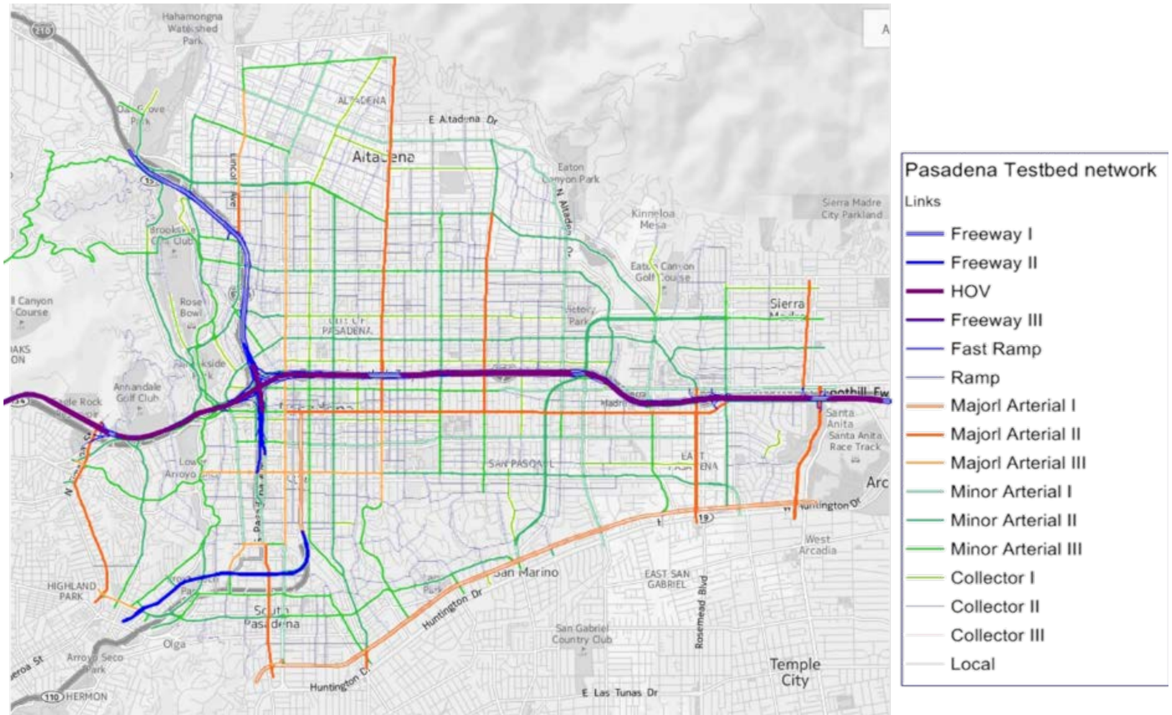

Figure 2-3 - Pasadena Testbed [Source: Booz Allen]

2.1.3 Dallas

The US-75 Corridor in Dallas, Texas is used as one of the AMS Testbeds. As illustrated in Figure 4, the US-75 Corridor is a major north-south radial corridor connecting downtown Dallas with many of the suburbs and cities north of Dallas. It contains a primary freeway, an HOV facility in the northern section, continuous frontage roads, a light-rail line, park-and-ride lots, major regional arterial streets, and significant intelligent transportation system (ITS) infrastructure. The length of the corridor is about 21 miles and its width is in the range of 4 miles.

This Testbed takes both AM and PM peak periods into account. Figure 2-4 shows the geographic overlay map of the Testbed.

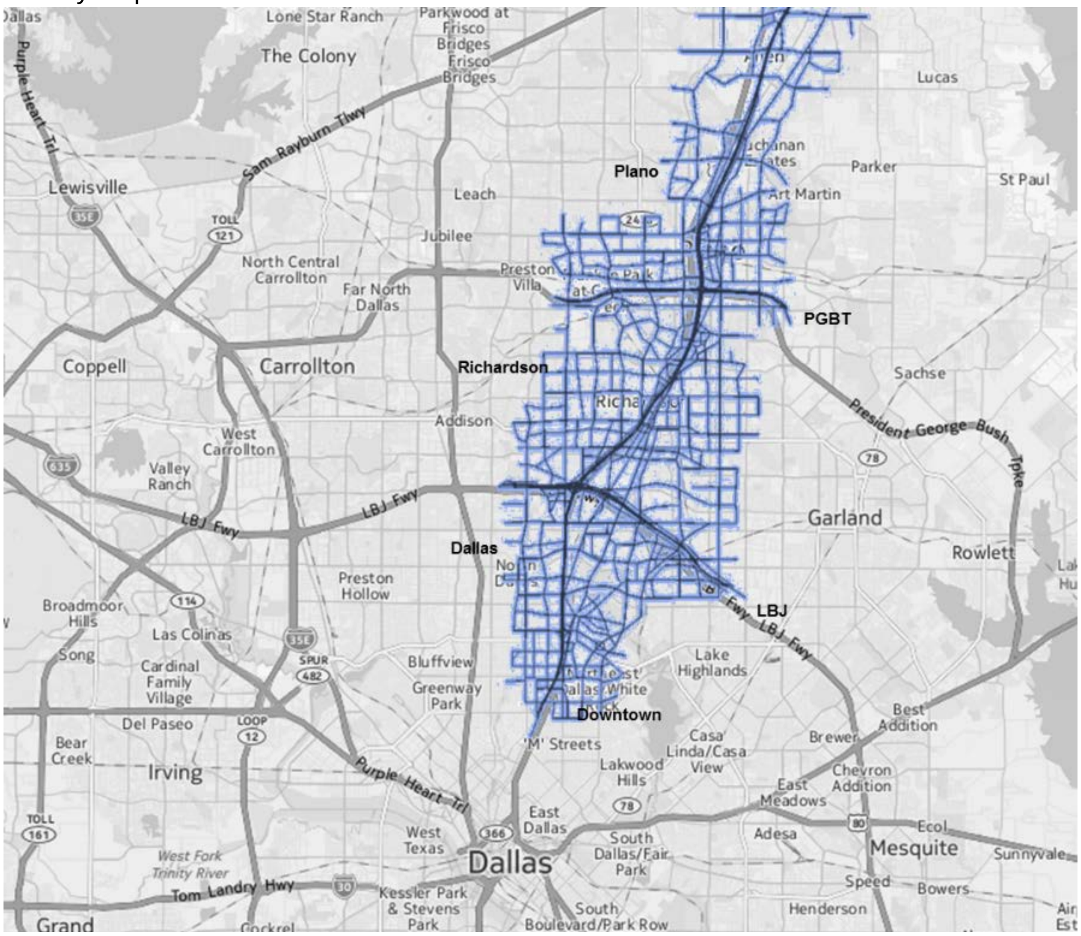

Figure 2-4 - Dallas Testbed [Source: Booz Allen]

2.1.4 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 will take multiple modes into account. 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 1 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 Tempe area which covers an area of 40 square miles.

This testbed only considers AM Peak traffic between 6:00 AM and 10:00 AM and PM peak traffic between 3PM and 7PM and considers both weekday and weekend traffic when selecting the operational conditions. The initial simulation scenarios focus only on PM peak. Figure 2-5 shows the geographic overlay map of the Testbed.

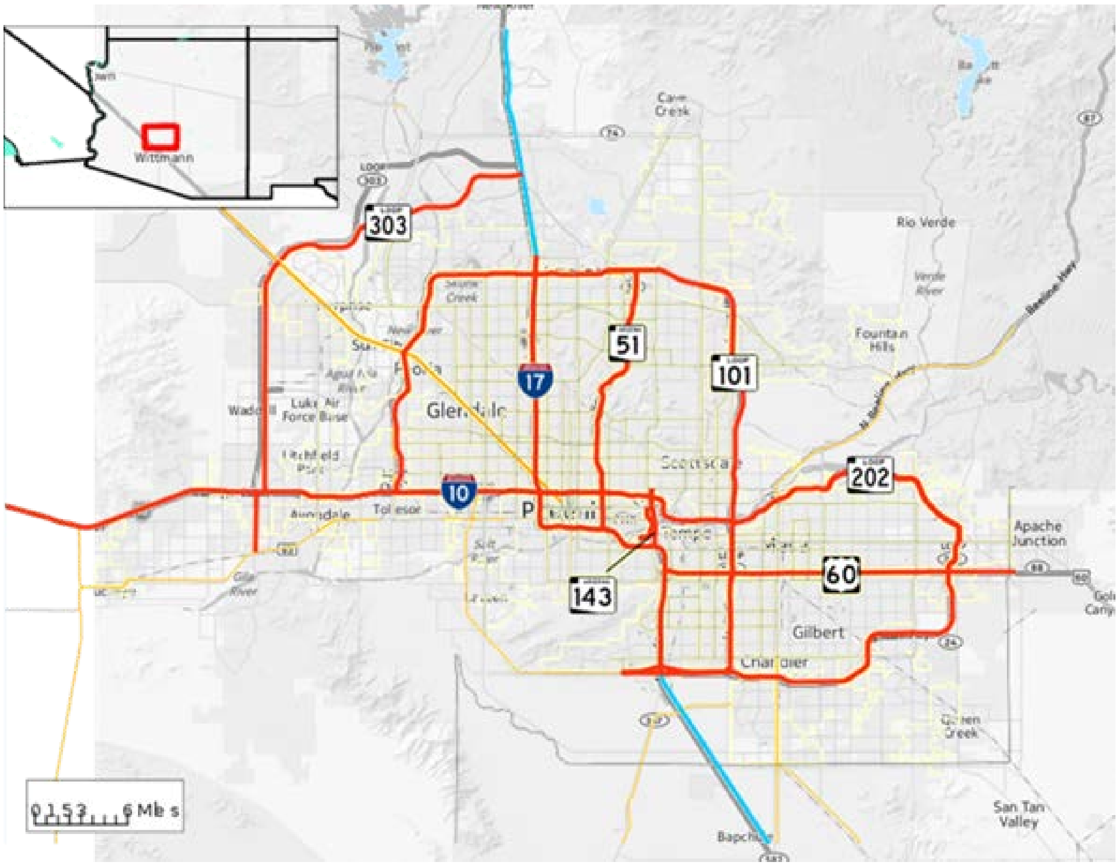

Figure 2-5 - Phoenix Testbed [Source: Booz Allen]

2.1.5 Chicago

The Chicago Testbed network includes Chicago downtown area located in the central part of the network, Kennedy Expressway of I-90, Eden's Expressway of I-94, Dwight D. Eisenhower Expressway of I-290, and Lakeshore Drive. The Testbed network is bounded on east by Michigan Lake and on west by Cicero Avenue and Harlem Avenue. Roosevelt Road and Lake Avenue are bounding the Testbed network from south and north, respectively.

The Testbed takes both AM and PM peak into its temporal scope for both weekends and weekdays for selecting operational conditions using cluster analysis. Figure 2-6 shows the geographic overlay map of the Testbed.

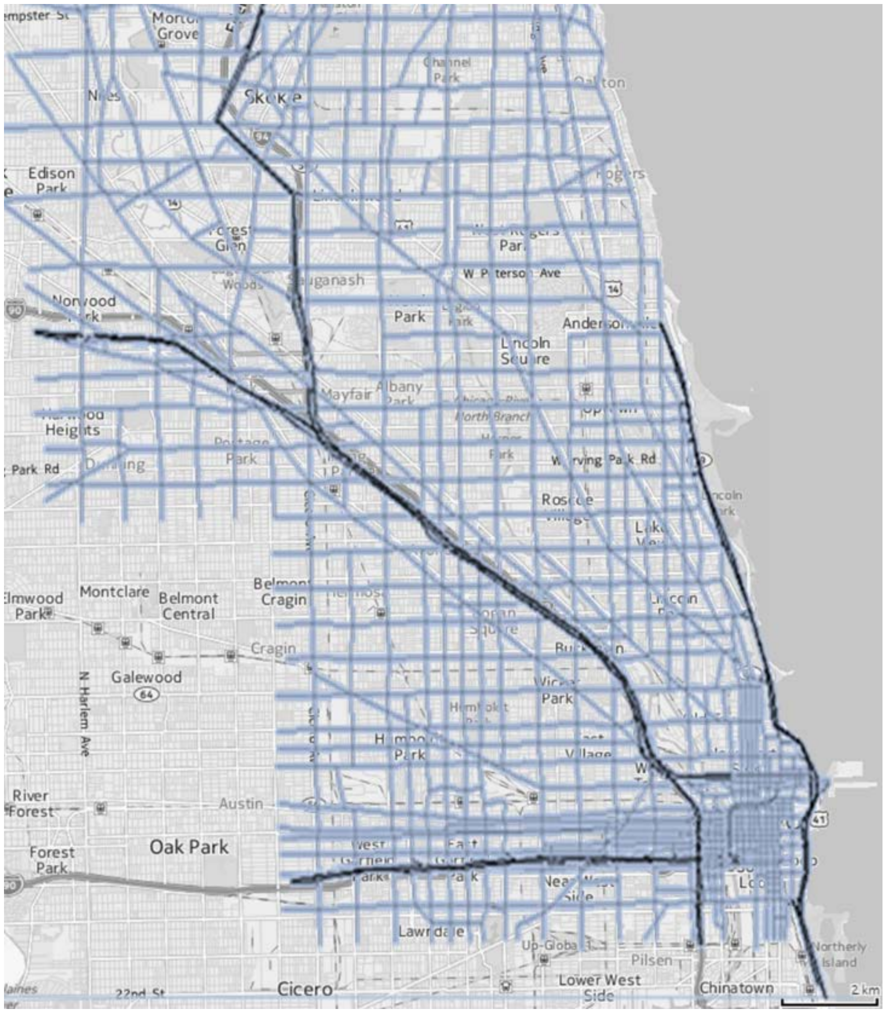

Figure 2-6 - Chicago Testbed [Source: Booz Allen]

2.1.6 San Diego

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 Balboa Avenue as shown in Figure 2-7. The express lanes are currently under construction from Beethoven Drive to SR-78 and will only be included in the future models. 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 Tolled (HOT) lanes.

