

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

## Gaps, Challenges, and Future Research

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# Executive Summary

The project titled *Analysis, Modeling, and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs* aims at developing and utilizing simulation-based testbeds for the evaluation of next-generation transportation applications and operational strategies, denoted as the DMA applications and ATDM strategies respectively. As part of this project, the team developed six capable, reliable AMS Testbeds that provide a laboratory to refine and integrate research concepts in virtual computer-based simulation environments prior to field deployments. The six testbeds replicated transportation networks in the following regions: San Mateo, Pasadena, Dallas, Phoenix, Chicago and San Diego. Using these six testbeds, the research team conducted cutting edge research by attempting to build robust AMS testbeds with capabilities that had not been developed or tested previously and using them to evaluate a variety of operational scenarios such as Connected Vehicle modeling, Active Traffic/Demand Management, Active Parking Management, Traffic State Prediction as well as demand-responsive ITS strategies.

The primary purpose of this report is to document the gaps and challenges identified by the testbed team and some of the future research directions that will take AMS research to the next level. Specifically, the report lists the different gaps and limitations in evaluating ATDM strategies and DMA applications using AMS Testbeds in this project with respect to modeling, calibration, performance measurement, tools development and benefit-cost analysis. The report also lists the numerous challenges faced by the testbed team to develop modeling tools, integrate them with existing tools and use them to effectively evaluate the research questions put forth by the USDOT. A section was also committed to discussing the identified accomplishments and values gained for each testbed developments. Finally, the report suggests future research directions based on the project.

The six testbeds selected for this project underwent a two-staged selection process that considered the following:

- The testbed's capabilities and potential to expand to incorporate the DMA and ATDM strategies
- The testbed's ability to provide a diverse set of operational conditions that could be tested through the project

These testbeds represent a range of geographic conditions, geographic extents, demand, urbanism, modes, state-of-the-practice ITS implementation as well as tools used. Additionally, when developing the testbeds, the project team integrated external tools that represent aspects such as DMA applications, ATDM strategies, prediction capabilities, communications emulation, scenario/system manager emulation, data bus capabilities etc.

The DMA applications emulated in this project include:

- Speed Harmonization
- Queue Warning
- Cooperative Adaptive Cruise Control
- Incident Zone Alerts
- Intelligent Traffic Signal
- Advanced Traveler Information
- Freight Advanced Traveler Information
- Dynamic Transit Dispatch
- Dynamic Ride-sharing
- Freight Dynamic Route Guidance

The ATDM strategies emulated in this project include:

- Dynamic Shoulder Lanes
- Dynamic Speed Limits
- Queue Warning
- Adaptive Ramp Metering
- Dynamic Junction Control
- Dynamic Traffic Signal Control
- Predictive Traveler Information
- Anti-icing and Deicing Operations
- Dynamic HOV
- Dynamic Managed Lanes
- Dynamic Routing
- Dynamically Priced Parking
- Shown Emergency Parking
- Preemption for Winter Maintenance
- Snowplow Routing

As far as the major lessons learned are concerned, the team primarily identified the following lessons learned:

1. Since each of the AMS testbeds are a system of multiple software pieces, scoping should include additional cost contingency when allocating resources, selecting tools and techniques and considering the overall range of scenarios. As the scope and complexity of the testbed increase, the resources required for development and testing increased exponentially.
2. Not all regions and not all roadways have traffic data available at the same accuracy, quality and resolution, which could lead to differences in quality of calibration. Future efforts of similar scope should account for the data availability for all roadway facilities within the network boundaries before scoping or developing an analysis plan for network calibration.
3. Throughout the AMS project, the project team integrated applications built by other teams to these testbeds. Our ability to include and exclude applications from our scope depended on application availability and features that exist in other applications. Additional cost contingency should be allocated to reflect the types of applications that will be analyzed to incorporate reliable technical support from the application developers.
4. The AMS testbeds were envisioned to be complex systems of multiple software-in-the-loop systems that communicate via a data bus. Depending on the original architecture of each of these software pieces, computationally complexity of the testbeds varied across the six AMS testbeds. A central data bus is crucial when managing multiple software-in-the-loop to communicate in a consistent manner.
5. Performance measurement capability of different simulation tools varied across the six testbeds. However, tool-selection was a trade-off that prioritized which one is the best for sets of applications or strategies and the performance measures it produced. There is no effective and consistent method of comparing results generated using different tools or simulation package.
6. The team tried getting statistical valid results through multiple repetitions of each of the simulation runs. Despite these efforts, some of the more complex simulations could not be tested for statistical validity owing to longer computation times. Significant resources will have been allocated to the calibration of a large and complex simulation model to reasonably replicate each operational condition before the application and strategies could be analyzed. Similar future projects may be faced with similar issue of choosing between committing resources and efforts to developing large variety of traffic operational conditions or more strategies and applications development.

The team also identified gaps and challenges with respect to the following:

1. The AMS requirements which could not be met completely consisted primarily of different factors that were specific to a user-type or facility-type. The team focused more on system-wide impacts.
2. DMA and ATDM research questions that remained unanswered consists primarily of policy-based questions for DMA and benefit-cost analysis questions for ATDM.

3. With respect to operational conditions, cluster analysis and calibration, the team had to make use of available data, which in some cases had gaps. Additionally, the teams had to prioritize certain operational conditions based on their number of instances in the model year.
4. The team had lot of technical challenges in modeling DMA applications and ATDM strategies, primarily due to (i) unavailability of robust existing applications, and (ii) increasing scope of testbeds.
5. As far as testbed development and system manager emulation is concerned, team had to make certain assumptions and simplifications to prevent scope creep.

The project team also identified several future directions for the AMS research in terms of addressing unanswered research questions from this project as well as DMA and ATDM research.

# 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. 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 several technical risks associated with developing an AMS Testbed that can facilitate detailed evaluation of the DMA and ATDM concepts. Therefore, instead of selecting a single testbed, a portfolio of AMS Testbeds was identified to mitigate the risks posed by a single testbed approach. After a rigorous two-staged AMS Testbed selection process, six (6) AMS Testbeds were selected to form a diversified portfolio to conduct DMA bundle and ATDM strategy evaluation: San Mateo, Pasadena, Dallas, Phoenix, Chicago and San Diego Testbeds. Using these six testbeds, the research team was able to conduct cutting edge research by attempting to build robust AMS testbeds with capabilities that had not been developed or tested previously and using them to evaluate a variety of operational scenarios such as Connected Vehicle modeling, Active Traffic/Demand Management, Active Parking Management, Traffic State Prediction as well as demand-responsive ITS strategies.

The primary purpose of this report is to document the lessons learned, gaps, and challenges, identified by the testbed team and supplemented with information on future research directions for conducting AMS research. The report discusses the lessons learned throughout the duration of this project then lists the different gaps and limitations in evaluating ATDM strategies and DMA applications using AMS Testbeds in this project with respect to modeling, calibration, performance measurement, tools development and benefit-cost analysis. The report also lists the numerous challenges faced by the testbed team to develop modeling tools, integrate them with existing tools, and use them to effectively evaluate the research questions put forth by the USDOT. Finally, the report suggests future research directions based on the project.