This Testbed considers both AM and PM peak travel and utilized ICM San Diego's Cluster Analysis-based operational conditions. The testbed also includes two typical weekday operational conditions.

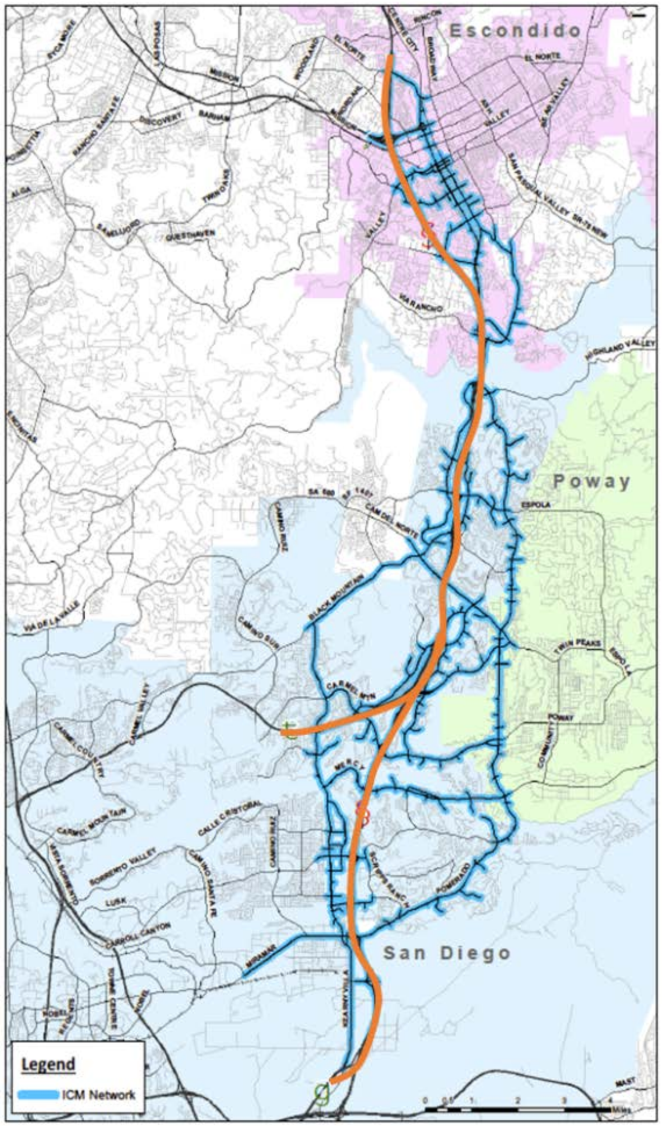

Figure 2-7 - San Diego Testbed Geographic Extent [Source: TSS]

2.2 Operational Conditions

Cluster analyses were done to develop operational conditions that would be included in the analysis by finding out representative days for using historical data. In general, three types of data are used for conducting cluster analysis and identifying prevalent operational conditions. They are:

1. Data that represents underlying phenomena such as traffic flows etc. This data will include demand for different modes of data such as SOV, HOV, Transit, and Freight.

2. Data that considers non-recurring measurements such as incident and weather data. This data was extracted from the respective weather stations, incident logs from highway patrol or similar sources.
3. Data that characterizes the system outcomes in terms of specific measures such as travel time to perform the cluster analysis. This will include data from loop detectors, Bluetooth sensors, cameras etc.

Once the data are assembled, cluster analysis is performed over all peak periods using cluster analysis algorithms or a statistical package that offers cluster analysis. This is a non-traditional use of cluster analysis, since it is normally used during the early explorative stage of data analysis to discover the structure in the data that has already been collected. In this case, cluster analysis is used to reduce some of the structure and to determine the best scenarios to represent the whole spectrum of traffic conditions for the evaluations of DMA application bundles and ATDM strategies later. Different statistical packages are used by different testbeds, but the approach remained consistent. Depending on the complexity of the testbed operational capabilities, three to six representative operational conditions are identified using cluster analysis. These are explained in Table 2-2. In addition, a few hypothetical operational conditions are assumed for some testbeds to demonstrate some hypothetical scenario 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 and will be included in the evaluation only if time and resources permit.

Table 2-2 - Operational Conditions for Each Testbed

Op. Con.	San Mateo	Pasadena	Dallas	Phoenix	Chicago	San Diego
OC-1	Low to Medium Demand, Major Incidents, Dry Weather Conditions	High Demand, Minor Incidents, Dry Weather Conditions	Medium to High Demand, Major Incident, Dry Weather Conditions	Low Demand, Minor Incidents, Dry Weather Conditions	High Demand, No Incidents, Dry Weather Conditions	Southbound (AM), Medium Demand, Medium Incident
OC-2	Low to Medium Demand, Major Incidents, Wet Weather Conditions	Medium to High Demand, Major Incidents, Dry Weather Conditions	High Demand, Medium Incident, Dry Weather Conditions	Medium 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	High Demand, Medium Incidents, Dry	Medium to High Demand, Minor Incident, Dry	Low Demand, Minor Incidents, Dry	Medium to High Demand, No Incidents,	Northbound (PM), Medium Demand, High Incident

Op. Con.	San Mateo	Pasadena	Dallas	Phoenix	Chicago	San Diego
	Weather Conditions	Weather Conditions	Weather Conditions.	Weather Conditions.	Snowy Weather Conditions	
OC-4	Medium to High Demand, Minor Incidents, Dry Weather Conditions		High Demand, Minor Incident, Dry Weather Conditions.	High Demand, Minor to Medium Incidents, Wet Weather Conditions.	Low to Medium Demand, No Incidents and Snowy Weather Conditions	Northbound (PM), Medium Demand, Medium Incident
OC-5	High Demand, Major Incidents, Dry Weather Conditions				High Demand, No Incidents, Rainy Weather Conditions	
OC-6					Medium to High Demand, No Incidents, Snowy Weather Conditions.	
HO-1*	Medium Demand, No Incidents and Snowy Weather Condition.		Low Demand, Major Incidents and Snowy Weather Conditions.	Medium Demand, Major Incident, Dry Weather Conditions.	Medium to High Demand, Minor Incidents, Snowy Weather Conditions	Northbound (PM), Medium Demand, High Incident condition around MMITSS-intersections.
HO-2*	Medium Demand, Minor Incidents and Snowy Weather Condition.		High Demand, No Incidents, Contra-flow Operations, Wet Weather Conditions.	Medium Demand, No Incidents, Low Visibility Weather Conditions (dust storms)		

Table 2-3 shows the operational conditions attributes with respect to demand, incident severity and weather conditions across Testbeds.

Table 2-3 - Operational Conditions Attributes Across Testbeds

Attribute	Value	San Mateo	Pasadena	Dallas	Phoenix	Chicago	San Diego
Demand	Low	●			●	●	
	Medium	●	●	●	●	●	●
	High	●	●	●	●	●	
Incident Severity	None	●				●	
	Low	●	●	●	●		
	Medium		●	●			●
	Major	●	●	●	●		●
Weather Conditions	Dry	●		●	●	●	●
	Light Rain	●				●	
	Moderate Rain				●	●	
	Heavy Rain					●	
	Moderate Snow					●	
	Heavy Snow					●	

2.2.1 Modes Considered

Each of the six testbeds considered uses a multitude of transport modes in the modeling and implementation process. This includes primarily transit vehicles, high occupancy cars, single occupancy cars, buses and trucks. A mapping of modes based on the six testbeds is provided in Table 2-4.

Table 2-4 - Transportation Modes Explicitly Considered in Modeling

Mode	San Mateo	Pasadena	Dallas	Phoenix	Chicago	San Diego
Single Occupancy Vehicles	●	●	●	●	●	●
High Occupancy Vehicles	●	●	●		●	●

Mode	San Mateo	Pasadena	Dallas	Phoenix	Chicago	San Diego
Transit	●		●	●		
Heavy Trucks	●			●		●
Park-and-ride Split Modes			●	●		

2.2.2 Tools Used

In order to achieve the AMS project goals, each of the Testbeds will use specific modeling tools to add capabilities such as wireless communication and prediction. Table 2-5 provides comprehensive listing of the major modeling tools associated with the Testbeds. This include Prediction Engine, Communications Emulator, Scenario Generator, System Manager Emulator, Demand Simulator, Network Simulator and Performance Measurement Data Bus. Please note that description on specific modeling tools are provided in the respective Testbed's analysis plan document. Modeling tools described as "custom" defines non-standard procedure to model specific assumption and are built specifically for this project.

Table 2-5 - Modeling Tools Used for Testbeds

Modeling Tools/ Assumptions	San Mateo	Pasadena	Dallas	Phoenix	Chicago	San Diego
Prediction Engine	None	TRANSIMS	DIRECT	Custom	P-DYNA	Aimsun
Communications Emulator	TCA Tool	Custom	None	Custom	None	TCA
Scenario Generator	Custom	Custom	Custom	Custom	Custom	Aimsun
System Manager Emulator	None	GeoDyn2	Custom	Custom	DYNASMART-X	Aimsun
Demand Simulator	None	VISUM	None	Open-AMOS	DYNASMART-X	Aimsun
Network Simulator	VISSIM	VISSIM	DIRECT	DTALite/ VISSIM	DYNASMART-X	Aimsun
Data Bus - Performance Measures	None	Custom	None	Custom	None	None

Chapter 3. Evaluation Plan for DMA Program

This section describes the overall plan for evaluating the system-wide impacts of individual DMA applications, individual DMA bundles, and logical combinations of bundles and applications, and identifying conflicts and synergies for maximum benefit. In particular, this section describes the plan to analyze a range of DMA applications under various conditions to evaluate their effectiveness in achieving the DMA program goals as outlined by the research questions and hypotheses.

In particular, this section describes the collective analysis conducted for DMA program across all testbeds including what the combined analyses is expected to reveal when considered as a whole, relevant to the goals of the DMA Program.

3.1 DMA Application Tested

Table 3-1 shows the mapping of the DMA applications that are being implemented and evaluated in each testbed. As shown, 15 out of 21 DMA applications are included in the analysis in some level of detail. Also, Dallas Testbed would remain exclusively for ATDM strategies. 6 applications are not within the current scope of evaluation owing to the fact that they are either not prototyped, or a version of application that could be simulated is not available. The modeled applications include applications from both tactical and strategic sets of DMA applications.

Table 3-1 - DMA Application Mapping with Testbeds

DMA Application	San Mateo	Pasadena	Dallas	Phoenix	Chicago	San Diego
EnableATIS						
ATIS				●		
S-PARK						
T-MAP						
WX-INFO						
INFLO						
Q-WARN	●	●				●
SPD-HARM	●	●			●	●
CACC						●
MMITSS						
I-SIG	●					●
TSP	●					●
PED-SIG	●					
PREEMPT	●					●
FSP	●					

DMA Application	San Mateo	Pasadena	Dallas	Phoenix	Chicago	San Diego
IDTO						
T-CONNECT						
T-DISP				●		
D-RIDE				●		
FRATIS						
F-ATIS				●		
DR-OPT						
F-DRG				●		
R.E.S.C.U.M.E.						
EVAC						
RESP-STG	●			●		
INC-ZONE	●			●		

The following applications were not included in the AMS Testbed Evaluation:

1. EnableATIS applications such as S-PARK, T-MAP and WX-INFO are not included in the evaluation since these applications are not prototyped by the DMA Program and cannot be developed within the scope of the AMS project.
2. INFLO application named CACC is not included in the current evaluation, since this prototyped application is specific to AIMSUN simulation program, which is not used in the current evaluation.
3. IDTO application named T-CONNECT is not included because 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, or 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.
4. FRATIS application named DR-OPT is not included since the prototyped application is a pre-trip optimization software with no microscopic modeling functionality.
5. R.E.S.C.U.M.E. application named EVAC is not included in the current evaluation, since the prototyped application is on a regional macroscopic scale. AMS Testbeds are built on a microscopic scale.

3.2 DMA Research Questions

This section enumerates the research questions identified by the DMA program[1] and which testbeds will address these questions. Most DMA research questions will be answered by San

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

Mateo and Phoenix Testbeds. The current evaluation plan is such that 21 out of the 29 research questions will be answered by the analysis at one or more testbeds. The mapping is provided in Table 3-2.

Table 3-2 - DMA Research Question Mapping with Testbeds

ID	DMA Research Question	San Mateo	Pasadena	Dallas	Phoenix	Chicago	San Diego
	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?	●			●		●
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,	●			●		●

ID	DMA Research Question	San Mateo	Pasadena	Dallas	Phoenix	Chicago	San Diego
	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						
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?	●					●

ID	DMA Research Question	San Mateo	Pasadena	Dallas	Phoenix	Chicago	San Diego
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 off-set costs, if costs are associated with it?						

ID	DMA Research Question	San Mateo	Pasadena	Dallas	Phoenix	Chicago	San Diego
27	How sensitive are individual applications to the availability (or lack thereof) of data from multiple sources/agencies?						
28	What type of data is 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?	•					•

Some of the research questions that are not currently being evaluated in any testbed will be qualitatively assessed in the last phase of the project to provide insights based on the results and understanding from the evaluation results. This will involve a break-down analysis of individual application's system design (either from the prototype or the impact assessment). For example, research question 27 states that: How sensitive are individual applications to the availability (or lack thereof) of data from multiple sources or agencies? This will be assessed based on the different data sources that are currently used as well as that could potentially be sourced by applications based on their design and functionality.

3.3 DMA Hypothesis

This section outlines the preliminary hypothesis used to assess different research questions identified for the AMS Project[2]. These are shown in Table 3-3. Please note that hypotheses for questions that are not within the current evaluation plan are also provided here.

Table 3-3 - 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	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

ID	DMA Research Question	Analysis Hypotheses
	augmented with data from legacy systems? What is the marginal benefit if data from legacy systems are augmented with data from connected vehicle technology?	
2	Are the DMA applications and bundles more beneficial when implemented in isolation or in combination?	DMA bundles that are synergistic will be more beneficial when implemented in combination than in isolation.
3	What DMA applications, bundles, or combinations of bundles complement or conflict with each other?	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.
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 plan.
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.
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.
10	Which DMA bundle or combinations of bundles will be most beneficial for certain facility types (freeway, transit,	Certain DMA bundles or combinations of bundles will yield the highest benefits for

ID	DMA Research Question	Analysis Hypotheses
	arterial) and under what operational conditions?	specific facility types and under certain 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?	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.
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-

ID	DMA Research Question	Analysis Hypotheses
		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 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.

ID	DMA Research Question	Analysis Hypotheses
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 participation varies within a regional deployment?	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 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 off-set 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	IDTO will be beneficial only with data from various transit agencies; FRATIS will be beneficial when there is data from freight

ID	DMA Research Question	Analysis Hypotheses
	thereof) of data from multiple sources/agencies?	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.

3.4 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 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.

3.4.1 Overall Performance Measures

Performance measures are identified across the applications which will be used to assess the individual application's impacts in the testbeds under different operational conditions. Since DMA applications are primarily driven for 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 considered are:

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:** Delay of vehicles 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. **95th Percentile Travel Time:** This measures the travel-time reliability under different operational conditions.

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

3.4.2 Application-specific Performance Measures

While universal performance measures are valued across the different applications, additional performance measures are defined to evaluate specific bundles/applications that are either specific to a class of vehicles, facility types or type of region. These additional performance measures are given:

3.4.2.1 EnableATIS

1. **Average Travel Time:** The average travel-time of vehicles are computed based on individual vehicle's travel-time and is compared against different operational conditions.
2. **Change in Modal Split:** Providing advanced traveler information may or may not affect the modal split of the travel. This is assessed using this metric.
3. **Change in Route Selection:** This will be assessed based on the vehicle miles traveled metric to assess the total number of miles covered between different scenarios.

3.4.2.2 INFLO

1. **Average Queue Length:** Average length of queues on the freeway bottlenecks are computed from individual vehicle records and can be used to assess mobility improvement by INFLO.
2. **Average Queue Duration:** Average duration of bottleneck queues on the freeways can be used to assess the mobility improvement by INFLO applications.
3. **Average/Maximum Speed Variation:** Average speed variation between adjacent sub-sections of the highway and the maximum speed variation within a sub-section of the highway are used as potential safety metric. Vehicles within a 0.5-mile long adjacent sub-section of the highway under a 15-minute time-resolution will be used for this analysis.
4. **Maximum Deceleration:** Maximum deceleration of vehicles within a sub-link is another safety metric to be used in evaluating INFLO.

3.4.2.3 MMITSS

1. **Maximum Queue Length:** Maximum queue length at an intersection approach is used to assess the performance of I-SIG application.
2. **Average Intersection Throughput:** The intersection throughput is defined as the number of vehicles that are served in a signal cycle of a given duration.
3. **Traveler-specific Delay:** This metric is applicable to MMITSS applications such as TSP, FSP which are user-specific and includes average transit delay, average first-responder delay.
4. **Average Number of Stops:** This metric computes the average number of stops (instances where vehicle speeds drop to under 10 miles per hour) within the vicinity of intersections.

3.4.2.4 IDTO

1. **Percentage of Connections Protected:** This is quantified by percentage of successful connections within an agency, within different agencies and within different modes. Fixed and flexible mode connections are also assessed.

2. **Average Passenger Wait-time:** Average percentage of idle time (wait-time) for transit users for a unit of trip time is also used as a performance measure.

3.4.2.5 FRATIS

1. **Average Terminal Wait-time:** Average Wait-time of freight vehicles at freight terminals is defined as a measure of how effective FRATIS is in distributing terminal arrivals over a course of time.
2. **Average Terminal Queue Length:** Average queue length of freight vehicles at terminals is a prime mobility measure for freight performance.
3. **Percentage of Bob-tail Trips:** Bobtails are defined as the truck trips without freight and is considered to negatively impact the effectiveness of truck movements.

3.4.2.6 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. **Maximum Deceleration of Vehicles:** Maximum deceleration of vehicles prior to the incident is an indirect safety measure in minimizing the probability of secondary crashes.
3. **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 3-4 shows a mapping of performance measures with testbeds and includes both application-specific and overall performance measures.

Table 3-4 - Mapping of DMA-based Performance Measures with Testbeds

Performance Measure	San Mateo	Phoenix	Chicago	San Diego
Average Travel Speed	X	X	X	X
Average Vehicle Delay	X	X	X	X
System Throughput	X	X	X	X
95th Percentile Travel Time	X	X	X	X
Average Travel Time		X		X
Change in Modal Split		X		
Average Length and Duration of Queues at Freeway Bottlenecks	X			
Average Speed Variation Within Adjacent Sub-links.	X		X	X
Maximum Speed Variation Within a Sub-link	X		X	X
Maximum Deceleration of Vehicles	X			
Maximum Intersection Queue Length	X			X
Average Intersection Throughput	X			X
Traveler-specific Delay	X			X
Average Number of Stops	X			X
Percentage of Connections Protected		X		
Average Passenger Wait-time		X		

Performance Measure	San Mateo	Phoenix	Chicago	San Diego
Terminal Wait-time and Queue Lengths for Freight		X		
Percentage of Bob-tail Trips		X		
Average Incident Zone Speed	X	X		
Incident Zone Throughput	X	X		

3.5 Analysis Scenarios

This section describes how testbed scenarios are constructed using a combination of operating conditions, DMA applications, and a range of application attributes. The full list of scenarios pertaining to different testbeds is included the Appendix.

3.5.1 DMA Application Combinations Tested

AMS Testbed goals and objectives are different from DMA Program Evaluation and similar impact assessment projects. One of the distinguishing characteristic is the use of combination of applications and bundles within the same operational condition to isolate synergies or conflicts between them. This section describes application combinations evaluated using different testbeds. For example, IDTO and EnableATIS combination is tested using the Phoenix Testbed. It has to be noted that only San Mateo and Phoenix Testbeds will be doing combinations of DMA applications. These are shown in Table 3-5.

Table 3-5 - DMA Application Combinations and Respective Testbeds

	EnableATIS	INFLO	MMITSS	IDTO	FRATIS	R.E.S.C.U.M.E.
EnableATIS						
INFLO						
MMITSS		San Mateo, San Diego				
IDTO	Phoenix					
FRATIS	Phoenix			Phoenix		
R.E.S.C.U.M.E.	Phoenix	San Mateo	San Mateo	Phoenix	Phoenix	

3.6 Assessment Attributes and Policies

In order to answer the DMA research questions, a number of parameters and attributes are included in the testbed-based analysis of communication technology. Some applications are designed with inherent communication assessment techniques, such as MMITSS, whereas some others are integrated with communication emulators for assessment, such as INFLO. The assessment will evaluate the effect of communication latency, messaging frequency and message losses. Table 3-6 shows the scenario attributes and assumptions used in evaluating the DMA Research Questions.

Table 3-6 - DMA Assessment Scenario Attributes and Assumptions

	Scenario Components, Attributes and Assumptions	Research Question Mapping		Testbed			
		Groups	IDs	San Mateo	Phoenix	Chicago	San Diego
Communication Attributes							
1	Communication Latency (eg: 1 minute, 5 minutes)	Connected Vehicle Technology vs Legacy Systems; Messaging Protocols; Communication Technology; Communication Latency/Errors; RSE/DSRC Footprint	16	•	•		•
2	Message Frequency (eg: 0.1 second, 0.5 second)		13	•	•		•
3	Message Errors or Loss (eg: 10% loss, 20% loss)		17	•	•		•
4	RSE Footprint (eg: 0.2 mile)		18 and 23	•			
5	Cellular Coverage (eg: full coverage, limited coverage)		18	•			
6	Market Penetration (eg: 20% equipped)		22 and 23	•	•	•	•
Communication Technologies and Policies							
1	Legacy Systems	Connected vehicle Technology vs Legacy Systems; Messaging Protocols; Communication Technology; Communication Latency/Errors; Deployment Readiness	1 and 19	•			
2	DSRC		1, 13 and 19	•	•		•
3	Cellular Coverage		1 and 19	•			
4	Nomadic Devices		15 and 19				
5	Message Protocol		13		•		

3.6.1 Communication Technology and Attributes

This section describes the different communication attributes that will be considered in the analysis across all the testbeds and the mapping of which communication attributes will be varied for each testbed and the associated research questions. The communication attributes to be included in the evaluation include

1. **Communication Latency:** This is defined as the time delay in wireless communication between vehicles and the infrastructure units. DSRC communication usually results in low latency than cellular communication.

2. **Message Frequency:** This is defined as the frequency at which DMA applications receive latest information so that the application outputs can be updated.
3. **Message Errors or Loss:** Message losses are considered in this evaluation using percentage of messaging packets being lost in transition.
4. **RSE Footprint:** This is the range of Road-Side Equipment and characterizes the distance within which vehicles would be able to use DSRC communication.
5. **Cellular Coverage:** This is the coverage extent of cellular connectivity within which vehicles would be able to broadcast and receive information.
6. **Market Penetration:** This is the percentage of vehicles that is considered connected and actively participate in broadcasting and receiving information. For some applications, market penetration also represents the number of travelers with access to DMA applications and associated information.

3.6.2 Communication Technologies and Policies

A description of the communication technology and policies that will be evaluated for the different operational scenarios is provided below along with a mapping of the associated research questions and testbeds:

1. **Legacy Systems:** This includes existing systems in the geographic locations of the testbeds, such as ramp metering systems, loop detectors etc.
2. **DSRC:** Low-latency Dedicated Short Range Communication that enables communication between Connected Vehicles within short range from the Road Side Equipment.
3. **Cellular:** Cellular communication will have a higher latency than DSRC, but wider coverage in terms of connectivity.
4. **Nomadic Devices:** This includes two classes of devices – the ones used in-vehicle by connected vehicles and the ones used by individual travelers in transit and pedestrian mode (mobile devices).
5. **Message Protocol:** SAE J2735 Protocol would be used for the generation of Basic Safety Messages. Basic Mobility Message protocols are still under investigation.

3.7 Evaluation Approach

This section highlights the approach to evaluating the different research questions under different testbeds. This includes which scenarios will help in the evaluation. Table 3-7 enlists the approach mapped to the testbeds. Please note that Dallas Testbed is not included in the table since it is not used for DMA Evaluation. A listing of scenarios are provided in the Appendix.

Table 3-7 - DMA Research Questions' Evaluation Approach Mapping to Testbeds

No.	Research Question	San Mateo	Phoenix	Chicago	San Diego
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?	Both INFLO and MMITSS applications would be assessed with and without Connected Vehicle data, by using traditional sensor data (intersection and freeway sensors). A comparison of this results will be performed to answer this research question.	N/A	SPD-HARM application would be used to analyze this.	This will be assessed using INFLO and MMITSS applications.
2	Are the DMA applications and bundles more beneficial when implemented in isolation or in combination?	Initial operational scenarios are designed to study applications in combination or isolation. For this testbed, INFLO, R.E.S.C.U.M.E. and MMITSS are used.	Applications such as ATIS, FRATIS and RESCUME. IDTO will be assessed individually and in combination as given in Appendix.	N/A	Applications within INFLO and MMITSS bundles will be evaluated in the first two phases in combination and isolation.

No.	Research Question	San Mateo	Phoenix	Chicago	San Diego
3	What DMA applications, bundles, or combinations of bundles complement or conflict with each other?	Initial operational scenarios are designed to study applications in combination or isolation. For this testbed, INFLO, R.E.S.C.U.M.E. and MMITSS are used	Applications such as ATIS, FRATIS and RESCUME. IDTO will be assessed individually and in combination as given in Appendix.	N/A	Applications within INFLO and MMITSS bundles will be evaluated in the first two phases in combination and isolation.
4	Where can shared costs or cost-effective combinations be identified?	N/A	N/A	N/A	Benefit-cost analysis of these applications will be performed using available resources from DMA National Impacts Assessment Project.
5	What are the tradeoffs between deployment costs and benefits for specific DMA bundles and combinations of bundles?	N/A	N/A	N/A	Benefits and Impacts estimation models will be used for INFLO and MMITSS.
6	What DMA bundles or combinations of bundles yield the most benefits for specific operational conditions?	INFLO and MMITSS bundles will be evaluated in this testbed under different operational conditions.	Combination of 4 bundles will be carried out across this testbed. This includes EnableATIS, IDTO, FRATIS and R.E.S.C.U.M.E.	N/A	INFLO and MMITSS bundles will be evaluated in this testbed under different operational conditions.
7	Under what operational conditions are specific bundles the most beneficial?	Combinations of No/Short/Long incident along with Dry/Rainy/Show weather conditions are tested for different combinations across the overall analyses.	6 different operational conditions including two hypothetical will be assessed over the overall analyses.	N/A	Applications will be assessed under medium to high demand and medium to high incident severity and will be compared against each other.