## 1.1 AMS Project Overview

Figure 1-1 shows the overall process of the AMS testbed project and consists of several steps. The first step was the development of specific AMS requirements that each of the testbeds should satisfy for the successful completion of the AMS objectives. This is followed by site selection process during which a list of testbeds was reduced to six, prioritizing the technical needs, minimizing technical risks and addressing the requirements developed in this project. For each of the testbeds, the teams developed testbed-specific analysis plans which consequently formed an overall evaluation plan for the project. For each of the testbeds, the team collected data required for cluster analysis and calibration to match real-world operational conditions. Specifically, the cluster analysis process clustered the days in the data to specific day-types and the calibration was done to generate a set of operational conditions for each testbed that are reflective of these day-types. Development of testbed models also encompassed development of new

and integration of existing DMA applications and ATDM strategies into these testbeds. This is followed by scenario simulation and evaluation of DMA- and ATDM-specific research questions set forth by the USDOT, summarizing the results and recommending future research.



**Figure 1-1. Process Flow of the AMS Project**

## 1.2 Report Overview

This report aims at documenting the lessons learned by the team during the AMS Project, which could be of potential value to future AMS research. In addition, discussions focusing on the gaps and challenges as well as possibilities of future AMS research have been included in this report. The layout of the report is organized into seven chapters with the following contents:

- Chapter 1 – Introduction: This chapter introduces the report and identifies the purpose and overview of this document, and a brief description of the AMS Testbed Project.

- Chapter 2 – AMS Testbeds: This chapter provides a description of 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 – DMA Application and ATDM Strategy Summary: This chapter summarizes the different DMA Applications and ATDM Strategies that are evaluated in this project along with key analysis scenarios for each of the testbeds.
- Chapter 4 – Major Accomplishments and Lessons Learned: This chapter enlists the major lessons learned by the project team during this AMS research.
- Chapter 5 – AMS Gaps and Challenges: This chapter summarizes the gaps in research and the challenges that were faced by the AMS team in development of testbeds and tools as well as during the integration of different tools for effective AMS evaluation.
- Chapter 6 – Future Research Directions: This chapter summarizes the future research directions for the USDOT and other agencies on how to further the AMS-based evaluation. The chapter also provides a summary of resources and tools developed and shared by the AMS evaluation team so that agencies and interested parties can take advantage of them.
- Chapter 7 – Summary: This summary chapter summarizes the lessons learned, gaps, challenges, and future directions.

# Chapter 2. AMS Testbed Sites

The AMS project primarily aimed at evaluating DMA applications and ATDM strategies using virtual simulation-based test networks using Analysis, Modeling and Simulation. Using a two-staged testbed-selection process, six testbeds were selected that represented six different geographic locations in the United States<sup>1</sup>. They are: (1) San Mateo, CA, (2) Pasadena, CA, (3) Dallas, TX, (4) Phoenix, AZ, (5) Chicago, IL and (6) San Diego, CA. Chicago and San Diego Testbeds were not 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 by the other four testbeds. This section presents a high-level overview of these AMS Testbeds including:

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**

<i>Testbed</i>	<i>Geographic Details</i>	<i>Facility Type</i>	<i>Applications / Strategies</i>
<b>San Mateo, CA</b>	8.5-mile-long section of US 101 freeway and a parallel SR 82 arterial.	Freeway and Arterial	DMA only
<b>Pasadena, CA</b>	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
<b>Dallas, TX</b>	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
<b>Phoenix, AZ</b>	Covers the entire metropolitan region in Maricopa County including freeways, arterials, light rail lines etc.	Freeways/Arterials and Transit (Light-Rail and buses)	DMA and ATDM
<b>Chicago, IL</b>	Freeways and arterials in the downtown Chicago area including I-90, I-94, I-290	Freeways/Arterials	DMA, ATDM, and Weather-related strategies
<b>San Diego, CA</b>	22 miles of I-15 freeway and associated arterial feeders covering San Diego, Poway and Escondido	Freeway and Arterial System	DMA and ATDM

<sup>1</sup> Yelchuru, B., Zohdy, I., Singuluri, S., & Kamalanathsharma, R. (2016). *Analysis, Modeling, and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs—AMS Testbed Selection Report* (No. FHWA-JPO-16-355).

## 2.1 Geographic and Temporal Scope

Six simulation-based testbeds were used in the AMS project that 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 network modeled in 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 accounted 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. Further details on the testbed and its calibration are provided in the following USDOT documents:

1. FHWA-JPO-16-370, Analysis Plan for San Mateo Testbed.
2. FHWA-JPO-16-377, Calibration Report for San Mateo Testbed.



Further details on the testbed and its calibration are provided in the following USDOT documents:

1. FHWA-JPO-16-371, Analysis Plan for Pasadena Testbed.
2. FHWA-JPO-16-378, Calibration Report for Pasadena Testbed.

### 2.1.3 Dallas

The Dallas testbed is modeled after the US-75 Corridor in Dallas, Texas. 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 included both AM and PM peak periods. **Error! Reference source not found.** shows the geographic overlay map of the Testbed. Further details on the testbed and its calibration are provided in the following USDOT documents:

1. FHWA-JPO-16-373, Analysis Plan for Dallas Testbed.
2. FHWA-JPO-16-380, Calibration Report for Dallas Testbed.

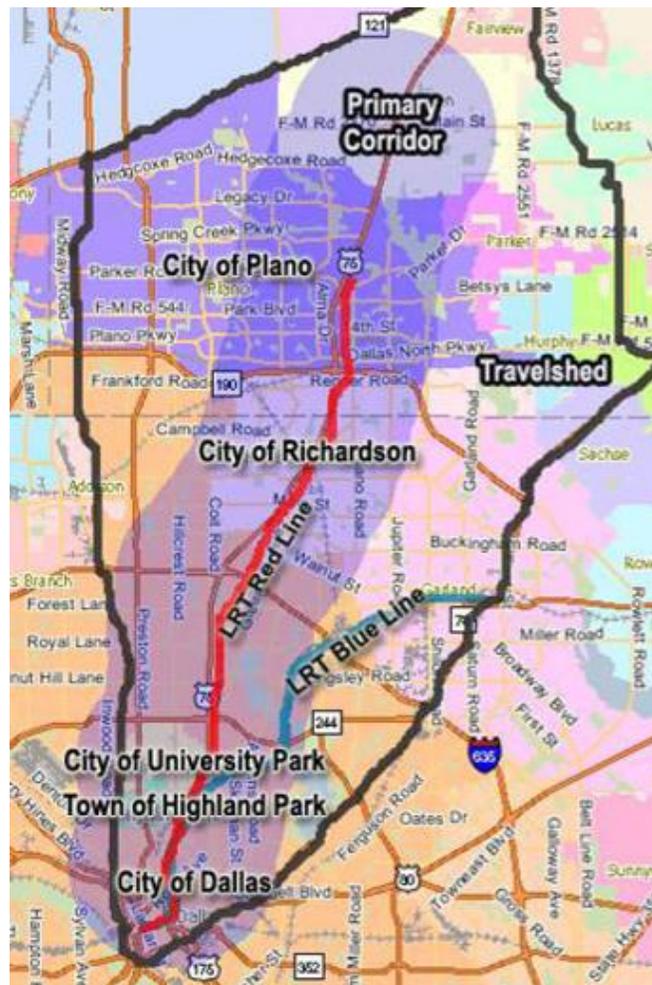
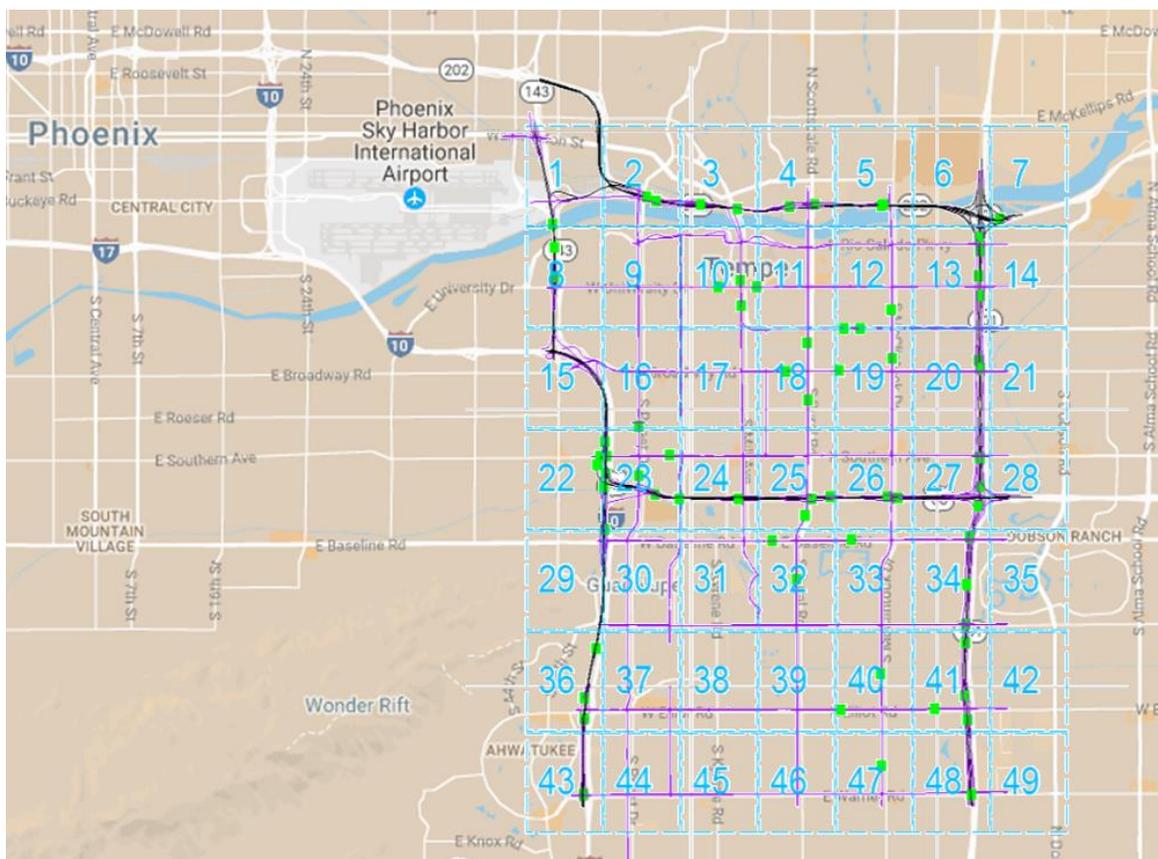


Figure 2-4: Dallas Testbed [Source: USDOT]

## 2.1.4 Phoenix

The Phoenix Testbed model was derived from the Maricopa Association of Governments (MAG) travel demand model which is home to more than 1.5 million households and 4.2 million inhabitants. This multi-resolution simulation model took multiple modes of transportation into account. The testbed was developed from the original MAG travel demand model which 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 final testbed is focused around the Tempe area which covers an area of 40 square miles. This testbed only considered AM Peak traffic between 6:00 AM and 10:00 AM and PM peak traffic between 3PM and 7PM for both weekday and weekend traffic when selecting the operational conditions. The initial simulation scenarios focused only on PM peak. Figure 2-5 shows the geographic overlay map of the Testbed. Further details on the testbed and its calibration are provided in the following USDOT documents:

1. FHWA-JPO-16-372, Analysis Plan for Phoenix Testbed.
2. FHWA-JPO-16-379, Calibration Report for Phoenix Testbed.



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

## 2.1.5 Chicago

The Chicago testbed is modeled to replicate the 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 took both AM and PM peak into its temporal scope for both weekends and weekdays for selecting operational conditions using cluster analysis. **Error! Reference source not found.** shows the geographic overlay map of the Testbed. Further details on the testbed and its calibration are provided in the following USDOT documents:

1. FHWA-JPO-16-374, Analysis Plan for Chicago Testbed.
2. FHWA-JPO-16-381, Calibration Report for Chicago Testbed.

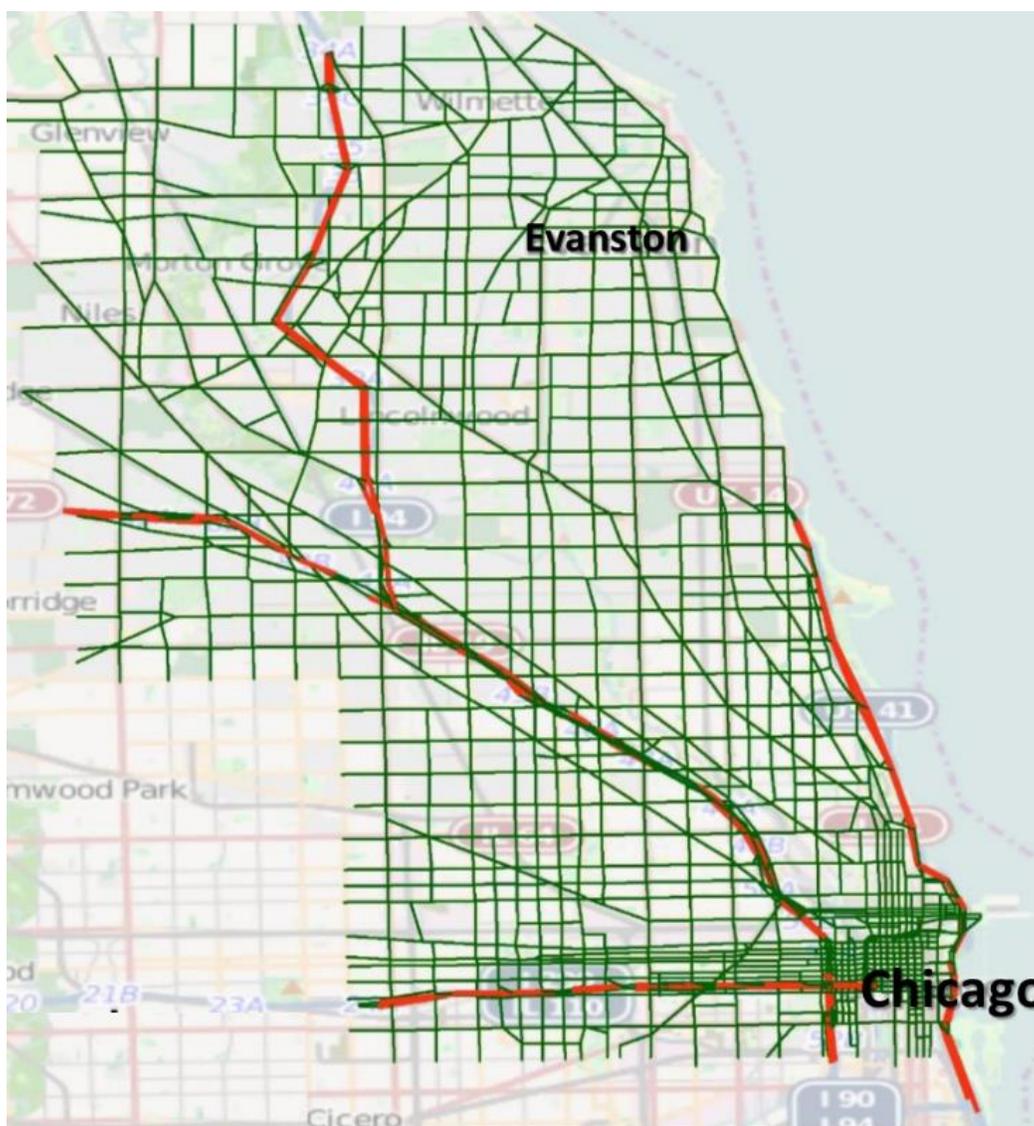


Figure 2-6: Chicago Testbed [Source: NWU]

## 2.1.6 San Diego

The San Diego testbed is modeled to include 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 **Error! Reference source not found.**. 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 Tolloed (HOT) lanes.

This testbed considered both AM and PM peak travel and utilized ICM San Diego's Cluster Analysis-based operational conditions discussed in the "Analysis Plan for San Diego Testbed" report listed below. The testbed also includes two typical weekday operational conditions. Further details on the testbed and its calibration are provided in the following USDOT documents:

1. FHWA-JPO-16-375, Analysis Plan for San Diego Testbed.
2. FHWA-JPO-16-382, Calibration Report for San Diego Testbed.

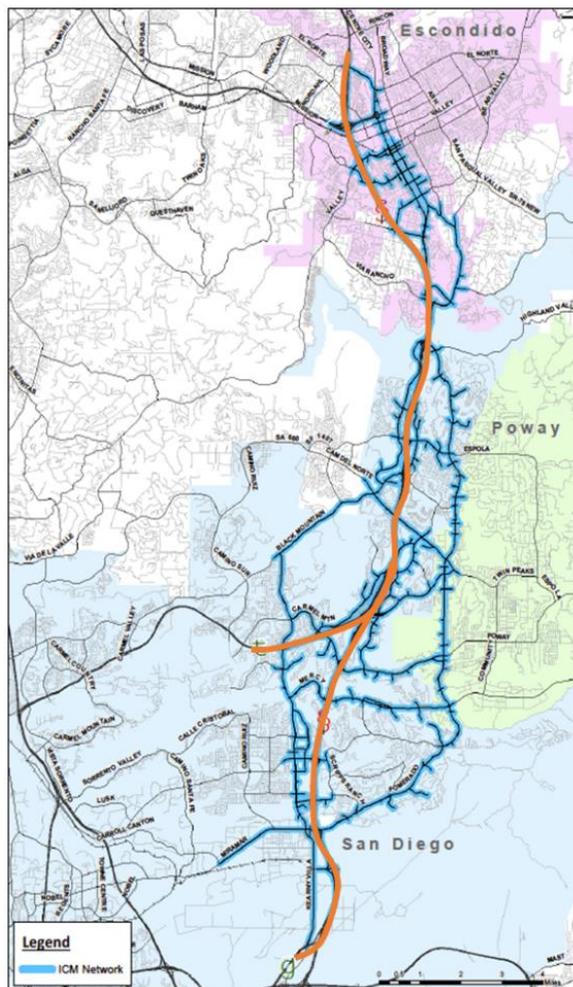


Figure 2-7: San Diego Testbed [Source: TSS]

## 2.2 Operational Conditions

For each of the testbeds, cluster analyses were done to identify commonly occurring operational conditions by finding out representative days using historical data. In general, three types of data were used for conducting cluster analysis and identifying prevalent operational conditions:

1. Data that represents underlying phenomena such as traffic flows etc. This data includes 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 were assembled, cluster analysis was performed over all peak periods using customized cluster analysis algorithms or off-the-shelf statistical package that offers cluster analysis. Cluster analysis was used to reduce some of the structure and to determine the best operational condition to represent the whole spectrum of traffic conditions for the evaluations of DMA application bundles and ATDM strategies later.

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

**Table 2-2. Operational Conditions for Each Testbed**

<b>Op. Con.</b>	<b>San Mateo</b>	<b>Pasadena</b>	<b>Dallas</b>	<b>Phoenix</b>	<b>Chicago</b>	<b>San Diego</b>
<b>OC-1</b>	Medium Demand, Major Incidents, Dry Weather Conditions	High Demand, Minor Incidents, Dry Weather Conditions	Medium to High Demand, Minor Incident, Dry Weather Conditions	High Demand, Minor Incidents, Dry Weather Conditions	High Demand, No Incidents, Dry Weather Conditions	Southbound (AM), Medium Demand, Medium Incident
<b>OC-2</b>	Medium Demand, Major Incidents, Wet Weather Conditions	Medium to High Demand, Major Incidents, Dry Weather Conditions	High Demand, Minor Incident, Dry Weather Conditions	High Demand, Major Incidents, Dry Weather Conditions	High Demand, No Incidents, Wet to Snowy Weather Conditions	Southbound (AM), Medium Demand and High Incident
<b>OC-3</b>	Medium Demand, No Incidents, Dry Weather Conditions	High Demand, Medium Incidents, Dry Weather Conditions	High Demand, Medium Incident, Dry Weather Conditions.	Low Demand, Minor Incidents, Dry Weather Conditions.	Medium to High Demand, No Incidents, Snowy Weather Conditions	Northbound (PM), High Demand, High Incident

<b>Op. Con.</b>	<b>San Mateo</b>	<b>Pasadena</b>	<b>Dallas</b>	<b>Phoenix</b>	<b>Chicago</b>	<b>San Diego</b>
<b>OC-4</b>	High Demand, Minor Incidents, Dry Weather Conditions		Medium to High Demand, Major Incident, Dry Weather Conditions.	High Demand, Medium Incidents, Wet Weather Conditions.	Low to Medium Demand, No Incidents and Snowy Weather Conditions	Northbound (PM), High Demand, Medium Incident
<b>OC-5</b>					Medium to High Demand, No Incidents, Snowy Weather Conditions.	
<b>HO-1*</b>			Low Demand, Major Incidents and Adverse Weather Conditions.		Medium to High Demand, Minor Incidents, Snowy Weather Conditions	
<b>HO-2*</b>			High Demand, No Incidents, Contra-flow Operations, Wet Weather Conditions.			