No.	Research Question	San Mateo	Phoenix	Chicago	San Diego
8	Under what operational conditions do particular combinations of DMA bundles conflict with each other?	Combinations of No/Short/Long incident along with Dry/Rainy/Show weather conditions are tested for different combinations across the overall analyses.	Applications will be assessed under medium to high demand and medium to high incident severity and will be compared against each other.	N/A	Applications will be assessed under medium to high demand and medium to high incident severity and will be compared against each other.
9	Which DMA bundle or combinations of bundles will be most beneficial for certain modes and under what operational conditions?	N/A	Freight and Transit vehicles are simulated to analyze modes.	N/A	N/A
10	Which DMA bundle or combinations of bundles will be most beneficial for certain facility types (freeway, transit, arterial) and under what operational conditions?	INFLO and INC-ZONE are tested for freeways and MMITSS are tested for arterials. Transit applications are not tested.	INC-ZONE application will be assessed at a freeway level, whereas applications such as IDTO will be assessed on a transit system level. EnableATIS and FRATIS work on a regional level and hence cannot be tested on a facility type.	N/A	INFLO will be assessed on freeways and MMITSS will be assessed on arterials.
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?	INFLO-MMITSS combination would only be utilized for this question, INFLO works on a freeway system and MMITSS will work on an arterial system. Region-wide deployment of these systems incorporate	N/A	N/A	N/A

No.	Research Question	San Mateo	Phoenix	Chicago	San Diego
		the two systems working in parallel.			
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 and negative impacts of individual applications would be quantified on a facility basis to evaluate this.	Benefits and negative impacts of individual applications would be quantified on a facility basis to evaluate this.	N/A	N/A
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 PDM, 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?	A qualitative analysis of INFLO and MMITSS bundles and applications would produce a set of minimum standards for data requirements based on DMA applications.	N/A	N/A	TCA Tool will be utilized to assess effectiveness of different messaging frequencies.
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?	N/A	This will be assessed as a part of EnableATIS where specific travelers will use information at different stages of trip to make/change their route and mode.	N/A	N/A
15	Will a nomadic device that is capable of communicating via both	N/A	N/A	N/A	N/A

No.	Research Question	San Mateo	Phoenix	Chicago	San Diego
	DSRC as well as cellular meet the needs of the DMA bundles? When is DSRC needed and when will cellular suffice?				
16	What are the impacts of communication latency on benefits?	Varying latency rates will be evaluated using TCA communications emulator	N/A	N/A	INFLO application will be assessed using different latency values.
17	How effective are the DMA bundles when there are errors or loss in communication?	Varying loss rates will be emulated using artificially removing data packets produced by TCA.	Applications tested under Phoenix will qualitatively assess the impact of losses in communication by analyzing the data elements and frequency required by these applications.	N/A	INFLO application will be assessed using different latency values.
18	What are the benefits of widespread deployment of DSRC-based RSEs compared with ubiquitous cellular coverage?	Applications that require less-than-cellular latency will be quantified to compare benefits of DSRC-based RSE deployment.	N/A	N/A	N/A
19	Which technology or combination of technologies best supports the DMA bundles in terms of benefit-cost analysis?	N/A	N/A	N/A	N/A
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	N/A	Predictive traveler information will be utilized with EnableATIS framework to assess this question.	N/A	N/A

No.	Research Question	San Mateo	Phoenix	Chicago	San Diego
	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?	A thorough evaluation of minimum data requirements for various DMA applications as well as data mapping of standard message sets will be done to potentially answer this question.	N/A	N/A	A thorough evaluation of minimum data requirements for various DMA applications as well as data mapping of standard message sets will be done to potentially answer this question.
22	At what levels of market penetration of connected vehicle technology do the DMA bundles (collectively or independently) become effective?	Various levels of market penetration would be simulated with INFLO and MMITSS applications.	Various levels of market penetration would be simulated with FRATIS, IDTO and RESCUME applications.	Various levels of market penetration would be simulated with SPD-HARM application.	Various levels of market penetration would be simulated with INFLO and MMITSS applications.
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)?	Varying market penetration would be assessed for applications. RSE deployment density will be assessed as a function of geographic coverage for applications.	Varying market penetration would be assessed for applications. RSE deployment density will be assessed as a function of geographic coverage for applications.	N/A	Team will use NHTSA-based market penetration levels to assess near-, mid- and long-term impacts.
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	N/A	N/A	N/A	N/A

No.	Research Question	San Mateo	Phoenix	Chicago	San Diego
	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?	N/A	Local agency participation for IDTO application will assessed as a function of transit agencies that will influence the applications. Similar analysis with FRATIS will be done where sensitivity to agency participation will be assessed as a function of class of freight vehicles being influenced.	N/A	N/A
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 off-set costs, if costs are associated with it?	N/A	N/A	N/A	N/A
27	How sensitive are individual applications to the availability (or lack thereof) of data from multiple sources/agencies?	N/A	N/A	N/A	N/A
28	What type of data are necessary from non-transportation entities (for instance, hospitals or	N/A	N/A	N/A	N/A

No.	Research Question	San Mateo	Phoenix	Chicago	San Diego
	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?	Simulation-based vehicle records will be used to assess the difference in benefits to the application's participants versus non-participants.	N/A	N/A	N/A

3.8 Reporting Benefits and Costs

Benefit-Cost Analysis can help make sense of the modeling results and can be used to estimate national-level net benefits for each of the DMA application. Reporting of benefits and costs will entail two parallel analysis streams

3.8.1 Computation of Benefits:

Benefits are estimated based primarily on the mobility benefits for DMA applications and bundles for the various testbeds. The benefit computation will be done using the following steps:

1. Identifying Benefit Categories: This involves narrowing down the overall performance measures to select the benefit categories that will best capture the features of different DMA applications and bundles. Benefit categories selected could be direct mobility measures such as reduction in delay or indirect measures such as reduction in probability of crashes. Overall performance measures such as delay, throughput and travel-time reliability will be used in the computation of benefits.
2. Estimate Benefits for Applications: Once the benefit category is selected, modeling results would be used to estimate unit benefits that each application will realize. The values would be normalized to a unit basis depending on the type of application (e.g., delay minutes per VMT or delay minutes per intersection signal crossing as appropriate). The unit benefits will be assigned a monetary value based on the social and monetary costs associated with the benefit categories.
3. Conduct Uncertainty and Sensitivity Analysis: Uncertainty and sensitivity analyses would be done to analyze any uncertainties in the selected benefit categories as well as sensitivity with other variables.

3.8.2 Computation of Costs:

Costs estimation including implementation costs from the agencies and the road-users will be assessed using FHWA's Cost Overview for Planning Ideas & Logical Organization Tool (CO-PILOT). The tool allows cost estimation for 56 applications in the Vehicle to Infrastructure Safety, Vehicle to Vehicle Safety, Agency Data, Environment, Road Weather, Mobility, and Smart Roadside application groups. The tool will be used to assess full lifecycle costs and will assume an implementation time-frame of 5, 10 and 20 years. Qualitative research will be done to assess maintenance and other indirect costs that are not addressed by the tool.

3.9 Collective Research Findings for DMA Program

This section describes how the analysis performed with each testbed will be combined to answer the research questions and test each hypothesis. This section provides a synthesis of what the combined analyses is expected to reveal when considered as a whole, relevant to the goals of the DMA. An assessment of what can be expected from the collective analyses and what cannot be expected will be documented. Research questions and hypotheses indirectly or not addressed will be documented.

*Please note that the figures are for illustrative purposes only and will be updated as results are collected from the analysis.

3.9.1 Connected Vehicle Technology Vs Legacy Systems

Certain DMA applications subscribe to both connected vehicle and legacy system data. Wherever the application permits, the analyses would be conducted to assess the impact of one type of data over the other. For example, INFLO application uses both detector data and CV data.

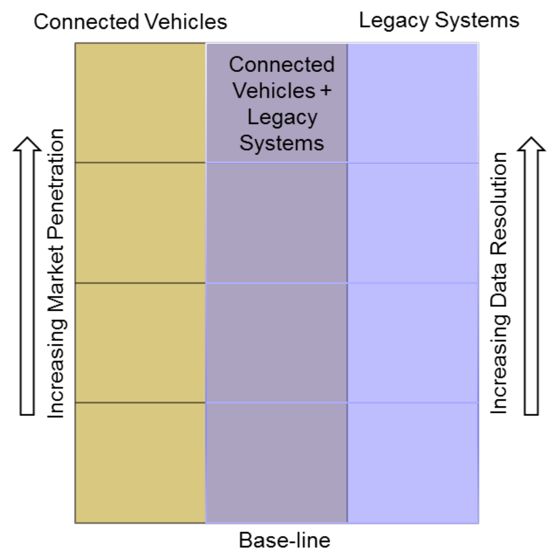

Figure 3-1 - Synergies between Connected Vehicle Data and Legacy Systems Data [Source: Booz Allen]

Please note that the figures are for illustrative purposes only and will be updated as results are collected from the analysis.

3.9.2 Synergies and Conflicts

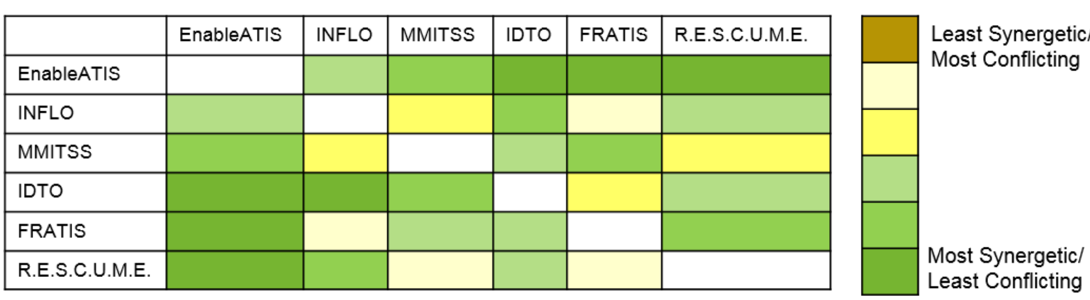

Figure 3-2 - Synergies and Conflicts between Combinations of Application Bundles [Source: Booz Allen].

Please note that the figures are for illustrative purposes only and will be updated as results are collected from the analysis.

Tactical DMA applications such as INFLO and MMITSS are primarily simulated in the San Mateo Testbed and the Strategic DMA applications such as IDTO and EnableATIS are evaluated using Phoenix Testbed. While the synergies and conflicts between specific applications within the tactical and strategic groups can be derived quantitatively using the established set of operational conditions, additional qualitative analysis would be done to assess the synergies and conflicts between two applications that fall under different groups. Primarily this will involve a step-by-step assessment of the application including the data requirement, data processing and data dissemination. For example, FRATIS applications are primarily aimed at freight vehicle assignment which is done pre-trip and therefore will not conflict or synergize en-route application such as INFLO.

3.9.3 Operational Conditions, Modes, Facility Types

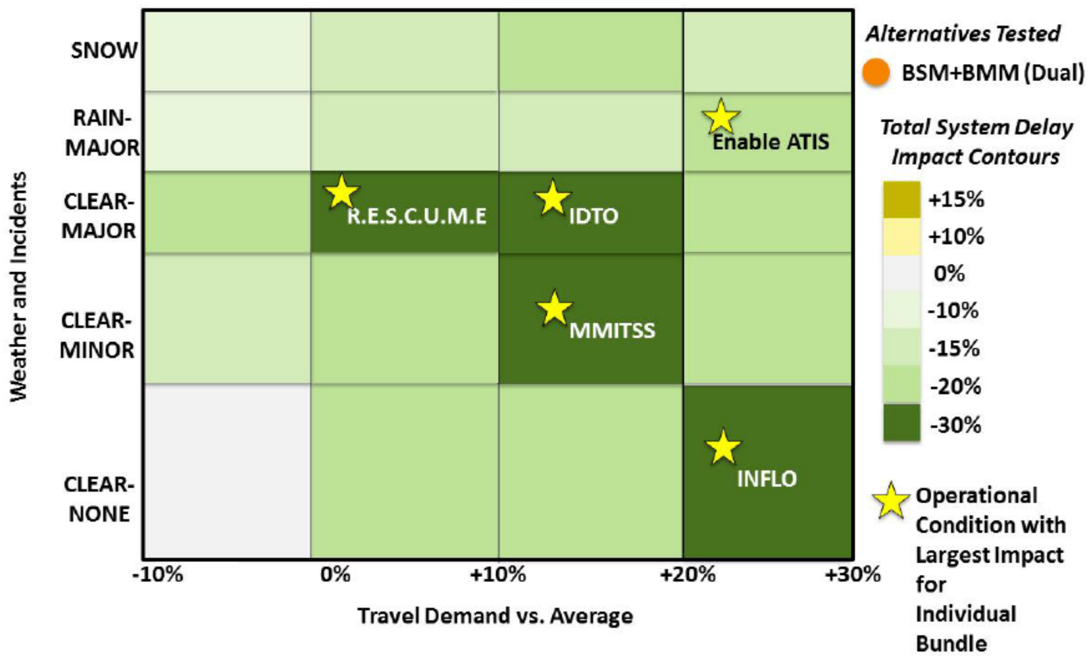

Figure 3-3 - Operational Conditions Mapping with Individual Bundles with Largest Impact [Source: FHWA-JPO-13-097]

Please note that the figures are for illustrative purposes only and will be updated as results are collected from the analysis. Specifically, applications will be assessed based on individual performance measures and will be ranked according to different operational conditions. Applications, with the exception of mode and facility-specific ones, will be assessed based on their performance under different modes and facility types.

3.9.4 Messaging Protocols and Communication Technology

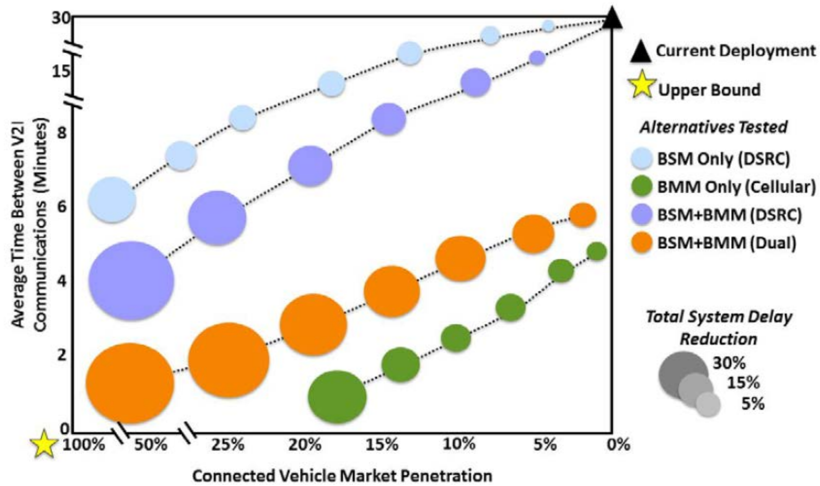

Figure 3-4 - Impact of Messaging Protocols and Communication Technology Under Varying Market Penetration. [Source: FHWA-JPO-13-097]

Please note that the figures are for illustrative purposes only and will be updated as results are collected from the analysis. This analysis is testbed-specific and primarily involves the following alternatives: BSM over DSRC and BSM over Cellular. The analysis will also involve a qualitative assessment of messaging protocols mapped to the data elements used by individual applications and bundles. This analysis is expected to yield insights into what communication technology and messaging protocols have most benefits at least implementation cost.

3.9.5 Communication Latency and Errors

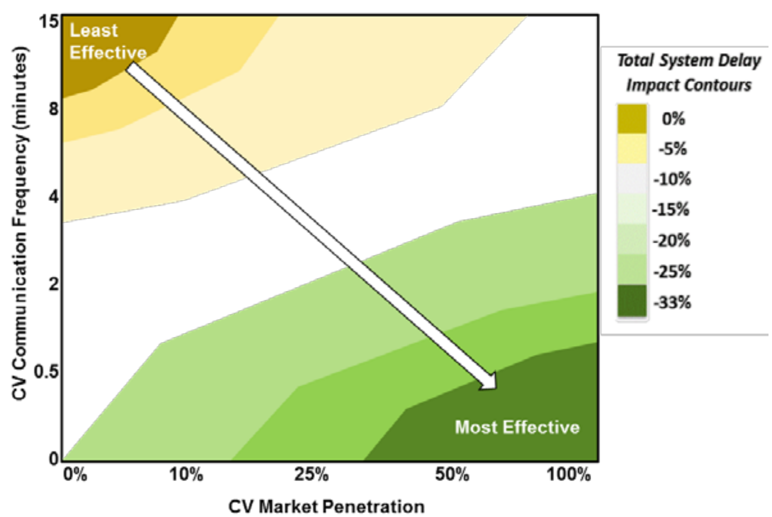

Figure 3-5 - Impact of Latency and Errors on Applications. [Source: Booz Allen]

Please note that the figures are for illustrative purposes only and will be updated as results are collected from the analysis. Primarily, San Mateo Testbed will be used for communication assessment under different latency and frequency values using the TCA- communications emulator. Strategic applications that are not assessed under San Mateo Testbed will be assessed at an application level using testbed-specific tools.

3.9.6 Deployment Readiness

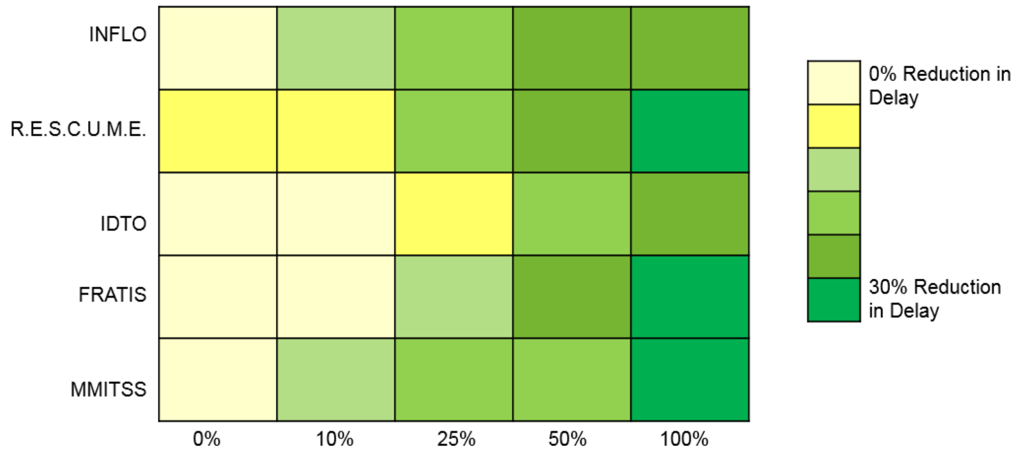

Figure 3-6 - Impact of Application Bundles at Different Percentages of Market Penetration [Source: Booz Allen]

Please note that the figures are for illustrative purposes only and will be updated as results are collected from the analysis.

Chapter 4. Evaluation Plan for ATDM Program

This section describes the overall plan for evaluating the system-wide impacts of ATDM strategies when implemented individually and in logical combinations, and identifying conflicts and synergies for maximum benefit. In particular, this section describes the plan to analyze a range of ATDM strategies under various conditions to evaluate their effectiveness in achieving the ATDM program goals as outlined by the research questions and hypotheses.

In particular, this section describes the collective analysis conducted for ATDM program across all testbeds including what the combined analyses is expected to reveal when considered as a whole, relevant to the goals of the ATDM Program

4.1 ATDM Strategies Tested

Table 4-1 shows a mapping of the different ATDM strategies that are tested as part of the AMS Testbed project and a mapping to which testbed each of them would be implemented in. As shown, 16 out of 27 strategies are included in the AMS project. Please note that San Mateo Testbed would remain exclusive for DMA applications. Strategies such as dynamic way-finding, transfer connection protection are too complex to be simulated in the current scope of work owing to its traveler-centric and route-centric nature.

Table 4-1 – ATDM Strategy Mapping with Testbeds

ATDM Strategies	Pasadena	Dallas	Phoenix	Chicago	San Diego
Active Traffic Management					
Dynamic Shoulder Lanes	●	●		●	
Dynamic Lane Use Control	●			●	●
Dynamic Speed Limits	●			●	●
Queue Warning	●				
Adaptive Ramp Metering	●	●	●		
Dynamic Junction Control	●				
Dynamic Merge Control					●
Dynamic Traffic Signal Control	●	●	●	●	
Transit Signal Priority					
Dynamic Lane Reversal					
Active Demand Management					
Dynamic Ridesharing					
Dynamic Transit Capacity Assignment					
On-demand Transit					

ATDM Strategies	Pasadena	Dallas	Phoenix	Chicago	San Diego
Predictive Traveler Information		●	●	●	●
Dynamic Pricing					
Dynamic Fare Reduction					
Transfer Connection Protection					
Dynamic HOV/Managed Lanes					●
Dynamic Routing	●	●	●	●	●
Active Parking Management					
Dynamically Priced Parking		●			
Dynamic Parking Reservation					
Dynamic Wayfinding					
Dynamic Overflow Transit Parking					
Weather Related Strategies					
Snow Emergency Parking				●	
Preemption for Winter Maintenance				●	
Snowplow Routing				●	
Anti-Icing and Deicing Operations				●	

4.2 ATDM Research Questions

This section enumerates the research questions identified for evaluating ATDM strategies from the ATDM Preliminary Evaluation Plan that Noblis developed for USDOT[3]. San Mateo and Phoenix Testbeds will be primarily used for the DMA evaluation. Table 4-2 provides this mapping.

Table 4-2 - ATDM Research Question Mapping with Testbeds

ID	ATDM Research Question	Pasadena	Dallas	Phoenix	Chicago	San Diego
	Synergies and Conflicts					
1	Are ATDM strategies more beneficial when implemented in isolation or in combination (e.g., combinations of ATM, ADM, or APM strategies)?	●	●	●	●	●

[3] Vasudevan and Wunderlich, Analysis, Modeling, and Simulation (AMS) Testbed Preliminary Evaluation Plan for Active Transportation and Demand Management (ATDM) Program, FHWA-JPO-13-096, November 2013.

ID	ATDM Research Question	Pasadena	Dallas	Phoenix	Chicago	San Diego
2	Which ATDM strategy or combinations of strategies yield the most benefits for specific operational conditions?	●	●		●	●
3	What ATDM strategies or combinations of strategies conflict with each other?	●	●		●	●
	Prediction Accuracy					
4	Which ATDM strategy or combination of strategies will benefit the most through increased prediction accuracy and under what operational conditions?	●		●	●	●
5	Are all forms of prediction equally valuable, i.e., which attributes of prediction quality are critical (e.g., length of prediction horizon, prediction accuracy, prediction speed, and geographic area covered by prediction) for each ATDM strategy?	●	●	●	●	●
	Active Management or Latency					
6	Are the investments made to enable more active control cost-effective?	●			●	
7	Which ATDM strategy or combinations of strategies will be most benefited through reduced latency and under what operational conditions?	●		●	●	●
	Operational Conditions, Modes and Facility Types					
8	Which ATDM strategy or combinations of strategies will be most beneficial for certain modes and under what operational conditions?	●	●		●	●
9	Which ATDM strategy or combinations of strategies will be beneficial for certain facility types (freeway, transit, arterial) and under what operational conditions?	●	●		●	●
10	Which ATDM strategy or combinations of strategies will have the most benefits for individual facilities versus system-wide deployment versus region-wide deployment and under what operational conditions?		●		●	
	Prediction, Latency and Coverage Tradeoffs					
11	What is the tradeoff between improved prediction accuracy and reduced latency with existing communications for maximum benefits?	●		●	●	●
12	What is the tradeoff between prediction accuracy and geographic coverage of ATDM deployment for maximum benefits?	●		●	●	

ID	ATDM Research Question	Pasadena	Dallas	Phoenix	Chicago	San Diego
13	What is the tradeoff between reduced latency (with existing communications) and geographic coverage for maximum benefits?	●			●	
14	What will be the impact of increased prediction accuracy, more active management, and improved robust behavioral predictions on mobility, safety, and environmental benefits?	●		●	●	
15	What is the tradeoff between coverage costs and benefits?	●			●	
	Connected Vehicle Technology and Prediction					
16	Are there forms of prediction that can only be effective when coupled with new forms of data, such as connected vehicle data?				●	●
	Short-Term and Long-Term Behaviors					
17	Which ATDM strategy or combinations of strategies will have the most impact in influencing short-term behaviors versus long term behaviors and under what operational conditions?				●	●
18	Which ATDM strategy or combinations of strategies will yield most benefits through changes in short-term behaviors versus long-term behaviors and under what operational conditions?				●	●

4.3 ATDM Hypothesis

This section outlines the mapping of hypotheses to the ATDM research question from the ATDM Preliminary Evaluation plan that Noblis developed for USDOT[4]. These hypotheses are listed in Table 4-3.

Table 4-3 - ATDM Research Question Analysis Hypothesis

Category	ID	ATDM Research Question	Analysis Hypotheses
Synergies and Conflicts	1	Are ATDM strategies more beneficial when implemented in isolation or in combination (e.g., combinations of ATM, ADM, or APM strategies)?	ATDM strategies that are synergistic (e.g., ADM, APM, ATM) will be more beneficial when implemented in combination than in isolation.

[4] Vasudevan and Wunderlich, Analysis, Modeling, and Simulation (AMS) Testbed Preliminary Evaluation Plan for Active Transportation and Demand Management (ATDM) Program, FHWA-JPO-13-096, November 2013.

Category	ID	ATDM Research Question	Analysis Hypotheses
Synergies and Conflicts	2	Which ATDM strategy or combinations of strategies yield the most benefits for specific operational conditions?	An ATDM strategy will yield higher benefits only under certain operational conditions. Certain combinations of ATDM strategies will yield the highest benefits for specific operational conditions.
Synergies and Conflicts	3	What ATDM strategies or combinations of strategies conflict with each other?	Certain ATDM strategies will be in conflict with each other, resulting in no benefits or reduced benefits.
Prediction Accuracy	4	Which ATDM strategy or combination of strategies will benefit the most through increased prediction accuracy and under what operational conditions?	Improvements in prediction accuracy will yield higher benefits for certain ATDM strategies and combinations of strategies than for others. An ATDM strategy or combinations of strategies will yield the most benefits with improvements in prediction accuracy only under certain operational conditions.
Prediction Accuracy	5	Are all forms of prediction equally valuable, i.e., which attributes of prediction quality are critical (e.g., length of prediction horizon, prediction accuracy, prediction speed, and geographic area covered by prediction) for each ATDM strategy?	Increased prediction accuracy is more critical for certain ATDM strategies over others, with certain attributes (e.g., length of prediction horizon, prediction accuracy, prediction speed, and geographic area covered by prediction) of prediction quality being most critical.
Active Management or Latency	6	Are the investments made to enable more active control cost-effective?	Incremental improvements in latency will result in higher benefit-cost ratio for certain ATDM strategy or combinations of strategies up to a certain latency threshold, after which benefit-cost ratio will be reduced.
Active Management or Latency	7	Which ATDM strategy or combinations of strategies will be most benefited through reduced latency and under what operational conditions?	Reductions in latency will yield higher benefits for certain ATDM strategies and combinations of strategies than for others. An ATDM strategy or combinations of strategies will yield the most benefits with reduced latency only under certain operational conditions.
Operational Conditions, Modes, Facility	8	Which ATDM strategy or combinations of strategies will be most beneficial for certain	Certain ATDM strategies and combinations of strategies will yield the highest benefits for specific

Category	ID	ATDM Research Question	Analysis Hypotheses
Types with most benefit.		modes and under what operational conditions?	modes and under certain operational conditions.
Operational Conditions, Modes, Facility Types with most benefit.	9	Which ATDM strategy or combinations of strategies will be most beneficial for certain facility types (freeway, transit, arterial) and under what operational conditions?	Certain ATDM strategies and combinations of strategies will yield the highest benefits for specific facility types and under certain operational conditions.
Operational Conditions, Modes, Facility Types with most benefit.	10	Which ATDM strategy or combinations of strategies will have the most benefits for individual facilities versus system-wide deployment versus region-wide deployment and under what operational conditions?	Certain synergistic ATDM strategies will yield 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
Prediction, Latency and Coverage Tradeoffs	11	What is the tradeoff between improved prediction accuracy and reduced latency with existing communications for maximum benefits?	Incremental improvements in prediction accuracy will result in higher benefits, when latency is fixed up to a certain threshold, after which marginal benefits will be reduced and vice-versa. Maximum system benefit will be obtained at an intermediate point balancing prediction accuracy and latency.
Prediction, Latency and Coverage Tradeoffs	12	What is the tradeoff between prediction accuracy and geographic coverage of ATDM deployment for maximum benefits?	Incremental improvements in prediction accuracy will result in higher benefits when geographic coverage is fixed up to a certain threshold, after which marginal benefits will be reduced and vice-versa. Maximum system benefit will be obtained at an intermediate point balancing prediction accuracy and geographic coverage.
Prediction, Latency and Coverage Tradeoffs	13	What is the tradeoff between reduced latency (with existing communications) and geographic coverage for maximum benefits?	Incremental improvements in latency will result in higher benefits when geographic coverage is fixed up to a certain threshold, after which marginal benefits will be reduced and vice-versa. Maximum system benefit will be obtained at an intermediate point balancing latency and geographic coverage.