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**

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

## 2.2.1 Modes Considered

Each of the six testbeds considered 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**

<i>Mode</i>	<i>San Mateo</i>	<i>Pasadena</i>	<i>Dallas</i>	<i>Phoenix</i>	<i>Chicago</i>	<i>San Diego</i>
<i>Single Occupancy Vehicles</i>	•	•	•	•	•	•
<i>High Occupancy Vehicles</i>	•	•	•		•	•
<i>Transit</i>	•		•	•		
<i>Heavy Trucks</i>	•			•		•
<i>Park-and-ride Split Modes</i>			•	•		

## 2.2.2 Tools Used

In order to achieve the AMS project goals, each of the Testbeds used a range of customized and commercial-off-the-shelf 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 list includes Prediction Engine, Communications Emulator, Scenario Generator, System Manager Emulator, Demand Simulator, Network Simulator and Performance Measurement Data Bus. Please note that description of the 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**

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

# Chapter 3. DMA Application and ATDM Strategy Summary

As part of the AMS project, the research team evaluated several connected vehicle applications envisioned under the USDOT’s Dynamic Mobility Applications (DMA) program and active management strategies under USDOT’s Active Transportation and Demand Management (ATDM) program. These are listed in this chapter.

## 3.1 DMA Applications Evaluated

The DMA program has developed six bundles of applications with three to six applications within each bundle. A description of these applications can be found in the USDOT’s DMA website<sup>2</sup>. The AMS Testbed analysis includes all the six bundles. Table 3-1 shows the mapping of the DMA applications that were evaluated in each testbed. Dallas remained the ATDM-centric testbed without any DMA application. The applications that were not evaluated were either not prototyped under the DMA program, or a simulation version of the application was not available. The modeled applications include applications from both tactical and strategic sets of DMA applications.

**Table 3-1. Planned DMA Application Mapping with Testbeds**

<i>DMA Application</i>	<i>San Mateo</i>	<i>Pasadena</i>	<i>Dallas</i>	<i>Phoenix</i>	<i>Chicago</i>	<i>San Diego</i>
<b>EnableATIS</b>						
ATIS				•		
S-PARK						
T-MAP						
WX-INFO						
<b>INFLO</b>						
Q-WARN	•					•
SPD-HARM	•				•	•
CACC						•
<b>MMITSS</b>						
ISIG	•					•
TSP						
PED-SIG						
PREEMPT						
FSP						
<b>IDTO</b>						
T-CONNECT						
T-DISP				•		
D-RIDE				•		
<b>FRATIS</b>						
F-ATIS				•		

<sup>2</sup> [https://www.its.dot.gov/research\\_archives/dma/index.htm](https://www.its.dot.gov/research_archives/dma/index.htm)

<b>DMA Application</b>	<b>San Mateo</b>	<b>Pasadena</b>	<b>Dallas</b>	<b>Phoenix</b>	<b>Chicago</b>	<b>San Diego</b>
<i>DR-OPT</i>						
<i>F-DRG</i>				•		
<b>R.E.S.C.U.M.E.</b>						
<i>EVAC</i>						
<i>RESP-STG</i>	•					
<i>INC-ZONE</i>	•					

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. TSP, PED-SIG, PREEMPT and FSP applications under the MMITSS program were not included, since they were user-type specific variants of I-SIG that prioritized certain category of road-users. The San Mateo simulation testbeds did not explicitly model such user categories such as pedestrians, freight vehicles etc.
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 ATDM Strategies Implemented

The ATDM program has envisioned three bundles of active management strategies along with weather-related strategies. They are: Active Traffic Management, Active Demand Management and Active Parking Management. Table 3-2 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 was implemented in. Please note that San Mateo Testbed was a DMA-centric Testbed. 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 3-2. ATDM Strategy Mapping with Testbeds**

<b>ATDM Strategies</b>	<b>San Mateo</b>	<b>Pasadena</b>	<b>Dallas</b>	<b>Phoenix</b>	<b>Chicago</b>	<b>San Diego</b>
<b>Active Traffic Management</b>						
<i>Dynamic Shoulder Lanes</i>		•	•		•	
<i>Dynamic Lane Use Control</i>		•			•	•
<i>Dynamic Speed Limits</i>		•			•	•
<i>Queue Warning</i>		•				
<i>Adaptive Ramp Metering</i>		•	•	•		

<b>ATDM Strategies</b>	<b>San Mateo</b>	<b>Pasadena</b>	<b>Dallas</b>	<b>Phoenix</b>	<b>Chicago</b>	<b>San Diego</b>
<i>Dynamic Junction Control</i>		•				
<i>Dynamic Merge Control</i>						•
<i>Dynamic Traffic Signal Control</i>		•	•	•	•	
<i>Transit Signal Priority</i>						
<i>Dynamic Lane Reversal</i>						
<b>Active Demand Management</b>						
<i>Dynamic Ridesharing</i>						
<i>Dynamic Transit Capacity Assignment</i>						
<i>On-demand Transit</i>						
<i>Predictive Traveler Information</i>			•	•	•	•
<i>Dynamic Pricing</i>						
<i>Dynamic Fare Reduction</i>						
<i>Transfer Connection Protection</i>						
<i>Dynamic HOV/Managed Lanes</i>						•
<i>Dynamic Routing</i>		•	•	•	•	•
<b>Active Parking Management</b>						
<i>Dynamically Priced Parking</i>			•			
<i>Dynamic Parking Reservation</i>						
<i>Dynamic Wayfinding</i>						
<i>Dynamic Overflow Transit Parking</i>						
<b>Weather-Related Strategies</b>						
<i>Snow Emergency Parking</i>					•	
<i>Preemption for Winter Maintenance</i>					•	
<i>Snowplow Routing</i>					•	
<i>Anti-Icing and Deicing Operations</i>					•	

### 3.3 Modeling Approach

As shown in the previous chapter, each of the testbeds was developed for different operational conditions using distinct set of tools. However, each of the testbeds followed a generalized framework structure, as demonstrated in Figure 3-1 to help assess these DMA and ATDM applications and strategies. As shown, each of the testbeds developed a system manager that is capable of emulating vehicle decision making, either in response to the DMA applications or bundles or in response to the ATDM strategies. Each of the testbeds also included simulators for vehicular flow emulation. Some of the testbeds also emulated Connected Vehicle communication and travel demand models. For example, TCA connected vehicle emulator was used in the San Mateo testbed.

While the testbeds were originally planned to use a similar model architecture as shown in Figure 3-1, the complexity of the tools integrated with each testbed as well as the lack of interoperability of certain

applications and strategy modules caused each of the testbeds to develop its own independent modeling frameworks with the generalized architecture as a starting point. A description of this architecture is provided in the following report: Booz Allen Hamilton, *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*, FHWA-JPO-16-376, July 2016.

In this subsection, we review the modeling framework used by each of the testbeds briefly.