Category	ID	ATDM Research Question	Analysis Hypotheses
Prediction, Latency and Coverage Tradeoffs	14	What will be the impact of increased prediction accuracy, more active management, and improved robust behavioral predictions on mobility, safety, and environmental benefits?	Increases in prediction accuracy, more active management, and improvements in robust behavioral predictions will result in significant mobility, safety, and environmental benefits. ATDM strategies will reduce the impact of congestion by delaying its onset, and reducing its duration and geographic extent. ATDM strategies will impact all three characteristics of congestion (onset, duration, and extent) but different strategies will impact specific congestion characteristics differently. Traveler and system mobility measures will vary inversely with respect to congestion characteristics, but not uniformly by characteristic.
Prediction, Latency and Coverage Tradeoffs	15	What is the tradeoff between coverage costs and benefits?	Incremental increase in geographic coverage will result in higher benefit-cost ratio up to a certain coverage cost threshold, after which benefit-cost ratio will be reduced.
Connected Vehicle Technology and Prediction	16	Are there forms of prediction that can only be effective when coupled with new forms of data, such as connected vehicle data?	Prediction will be most effective only when coupled with connected vehicle data capture and communications technologies that can systematically capture motion and state of mobile entities, and enable active exchange of data between vehicles, travelers, roadside infrastructure, and system operators.
Short-term and Long-term Behaviors	17	Which ATDM strategy or combinations of strategies will have the most impact in influencing short-term behaviors versus long term behaviors and under what operational conditions?	Certain ATDM strategies and combinations of strategies will influence short-term behaviors more than long-term behaviors under certain operational conditions, while others will influence long-term behaviors more than short-term behaviors under certain operational conditions.
Short-term and Long-term Behaviors	18	Which ATDM strategy or combinations of strategies will yield most benefits through changes in short-term	Certain ATDM strategies and combinations of strategies will have the most impact through changes in short-term behaviors under certain

Category	ID	ATDM Research Question	Analysis Hypotheses
		behaviors versus long-term behaviors and under what operational conditions?	operational conditions, while others will have the most impact through changes in long-term behaviors under certain operational conditions.

4.4 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 ATDM strategies to improve corridor mobility, throughput, and reliability based on current and future conditions.

Just as in a typical alternatives analysis, analysts will use rigorous hypothesis-testing experimental design. When possible, statistical tests that assume a functional form of the underlying probability density function (e.g., the Student's t-test) would be avoided unless there is sufficient evidence to support the assumption. In the absence of such evidence, non-parametric methods such as bootstraps are preferable. Here, the null hypothesis is that the ATDM strategy will not have any influence on the facility speed, density, or point-to-point travel time. Exploring these alternatives could include many simulation runs with perturbations in trip volumes and trip distributions.

1. **Average Vehicle Travel-Time:** This is a simulation-based performance measures and could be either at an aggregate Vehicle Hours Traveled (VHT) level or at a disaggregate O-D or sub-path O-D level.
2. **Average Vehicle Delay:** This is another simulation-based performance measure which is computed on the overall network under the "do-nothing" and the ATDM-based scenarios. Delay of a vehicle is computed as the deviation in its travel-time from the free-flow case.
3. **Ratio of VMT-Demand and VMT-Served:** Both measures incorporate the notion of vehicle-miles traveled (VMT), and each captures a separate perspective on that statistic. VMT-Demand captures any effect that the ATDM strategy has on the net demand for using the facilities, such as a scheme to spread in time or even discourage demand at certain times of the day. VMT-Served captures the throughput of the facility, which an ATDM strategy seeks to modulate. These statistics are interesting independently and as a ratio.
4. **Throughput:** This simulation-based performance measure can be used to look at how, if at all, the strategy implemented has affected a facility's rate of serving vehicles. Key locations could include important bottlenecks that lead to significant queuing. The statistic is calculated as the maximum number of vehicles per hour per lane that can pass by an infinitesimal point on the facility.
5. **Reliability Measures:** Here, the cumulative distribution function (CDF) of point-to-point travel time of relevant sub-path O-D's across multiple simulations with varying random number seeds and operating conditions is the most important performance measure. Important point statistics include the 95th percentile travel time for the given sub-path O-D. The logic here is that this metric captures the travel time a journey-to-work traveler

must budget for in order to be on time all but one day a month (i.e., assuming that there are 20 work-days in a month). A rational case can similarly be made for any other percentile – that is, other than the 95th – of the travel time CDF.

6. **Travel Time Index (TTI):** It is the ratio of the actual travel time and the free-flow travel time. ATDM strategies like variable speed limit signs, for example, aim specifically to increase reliability – the predictability of travel times -- by increasing the travel time relative to the free-flow travel time. The variable speed limit sign thus reduces the likelihood of a breakdown in flow, increasing the likelihood of a predictable, reliable travel time for a facility that is frequently or occasionally close to the facility's critical density. The TTI, as suggested by the SHRP2 L08 work, can be calculated across varying lengths of facilities, up to and including an entire trip length.
7. **Travel Time Ratios:** Ratios such as 75th or 95th percentile travel time to the median or mode (most likely or typical) travel time may also be used to supplement the above measures. These ratios, as suggested by the SHRP2 L08 work, can be calculated across varying lengths of facilities, up to and including an entire trip length.
8. **Environmental Measures:** Statistics such as emissions rates for criteria (PM-10, NOX, SOX, etc.) and other (CO2, CH4, etc.) pollutants can be important for many projects. Fuel consumption is often relevant in similar assessments. Many software packages, such as the Environmental Protection Agency's (EPA) Motor Vehicle Emission Simulator (MOVES) and University of California Riverside's Comprehensive Modal Emission Model (CMEM), can be used to process these emissions estimates from a simulation model either in parallel or as a post-process.
9. **Surrogate Crash Metrics:** Safety of strategies or combination of strategies are assessed by surrogate crash metrics such as maximum value of deceleration, occurrences of deceleration events greater than 0.5g, average headway between vehicles, number of lane changes etc. and are computed using individual vehicle records.
10. **Changes in Modal Split:** Some of the strategies such as dynamically priced parking may influence mode shifts. This performance measure captures the changes in demand across modes and is computed as demand split between modes.

4.5 Analysis Scenarios

This section describes how testbed scenarios are constructed using a combination of operating conditions, ATDM strategies, and a range of application attributes.

4.5.1 ATDM Strategy Combinations Tested

Table 4-4 describes the combinations of ATDM strategies that will be tested using different testbeds. Please note that, most scenarios include testing of more than two strategies which are supplementary to each other.

Table 4-4 - ATDM Strategy Combinations and Respective Testbeds

	Dynamic Merge Control	Dynamic Shoulder Lanes	Dynamic Lane Use Control	Dynamic Speed Limits	Queue Warning	Dynamic HOV/Managed Lanes	Adaptive Ramp Metering	Dynamic Junction Control	Dynamic Traffic Signal Control	Predictive Traveler Information	Dynamic Routing
Dynamic Merge Control											
Dynamic Shoulder Lanes											
Dynamic Lane Use Control		Chi									
Dynamic Speed Limits		Pas	SD								
Queue Warning		Pas		Pas							
Dynamic HOV/ Managed Lanes	SD		SD								
Adaptive Ramp Metering		Pas		Pas	Pas						
Dynamic Junction Control		Pas		Pas	Pas		Pas				
Dynamic Traffic Signal Control		Pas Dall		Pas Chi	Pas		Pas Pho	Pas Dal			
Predictive Traveler Information				Chi			Pho		Pho Chi		
Dynamic Routing	SD	Dal	Chi	Chi		SD	Pho	Dal	Dal Pho Chi	Pho Chi	

Legend: SD = San Diego; Pas = Pasadena; Dall = Dallas; Chi = Chicago; Pho = Phoenix

4.6 Assessment Attributes

This section describes the different assessment attributes that will be considered in the analysis across all the testbeds. The prediction attributes to be included in the evaluation include

1. Communication Latency
2. Predicting Future Congestion
3. Predicting Future Demand (including strategy impact)

4. Time Horizon Sensitivity (e.g., 20, 30,... minutes)
5. Prediction Latency Sensitivity (e.g., 5, 10,... minutes)
6. Prediction Accuracy Sensitivity (e.g., 80% of actual)
7. Coverage Extent Variation (e.g., corridor only, regional)
8. Traveler Response (e.g., 50% comply)

Table 17 provides the listing of ATDM-based assessment attributes as well as the corresponding research questions and testbeds.

Table 4-5 - ATDM Assessment Attributes

Scenario Components, Attributes and Assumptions	Research Question Mapping Groups	Research Question Mapping IDs	Pasadena Testbed	San Diego Testbed	Dallas Testbed	Chicago Testbed
Communication Latency	Active Management or Latency; Prediction, Latency and Coverage Tradeoffs	7,11	●	●	●	●
Predict Future Congestion	Connected Vehicle Technology and Prediction	16		●	●	●
Predict Future Demand (including strategy impact)	Connected Vehicle Technology and Prediction	16		●	●	
Time Horizon Sensitivity (e.g., 20, 30,... minutes)	Prediction Accuracy		●	●	●	●
Prediction Accuracy Sensitivity (e.g., 80% of actual)	Prediction Accuracy	4,5	●		●	●
Prediction Latency Sensitivity (e.g., 5, 10,... minutes)	Prediction , Latency, and Coverage Tradeoffs	11,13	●		●	●
Coverage Extent Variation (e.g., corridor only, regional)	Prediction , Latency, and Coverage Tradeoffs	12, 13, 15			●	
Traveler Response (e.g., 50% comply)	Policy		●	●	●	●

4.7 Evaluation Approach

This section highlights the approach to evaluating the different research questions under different testbeds. This includes which scenarios will help in the evaluation. Table 18 enlists the approach mapped to the testbeds. Please note that San Mateo Testbed is not included in the table since it is not used for ATDM Evaluation. The different scenarios that will be simulated for different testbeds are listed in the Appendix.

Table 4-6 - ATDM Research Questions' Evaluation Approach Mapping to Testbeds

ID	ATDM Research Question	Pasadena	Dallas	Phoenix	Chicago	San Diego
1	Are ATDM strategies more beneficial when implemented in isolation or in combination (e.g., combinations of ATM, ADM, or APM strategies)?	Scenarios are included which assess combinations of 6 different ATM strategies and 1 ADM strategy as part of this project. The performance measures from these scenarios will be used to answer this question.	Dallas will also run scenarios with combinations of Adaptive Ramp Metering, Dynamic Traffic Signal Control, Dynamic Shoulder Lanes and Dynamic Routing.	Phoenix will run combinations of Adaptive Ramp metering, Dynamic Traffic Signal Control, Predictive Traveler Information and Dynamic Routing.	Chicago will be running scenarios that represent combinations of Dynamic Speed Limits, Dynamic Traffic Signal Control, Predictive Traveler Information and Dynamic Routing.	Scenarios for combinations of applications will be assessed with different ATM and ADM strategies.
2	Which ATDM strategy or combinations of strategies yield the most benefits for specific operational conditions?	7 different strategies will be tested (along with their combinations) on three different operational conditions.	5 different strategies spanning ATM, ADM and APM will be assessed using 6 different operational conditions.	N/A	6 ATDM strategies and 4 Weather Related Strategies are assessed using 6 operational conditions.	Four operational conditions would be assessed using different strategies and their combinations

ID	ATDM Research Question	Pasadena	Dallas	Phoenix	Chicago	San Diego
3	What ATDM strategies or combinations of strategies conflict with each other?	The same scenarios as in Question 1 would be used to assess if there are synergies or conflicts between the strategies.	The same scenarios as in Question 1 would be used to assess if there are synergies or conflicts between the strategies.	N/A	The same scenarios as in Question 1 would be used to assess if there are synergies or conflicts between the strategies.	Four operational conditions would be assessed using different strategies and their combinations
4	Which ATDM strategy or combination of strategies will benefit the most through increased prediction accuracy and under what operational conditions?	Prediction accuracy sensitivity will be assessed across most scenarios tested in the Pasadena Testbed.	N/A	Predictive Traveler Information would be assessed with EnableATIS bundle to assess this parameter.	Prediction accuracy sensitivity is part of four of the scenarios and will use two operational conditions.	Strategies will be tested under different prediction accuracies. Additionally, the simulations will vary prediction speed and horizon.
5	Are all forms of prediction equally valuable, i.e., which attributes of prediction quality are critical (e.g., length of prediction horizon, prediction accuracy, prediction speed, and geographic area covered by prediction) for each ATDM strategy?	The prediction attributes that will be tested in Pasadena are Time Horizon Sensitivity, Prediction Latency Sensitivity and Prediction Accuracy Sensitivity.	Over the course of the project, multiple prediction attributes are considered including sensitivity to time horizon, prediction accuracy, prediction latency and geographic coverage.	Predictive Traveler Information would be assessed with EnableATIS bundle to assess this parameter.	Attributes such as sensitivity to time horizon, prediction latency, and prediction accuracy and traveler response are included.	Strategies will be tested under different prediction accuracies. Additionally, the simulations will vary prediction speed and horizon.