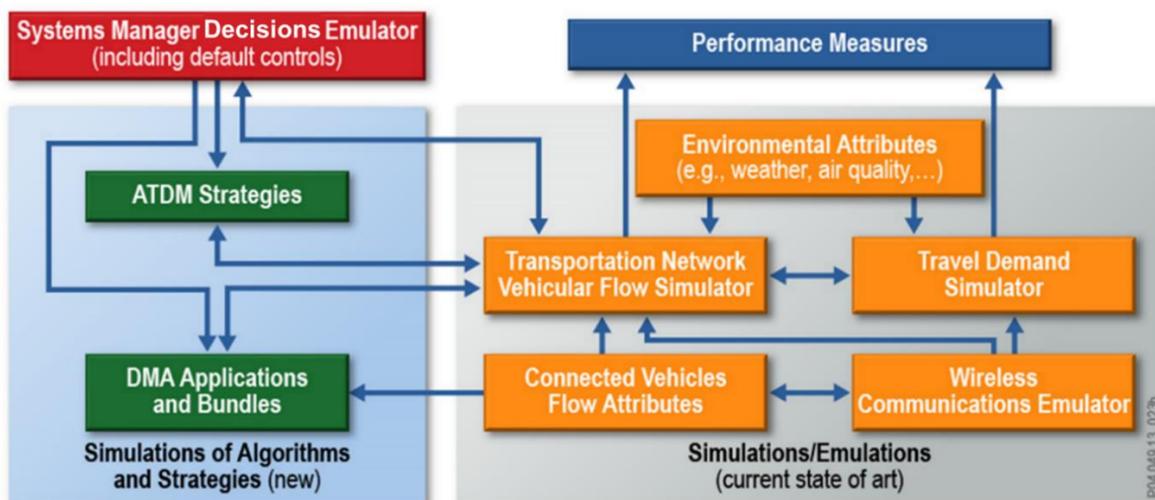


Figure 3-1. Generalized Testbed Framework [Source: Booz Allen]

### 3.3.1 San Mateo Testbed

Figure 3-2 shows the modeling framework for the San Mateo testbed. More details on this framework is available in: Booz Allen Hamilton, *Analysis, Modeling, and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs – Evaluation Report for the DMA Program*, FHWA-JPO-16-383, July 2017. The testbed, being DMA-centric, has a DMA application manager, like the envisioned System Manager, which controls the flow of information and decision making between the applications and the VISSIM microscopic simulations. In addition, the BSM generators and emulators are used to test different CV parameters such as latency, packet loss etc.

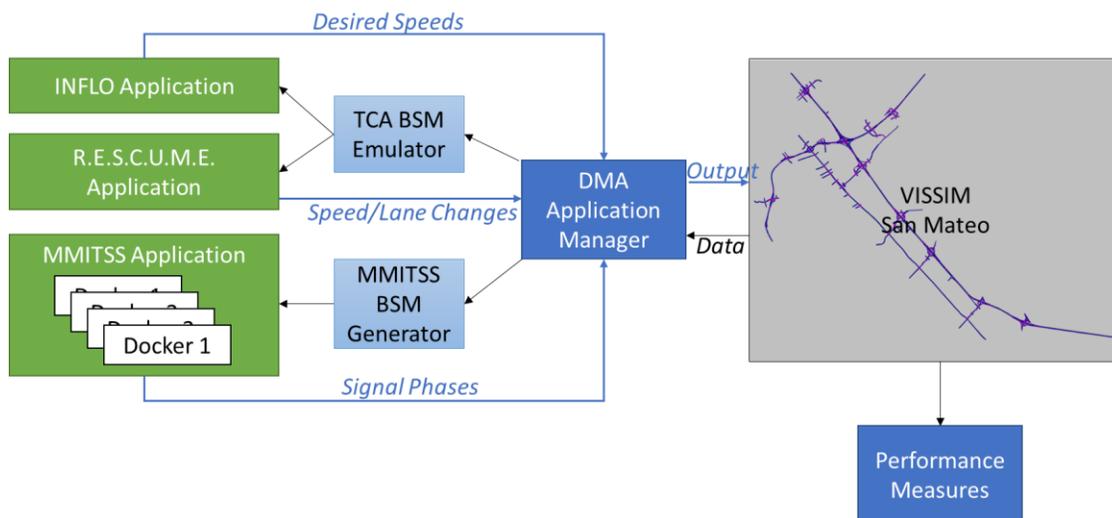


Figure 3-2. San Mateo Testbed Modeling Framework [Source: Booz Allen]

### 3.3.2 Phoenix Testbed

As far as the Phoenix Testbed is concerned, the complexity of modeling DMA and ATDM applications were major. For example, DMA applications worked at a microscopic vehicular level which required high-definition simulators such as the HD-DTA. However, ATDM applications utilized diverse tool to interact with the vehicle paths. For example, VISSIM’s ASC/3 controller was used for Adaptive Signal Control. Therefore, the testbed utilized two different modeling frameworks for DMA and ATDM evaluation as shown in Figure 3-3 and Figure 3-4. Additional details on these frameworks are available in: Booz Allen Hamilton, *Analysis, Modeling, and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs – Evaluation Report for the DMA Program*, FHWA-JPO-16-383, July 2017 and Booz Allen Hamilton, *Analysis, Modeling, and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs – Evaluation Report for the ATDM Program*, FHWA-JPO-16-385, July 2017.

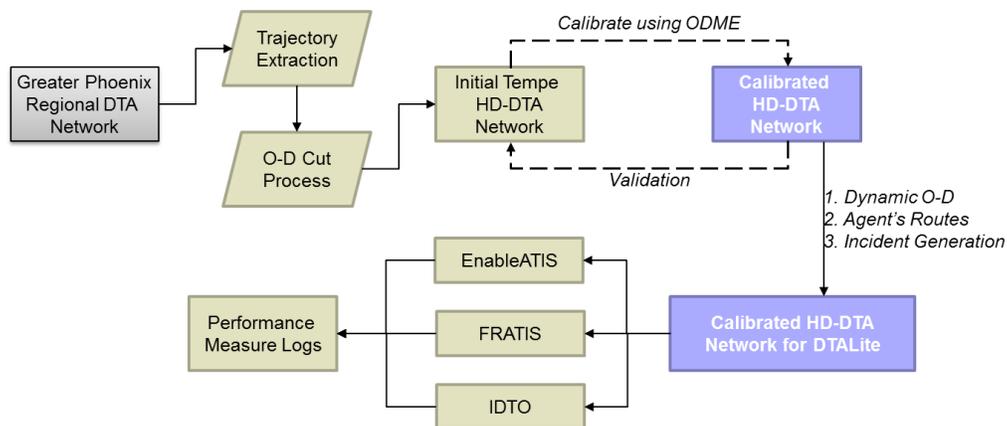


Figure 3-3. Phoenix Testbed DMA Modeling Framework [Source: Booz Allen]

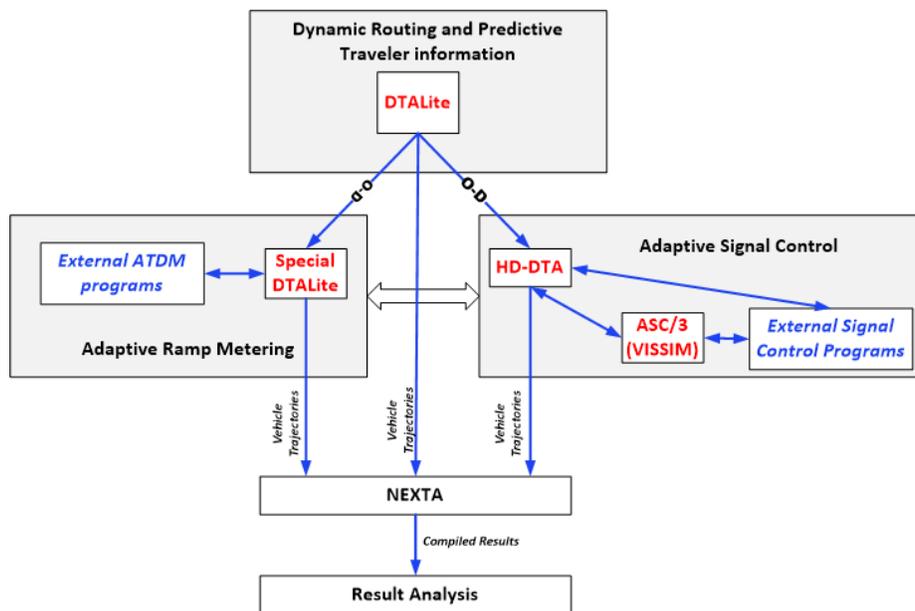


Figure 3-4. Phoenix Testbed ATDM Modeling Framework [Source: Arizona State University]