ID	ATDM Research Question	Pasadena	Dallas	Phoenix	Chicago	San Diego
6	Are the investments made to enable more active control cost-effective?	Benefit-cost analysis would be done to assess the cost-effectiveness of different levels of active-control and the costs associated with that.	N/A	N/A	Benefit-cost analysis would be done to assess the cost-effectiveness of different levels of active-control and the costs associated with that.	N/A
7	Which ATDM strategy or combinations of strategies will be most benefited through reduced latency and under what operational conditions?	Communication latency and prediction latency will be assessed with all these testbeds under different operational conditions.	N/A	Communication latency and prediction latency will be assessed with all these testbeds under different operational conditions.	ATDM strategies such as Predictive Traveler Information and Dynamic Routing will be assessed under different prediction latency.	Same as 4.
8	Which ATDM strategy or combinations of strategies will be most beneficial for certain modes and under what operational conditions?	Operational conditions such as varying demand (medium to high) and varying incident severity (low to high) are assessed for Pasadena and Dallas. However only dry weather conditions are assessed.	Operational conditions such as varying demand (medium to high) and varying incident severity (low to high) are assessed for Pasadena and Dallas. However only dry weather conditions are assessed.	N/A	Varying AM and PM demand combinations are assessed against varying weather conditions including Dry/Rainy/Snow conditions.	Results will be aggregated based on facility level to answer this.

ID	ATDM Research Question	Pasadena	Dallas	Phoenix	Chicago	San Diego
9	Which ATDM strategy or combinations of strategies will be most beneficial for certain facility types (freeway, transit, arterial) and under what operational conditions?	Individual strategies and combination of strategies would be assessed at a facility level. For example, Dynamically Priced Parking would be assessed for how it impact transit ridership.	Individual strategies and combination of strategies would be assessed at a facility level. For example, Dynamically Priced Parking would be assessed for how it impact transit ridership.	N/A	Individual strategies and combination of strategies would be assessed at a facility level.	Results will be aggregated based on facility level to answer this.
10	Which ATDM strategy or combinations of strategies will have the most benefits for individual facilities versus system-wide deployment versus region-wide deployment and under what operational conditions?	N/A	Qualitative analysis would be done to assess the impact of results on a system and a region.	N/A	Scenarios are defined in such a way that strategy combinations could be assessed for a system-wide deployment versus region-wide deployment.	N/A

ID	ATDM Research Question	Pasadena	Dallas	Phoenix	Chicago	San Diego
11	What is the tradeoff between improved prediction accuracy and reduced latency with existing communications for maximum benefits?	Different levels of prediction accuracy and communication latency combinations will be analyzed for sensitivity.	N/A	Different levels of prediction accuracy and communication latency combinations will be assessed in the analysis. An assessment of performance measures generated will give insights into the tradeoff between both.	Different levels of prediction accuracy and communication latency combinations will be assessed in the analysis. An assessment of performance measures generated will give insights into the tradeoff between both.	Different levels of prediction accuracy and communication latency combinations will be assessed in the analysis. An assessment of performance measures generated will give insights into the tradeoff between both.
12	What is the tradeoff between prediction accuracy and geographic coverage of ATDM deployment for maximum benefits?	For different coverage of ATDM strategies, the sensitivity of performance measures to prediction accuracy will be determined.	N/A	For different coverage of ATDM strategies, the sensitivity of performance measures to prediction accuracy will be determined across these testbeds. This will provide the tradeoff between prediction accuracy and geographic coverage.		N/A
13	What is the tradeoff between reduced latency (with existing communications) and geographic coverage for maximum benefits?	Existing prediction system would be utilized at different coverage levels to assess the sensitivity on performance measures.	N/A	N/A	Existing prediction system would be utilized at different coverage levels to assess the sensitivity on performance measures.	N/A

ID	ATDM Research Question	Pasadena	Dallas	Phoenix	Chicago	San Diego
14	What will be the impact of increased prediction accuracy, more active management, and improved robust behavioral predictions on mobility, safety, and environmental benefits?	Prediction accuracy and active management will be assessed through sensitivity analysis and performance measures on mobility, safety and environmental fronts will be reported.	N/A	Prediction accuracy and active management will be assessed through sensitivity analysis and performance measures on mobility, safety and environmental fronts will be reported. However, behavioral predictions are not included in the scope of this analysis.	Prediction accuracy and active management will be assessed through sensitivity analysis and performance measures on mobility, safety and environmental fronts will be reported. However, behavioral predictions are not included in the scope of this analysis.	N/A
15	What is the tradeoff between coverage costs and benefits?	Benefit-cost analysis would supplement finding the tradeoffs between implementation costs and the benefits.	N/A	N/A	Benefit-cost analysis would supplement finding the tradeoffs between implementation costs and the benefits.	N/A
16	Are there forms of prediction that can only be effective when coupled with new forms of data, such as connected vehicle data?	N/A	N/A	N/A	The baseline conditions which do not use connected vehicle data in the prediction system. This will be compared against test scenarios	The baseline conditions that do not use connected vehicle data in the prediction system. This will be compared against test scenarios

ID	ATDM Research Question	Pasadena	Dallas	Phoenix	Chicago	San Diego
17	Which ATDM strategy or combinations of strategies will have the most impact in influencing short-term behaviors versus long term behaviors and under what operational conditions?	N/A	N/A	N/A	Qualitative analysis of strategies will be performed to assess their long-term and short-term influence on traveler behavior.	Qualitative analysis of strategies will be performed to assess their long-term and short-term influence on traveler behavior.
18	Which ATDM strategy or combinations of strategies will yield most benefits through changes in short-term behaviors versus long-term behaviors and under what operational conditions?	N/A	N/A	N/A	Qualitative analysis of strategies will be performed to assess their long-term and short-term influence on traveler behavior.	Qualitative analysis of strategies will be performed to assess their long-term and short-term influence on traveler behavior.

4.8 Evaluation of ATDM Strategies with DMA Applications

In order to assess the effectiveness of DMA applications in the presence of ATDM strategies and vice-versa, scenarios were defined to combine the assessments to provide valuable insights. Specifically, Phoenix and San Diego Testbeds will be utilized for this purpose owing to its range of applications/strategies available for simulation. The following combinations are assessed in Phoenix Testbed:

1. Predictive Traveler Information with EnableATIS.
2. Predictive Traveler Information and Dynamic Routing with INC-ZONE.
3. Dynamic Routing with EnableATIS
4. Predictive Traveler Information with IDTO.
5. Dynamic Routing and Adaptive Ramp Metering with EnableATIS
6. Adaptive Traffic Signal, Adaptive Ramp Metering with EnableATIS.

The following combinations are assessed in San Diego Testbed:

1. Dynamic Merge Control with INFLO.
2. Dynamic Speed Limits with Speed Harmonization.
3. Predictive Traveler Information with INFLO.

As an overall hypothesis, ATDM applications such as Predictive Traveler Information and Dynamic Routing is expected to improve the results given by specific DMA applications. Similarly, applications such as Adaptive Ramp Metering and Adaptive Traffic Signal are supposed to improve the freeway and arterial performance of EnableATIS and FRATIS applications.

4.9 Reporting Benefits and Costs

Benefit-Cost Analysis can help make sense of the modeling results and can be used to estimate national-level net benefits for each ATDM strategy. Reporting of benefits and costs will entail two parallel analysis streams.

4.9.1 Computation of Benefits

Benefits are estimated based primarily on the benefits from ATDM strategies for the various testbeds. The benefit computation will be done using the following steps:

1. Identifying Benefit Categories: This involves narrowing down the overall performance measures to select the benefit categories that will best capture the features of different ATDM strategies and bundles. Benefit categories selected could be direct measures such as reduction in traveler delay or indirect measures such as reduction in probability of missing transit connections.

2. Estimate Benefits for Strategies: Once the benefit category is selected, modeling results would be used to estimate unit benefits that each application will realize. The values would be normalized to a unit basis depending on the type of application (e.g., delay minutes per VMT or delay minutes per intersection signal crossing as appropriate). The unit benefits will be assigned a monetary value based on the social and monetary costs associated with the benefit categories.
3. Conduct Uncertainty and Sensitivity Analysis: Uncertainty and sensitivity analyses would be done to analyze any uncertainties in the selected benefit categories as well as sensitivity with other variables.

4.9.2 Computation of Costs

The costs that are associated with implementation of ATDM strategies would be synthesized based on past FHWA report on The Active Transportation and Demand Management Program (ATDM): Lessons Learned[5]. Implementation costs from the agencies and the road-users costs will be used in the assessment along with maintenance costs estimates from other research records. Full lifecycle costs will be assessed assuming an implementation time-frame of 5, 10 and 20 years. The benefit-cost analysis would, however, be limited to a research-synthesis rather than market-research owing to the scope of this project.

4.10 Collective Research Findings for ATDM Program

Research findings for the ATDM program will not only incorporate specific answers to research questions, but a collective synthesis of these findings and comparison with the ATDM program evaluation results. This section will describe how the analysis performed with each testbed will be combined to answer the research questions and test each hypothesis. This section will also provide a synthesis of what the combined analyses is expected to reveal when considered as a whole, relevant to the goals of the ATDM. An assessment of what can be expected from the collective analyses and what cannot be expected will be documented. Research questions and hypotheses indirectly or not addressed will be documented so that recommendations for future research can be made. The collective research findings will be classified in to following sections:

4.10.1 Synergies and Conflicts

This section will provide the synergies and conflicts between ATM and ADM strategies. APM strategies are unlikely to conflict with other strategies, however can affect the demand and hence might have synergetic relationship with ADM strategies.

4.10.2 Prediction Accuracy

Prediction attributes such as length/duration of prediction horizon, accuracy of prediction, prediction speed and geographic coverage will be assessed against different ATM, ADM and

[5] Kuhn, Gopalakrishna and Schreffler, The Active Transportation and Demand Management Program (ATDM): Lessons Learned, FHWA-HOP-13-018, March 2013.

APM strategies. The research findings would also identify the top strategies that are directly affected by these parameters and that are least affected. This would be a result of sensitivity analyses that will be done in Pasadena and Chicago Testbeds.

4.10.3 Active Management or Latency

This section will describe how enabling active traffic control and active traffic management at different levels of latencies can affect the performance of strategies and the network. The performance will be assessed in terms of mobility and environmental factors.

4.10.4 Operational Conditions, Modes, and Facility Types

This section will identify and rank strategies that are best beneficial and least beneficial for specific operational conditions, modes and facility types. An illustrative example is given below:

Table 4-7 - Most and Least Beneficial Strategies based on Operational Conditions, Mode and Facility Types (*Illustrative Only)

Category	Most Beneficial	Least Beneficial
Operational Conditions		
Dry weather	Dynamic Speed Limits	Queue Warning
Medium Rain	Dynamic Routing	Dynamic Lane Reversal
Heavy Rain	Queue Warning	Dynamic Lane Reversal
Mode		
Auto	Queue Warning	Dynamic Traffic Signal
Transit	Predictive Traveler Information	Adaptive Ramp Metering
Facility Type		
Arterial	Dynamic Traffic Signal	Dynamic Lane Use Control
Freeway	Adaptive Ramp Metering	Dynamic Lane Reversal

4.10.5 Prediction Latency and Coverage Tradeoffs

This section will synthesize collective research findings on sensitivity of prediction latency and geographic coverage of prediction on ATDM strategies as well as analyze its tradeoffs.

4.10.6 Connected Vehicle Technology and Prediction

Connected Vehicle Technology and its impact on prediction would be assessed in this section as well as impact of prediction on connected vehicle technology. This could give answers to whether connected vehicle data can enhance prediction capabilities and whether prediction capabilities of testbeds can enhance the performance of connected vehicle applications.

4.10.7 Short-term and Long-term Behavior

Short-term and long-term travel behavior will be analyzed as a factor of ATDM strategies in terms of mode-choice and route-choice. Qualitative insights will supplement quantitative analysis so that results could be used in better understanding of implementation needs and market penetration.

Chapter 5. Risks and Mitigation Approach

The array 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 risks inherent in the approach that not all of the questions that this research set out to answer would be satisfactorily answered. This section aims to both outline those technical risks and also describe associated risk mitigation actions.

Each of the testbeds is a complex project that spans multiple pieces of software. 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.

For example, INFLO and MMITSS are two DMA applications that would be tested in the San Mateo Testbed. INFLO require vehicle inputs at a 20-second interval input into an access data-base whereas MMITSS require real-time vehicle inputs at 1-second interval derived from the driver-behavior model in VISSIM. The need for access data-base will make VISSIM 5.40 and 7.00 as the only feasible candidate to run INFLO, whereas the driver-model-based BSM (Basic Safety Message) generator makes VISSIM 6.00, the only feasible candidate to run MMITSS. Similar issues also run in implementing USDOT's TCA Communication Emulator with INFLO. TCA require VISSIM to dump vehicle information at a deci-second interval creating large-scale computation issues, given the size of the San Mateo Network. The required run-time is of the order of 0.05 times real-time at that speed.