### 3.3.3 Dallas Testbed

The Dallas Testbed, as shown in Figure 3-5, uses a rolling horizon prediction method to select the best ATDM strategy to implement based on a network state estimation module. The architecture is ATDM-centric and consists of a Network State Estimation Module, Network State Prediction Module, Demand Estimation and Prediction Module and a Decision-Making Module. All simulation for this testbed was performed using the DIRECT traffic simulation platform. Further details on the testbed is provided in the following document: Booz Allen Hamilton, *Analysis, Modeling, and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs – Analysis Plan for the Dallas Testbed*, FHWA-JPO-16-373.

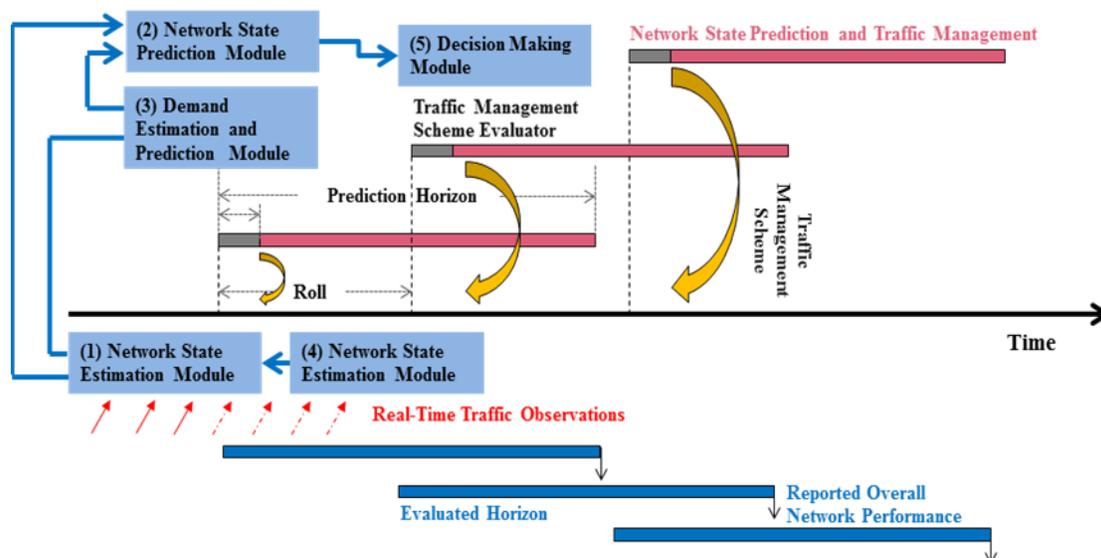


Figure 3-5. Dallas Testbed Modeling Framework with Rolling Prediction Horizon [Source: Southern Methodist University]

### 3.3.4 Pasadena Testbed

As for the Pasadena Testbed, the modeling framework (Figure 3-6) includes two sets of simulation loops. The VISSIM -based microsimulation represents the reality-simulation which can invoke ATDM strategies via internal and external API. A simulation manager which governs this simulation, also runs parallel TRANSIMS macroscopic simulations to predict future traffic states under different response plans. A decision support system utilizes this future predicted traffic state to decide the best ATDM response plan which is consequently implemented in the VISSIM microsimulation. The simulation manager also aggregates performance measures for evaluation purposes.

Additional details on this framework is provided in Booz Allen Hamilton, *Analysis, Modeling, and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs – Evaluation Report for the ATDM Program*, FHWA-JPO-16-385, July 2017.

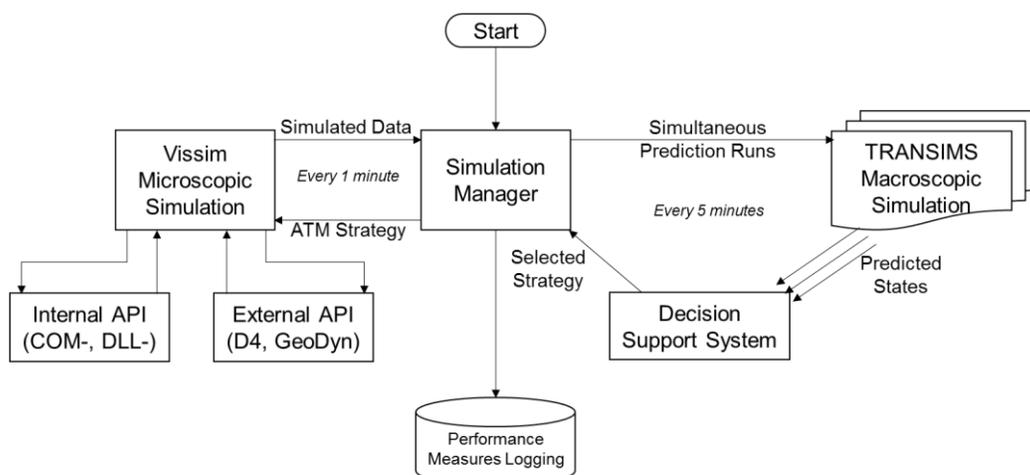


Figure 3-6. Pasadena Testbed Modeling Framework [Source: Booz Allen]

### 3.3.5 Chicago Testbed

Figure 3-7 shows the modeling framework for the Chicago Testbed that uses a rolling horizon approach to Active Management, similar to the Dallas Testbed. However, the platform that was used by the Testbed was DYNASMART. The network modules are also very similar to the Dallas Testbed. Additional details on this approach and architecture is provided in Booz Allen Hamilton, *Analysis, Modeling, and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs – Evaluation Report for the Chicago Testbed*, FHWA-JPO-16-387, April 2017.