Within those generalities, each of the testbeds offers its own set of risks and mitigation strategies. For example, in Chicago, every simulation run required integration with demand adjustment/prediction, activation of the prediction module, and activation of system management, among various other steps. Not only is this compartmentalization time consuming, the code interfaces between them introduce chances for error. As such, more time for the preparation and quality assurance of these runs is expected. However, the three-phase approach minimizes the technical risk as it enables the experimenters to leverage the knowledge and lessons learned from each phase into the subsequent phases. In addition, developing a detailed analysis plan is expected to minimize any uncertainty regarding the settings of the modeled scenarios.

In the Dallas US-75 Testbed, the technical risk is controllable. As in the Chicago model, the Dallas Testbed runs risks with its compartmentalized software architecture and a need for high numbers of simulation model runs. Those risks are similarly mitigated by staging the experimental design into multiple phases. Additionally, this Testbed requires advanced data analysis procedures such as cluster analyses. These various risks are mitigated through vigilant and thorough Quality Assurance procedures. The findings of those Quality Assurance procedures are then iterated back into the experimental procedures in order to guard against the future introduction of similar anomalies.

The dominant risk for the Pasadena Testbed is allowing the scope to increase. Often, these kinds of projects risk slippage on due dates and budgets as enough ‘just one more’ features result in significantly expanding the project scope. Within the original scope, it is expected that the system management and prediction system can complete their computation within a 5 minute real-time window. However, expansion of the scope could jeopardize managing to stay within that window. This risk is mitigated through thoughtful engagement of all of the testbed stakeholders. The Phoenix Testbed has similar risks and mitigation schemes to the other testbeds.

San Mateo Testbed must manage risks regarding specific software integration challenges. For example, the TTI SPDHARM and QWARN prototype has been interfaced in one direction with VISSIM 5.4. The prototype software reads VISSIM output, but VISSIM does not currently read prototype output. This will require the team to write the necessary software. The team is mitigating these risks by leveraging existing prototypes. Similar challenges were presented by the University of Arizona MMITSS Algorithm.

The risks presented by the testbeds are relatively similar across one another and more generally across other large software-based experimental designs.

The San Diego Testbed team also foresees certain challenges in incorporating certain DMA applications within the network. The current version of MMITSS application has been developed for Vissim simulation platform and was developed for Econolite controllers. Understanding that the San Diego network uses McCain 170-type controllers, a translator needs to be developed to accommodate this change. In addition, the MMITSS applications are coded as Docker Containers with specific IP addresses to enable communication between simulation controllers and the application. Limitations related to assigning number of IP addresses will limit the number of MMITSS-controlled intersections. The team is expanding on options to include a controller wrapper on Aimsun controllers so that can provide NTCIP interface for the MMITSS applications.

As far as Cooperative Adaptive Cruise Control is concerned, the Team had discussions with several teams developing the application. The application developed by the Saxton Transportation Operations Laboratory (STOL) team was found to be most applicable based on the discussions with Leidos. The current version, coded as a driver behavior model for Vissim need to be recoded for Aimsun given the fact that Vissim uses a “single” driver behavior model that defines a driver in terms of gap-acceptance, lane-change, car-following etc., whereas these are different models in the Aimsun interface.

INFLO application require infrastructure elements coded into the application. This will require extra effort for coding these new elements required by the application, both inside the simulation program as well as in the application configuration. The application can only run as a single instance with only one freeway direction being harmonized for speed. TCA Tool which is currently coded for Vissim and Paramics need a new wrapper to replicate the simulated data capture features from Aimsum simulation. As the team is working with Noblis’ developer team to expand on this tool and add the new wrapper, there may be further limitations to the addition which are unknown at this time.

APPENDIX. Analysis Scenarios

The tables in this Appendix describe the various scenarios to be simulated as part of each testbeds. The number of repetitions of the scenarios and number of sub-scenarios vary according to the purpose of the simulation.

Table A-1 - Scenarios for San Mateo Testbed

Scenario	Operational Conditions	Q-WARN	SPD-HARM	I-SIG	TSP	INC-ZONE	Communication Latency	Communication Frequency	Application Synergies
1	OC-1								
2	OC-1	X	X						
3	OC-1	X	X				X		
4	OC-1	X	X	X	X				X
5	OC-4								
6	OC-4	X	X				X		
7	OC-4					X		X	
8	OC-4	X	X			X			X
9	OC-4	X	X	X	X				X
10	OC-2								
11	OC-2	X	X				X		
12	OC-2					X		X	
13	OC-2	X	X			X			X
14	OC-2	X	X	X	X				X
15	OC-3								
16	OC-3	X	X				X		
17	OC-3					X		X	
18	OC-3	X	X			X			X
19	OC-3	X	X	X	X				X
20	HO-1								
21	HO-1		X						
22	HO-1	X	X						
23	HO-1	X	X	X	X				X
24	HO-2								
25	HO-2	X	X						
26	HO-2	X	X			X			X
27	HO-2	X	X	X	X				X

Table A-2 - Scenarios for Pasadena Testbed

Scenario	Operational Conditions	Q-WARN	SPD-HARM	Dynamic Shoulder Lanes	Dynamic Speed Limits	Queue Warning	Adaptive Ramp Metering	Dynamic Junction Control	Dynamic Traffic Signal Control	Dynamic Routing	Time Horizon Sensitivity	Prediction Latency Sensitivity	Prediction Accuracy Sensitivity	Traveler Response
1	OC-1						X				X	X	X	X
2	OC-1								X		X	X	X	X
3	OC-1			X				X			X	X	X	X
4	OC-1				X	X					X	X	X	X
5	OC-1									X	X	X	X	X
6	OC-1			X	X	X	X	X			X	X	X	X
7	OC-1								X	X	X	X	X	X
8	OC-1			X	X	X	X	X	X	X	X	X	X	X
9	OC-2						X				X	X	X	X
10	OC-2								X		X	X	X	X
11	OC-2			X				X			X	X	X	X
12	OC-2				X	X					X	X	X	X
13	OC-2									X	X	X	X	X
14	OC-2			X	X	X	X	X			X	X	X	X
15	OC-2								X	X	X	X	X	X
16	OC-2			X	X	X	X	X	X	X	X	X	X	X
17	OC-3						X				X	X	X	X
18	OC-3								X		X	X	X	X
19	OC-3			X				X			X	X	X	X
20	OC-3				X	X					X	X	X	X
21	OC-3									X	X	X	X	X
22	OC-3			X	X	X	X	X			X	X	X	X
23	OC-3								X	X	X	X	X	X
24	OC-3			X	X	X	X	X	X	X	X	X	X	X
25	OC-1	X	X											

Table A-3 - Scenarios for Dallas Testbed

Scenario	Operational Conditions	Dynamic Shoulder Lanes	Adaptive Ramp Metering	Dynamic Traffic Signal	Dynamic Routing	Dynamically Priced Parking	Predict Future Congestion	Predict Future Demand	Time Horizon Sensitivity	Prediction Latency Sensitivity	Prediction Accuracy Sensitivity	Coverage Extent Variation	Traveler Response
1	Base												
2	OC-4												
3	OC-2												
4	Base												
5	OC-3												
6	OC-3												
7	OC-2	X					X	X					
8	OC-2	X			X		X	X					X
8a	OC-4	X			X		X	X					X
9	OC-2			X			X	X					X
10	OC-2			X	X		X	X					X
10a	OC-4			X	X		X	X					X
11	OC-2		X				X	X					X
12	OC-2		X	X	X		X	X					X
13	OC-2					X	X						X
14	OC-1	X					X	X					X
15	OC-1	X			X		X	X					X
15a	OC-3	X			X		X	X					X
16	OC-1			X			X	X					X
17	OC-1			X	X		X	X					X
17a	OC-3			X	X		X	X					X
18	OC-1		X				X	X					X
19	OC-1		X	X	X		X	X					X
20	OC-1					X	X	X					X
21	OC-2			X			X	X	X		X		
22	OC-2			X	X		X	X	X		X		
22a	OC-4			X	X		X	X	X		X		
23	OC-1			X			X	X	X		X		
24	OC-1			X	X		X	X	X		X		
24a	OC-3			X	X		X	X	X		X		
25	OC-2			X			X	X		X		X	
26	OC-2			X	X		X	X		X		X	
26a	OC-4			X	X		X	X		X		X	
27	OC-1			X			X	X		X		X	
28	OC-1			X	X		X	X		X		X	
28a	OC-3			X	X		X	X		X		X	
29	HO-1				X		X	X					
30	HO-2	X		X	X		X	X					

Table A-4 - Scenarios for Phoenix Testbed

Scenario	Operational Conditions	EnableATIS	T-DISP	D-RIDE	F-ATIS	F-DRG	INC-ZONE	Adaptive Ramp Metering	Dynamic Traffic Signal	Predictive Traveler Information	Dynamic Routing
1	OC-1	X								X	
2	OC-1				X					X	
3	OC-1				X	X				X	
4	OC-2								X	X	
5	OC-2						X			X	X
6	OC-2	X					X			X	X
7	OC-3			X						X	
8	OC-3	X		X						X	
9	OC-3	X		X			X			X	X
10	OC-3				X	X	X			X	X
11	OC-3	X				X		X		X	X
12	OC-3				X	X	X	X	X	X	X
13	OC-3	X		X			X	X	X	X	X
14	OC-4		X							X	
15	OC-4	X	X	X						X	
16	OC-4	X	X	X					X	X	X
17	OC-4	X	X	X			X	X		X	X
18	OC-4	X	X	X	X	X	X	X	X	X	X
19	HO-1	X					X	X	X	X	X
20	HO-2	X	X	X	X	X	X	X	X	X	X

Table A-5 - Scenarios for Chicago Testbed

Scenario	Operational Conditions	SPD-HARM	Dynamic Shoulder Lanes	Dynamic Lane Use Control	Dynamic Speed Limits	Dynamic Traffic Signal Control	Predictive Traveler Information	Dynamic Routing	Snow Emergency Parking	Preemption for Winter Maintenance	Snowplow Routing	Anti-Icing and Deicing Operations	Predict Future Congestion	Time Horizon Sensitivity	Prediction Latency Sensitivity	Prediction Accuracy Sensitivity	Traveler Response
1	OC-1												X				
2	OC-2												X				
3	OC-3												X				
4	OC-4												X				
5	OC-5												X				
6	OC-6												X				
7	OC-1		X	X									X	X			
8	OC-2		X	X									X	X			
9	OC-3		X	X									X	X			
10	OC-5		X	X									X	X			
11	OC-6		X	X									X	X			
12	OC-1				X	X	X	X					X	X			X
13	OC-2				X	X	X	X					X	X			X
14	OC-3				X	X	X	X					X	X			X
15	OC-4				X	X	X	X					X	X			X
16	OC-6				X	X	X	X					X	X			X
17	OC-1				X		X	X					X		X		
18	OC-6				X		X	X					X		X		
19	OC-1				X		X	X					X			X	
20	OC-6				X		X	X					X			X	
21	OC-1	X											X			X	
22	OC-6	X											X			X	
23	OC-3								X	X	X		X	X			X
24	OC-6								X	X	X		X	X			X
25	OC-2											X	X	X			X
26	OC-6												X				X

Table A-6 - Scenarios for San Diego Testbed

Scenario	Operational Conditions	SPD-HARM	Q-WARN	CACC	MMITSS	Dynamic Lane Use	Dynamic Speed Limits	Dynamic Merge Control	Predictive Traveler Info.	Dynamic HOV/Managed	Dynamic Routing	Communication Latency	Predict Future Congestion	Time Horizon Sensitivity	Prediction Latency Sensitivity	Prediction Accuracy Sensitivity	Traveler Response
1	OC1																
2	OC2																
3	OC3																
4	OC4																
5	OC1					X				X							X
6	OC2					X				X							X
7	OC3					X				X							X
8	OC4					X				X							X
9	OC1						X										X
10	OC2						X										X
11	OC3						X										X
12	OC4						X										X
13	OC1							X									X
14	OC2							X									X
15	OC3							X									X
16	OC4							X									X
17	OC1	X	X														X
18	OC2	X	X														X
19	OC3	X	X														X
20	OC4	X	X														X
21	OC1								X		X		X				X
22	OC2								X		X		X				X
23	OC3								X		X		X				X
24	OC4								X		X		X				X
25	OC1				X												X
26	OC2				X												X
27	OC3				X												X
28	OC4				X												X
28a	HO1				X												X
29	OC1					X											X
30	OC2					X											X

Scenario	Operational Conditions	SPD-HARM	Q-WARN	CACC	MMITSS	Dynamic Lane Use	Dynamic Speed Limits	Dynamic Merge Control	Predictive Traveler Info.	Dynamic HOV/Managed	Dynamic Routing	Communication Latency	Predict Future Congestion	Time Horizon Sensitivity	Prediction Latency Sensitivity	Prediction Accuracy Sensitivity	Traveler Response
31	OC3					X											X
32	OC4					X											X
33	OC1					X	X			X							X
34	OC1							X		X							X
35	OC1							X									X
36	OC1	X	X					X									X
37	OC1	X	X				X										X
38	OC1	X	X						X				X	X			X
39	OC1	X	X		X												X
40	OC1							X		X	X						X
41	OC1	X	X	X													X
42	OC1								X				X		X	X	X
43	OC2								X				X		X	X	X
44	OC3								X				X		X	X	X
45	OC4								X				X		X	X	X
46	OC1	X	X									X					X
47	OC1	X	X									X					X
48	OC1			X								X					X

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