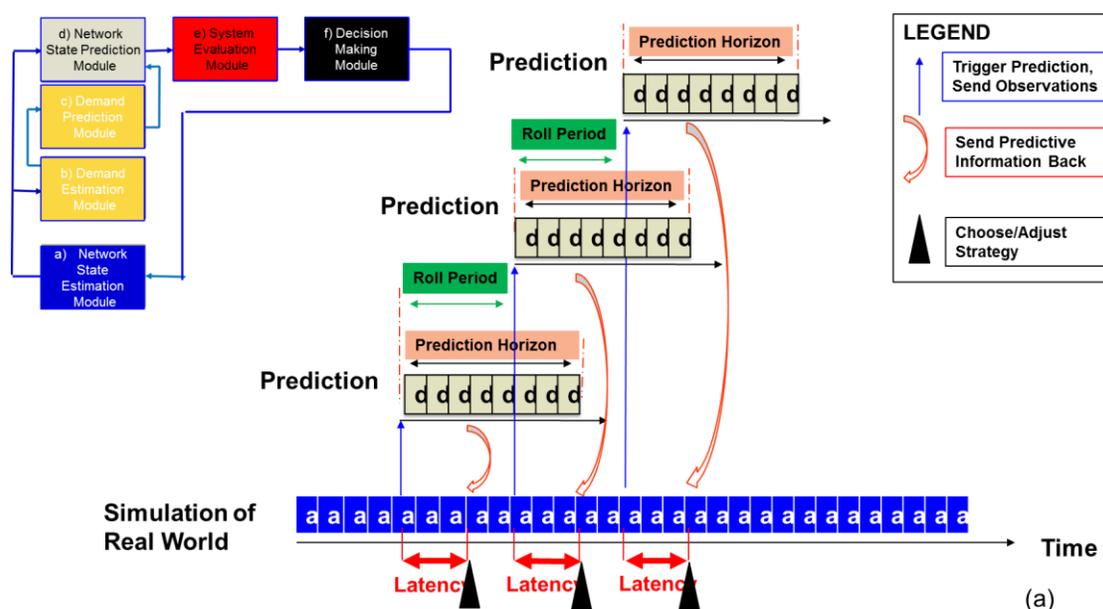


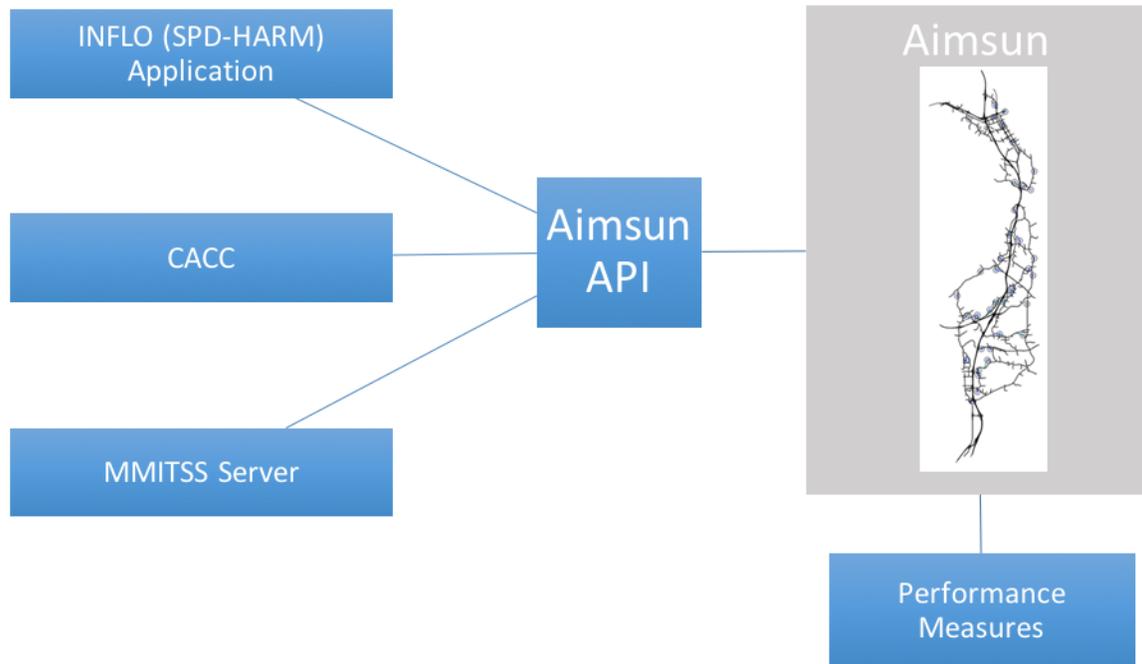
Figure 3-7. Chicago Testbed's Rolling Horizon Prediction and Modeling Platform [Source: Northwestern University]

### 3.3.6 San Diego Testbed

The modeling framework for the San Diego testbed is similar to the one deployed in San Mateo (Figure 3-8). The traffic simulation tool is Aimsun, developed by TSS-Transport Simulation Systems. Aimsun is a multi-resolution traffic modelling platform that includes macroscopic, mesoscopic, microscopic and hybrid mesoscopic-microscopic modelling engines. The microscopic simulator is the only one used for the evaluation. Aimsun features an Advanced Programming Interface (API) that allows implementing processes that during the simulation read outputs and implement changes to the infrastructure (signals, ramp meters, lane closures, etc.), or interfacing Aimsun with external processes. The API was used to model:

- ITS devices that are already operational in the corridor: San Diego Ramp Metering System (SDRMS), Congestion Pricing System (CPS), Changeable Express Lane System (CELS)
- Interfaces with external DMA applications and bundles

ATDM Strategies were modeled using the standard Traffic Management functionality provided by the software, which allows to code changes affecting the infrastructure (e.g. lane closure, turn closure, change of speed limit) or the vehicle behavior (e.g. forced turn, forced re-routing) at specific times or when a triggering condition occurs during the simulation.



**Figure 3-8. San Diego Testbed Modeling Framework [Source: TSS]**

Additional details on this framework is provided in Booz Allen Hamilton, *Analysis, Modeling, and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs – Evaluation Report for the San Diego Testbed*, FHWA-JPO-16-389, July 2017.

# Chapter 4. Major Project Accomplishments

The AMS project was a complex undertaking that aimed at developing computer-simulation-based testbeds that replicate real-world transportation networks and use them to assess the impact and evaluate upcoming transportation technology, such as Dynamic Mobility Applications and Active Transportation and Demand Management strategies. The project was unique in building a portfolio of testbeds with varying capabilities that could be effectively used to assess different aspects of these next generation operational improvements that utilize data-centric and predictive approaches. While this chapter is meant to highlight the major project accomplishments, readers are encouraged to use the set of other deliverables that were developed during this project to get a full picture.

1. The AMS project aimed to bring together the experts in transportation modeling and simulation in scoping and developing the portfolio of testbeds. The project included continuous stakeholder engagement with invited experts in the field as well as presentations and research papers at transportation conferences to gain this feedback. Additionally, the project team comprised four research universities, and five consulting companies who are leaders in transportation modeling and simulation.
2. For each of the testbeds, the project team used a data-centric approach to understand the operational conditions that occur in real-world. This approach, known as the cluster analysis approach, is one of the first implementations after getting added to the Volume 3 of the Traffic Analysis Toolbox, and aims at using not just the traffic data (underlying phenomenon), but also non-recurring measurements such as incidents and weather data as well as data that characterizes system outcomes such as travel time. Therefore, the results demonstrated from this project are not indicative of “typical” day behavior, but a weighted impacts of different day types.
3. The project included documenting each step of our approach that led to nearly 25 publications as listed in Appendix B. The publications included our stakeholder engagement plans, analysis plans for each of the testbeds, overall evaluation plan, calibration and cluster analysis reports, evaluation reports, and summary documents.
4. The project also yielded several deliverables in the open source space. Specifically, all the data collected and generated during the testbed activity, along with testbed’s simulation networks are provided in the USDOT’s Research Data Exchange. The team also published all the source code developed under this project in the USDOT’s Open Source Application Development Portal.
5. While individual DMA applications have been prototyped before and simulated for their impacts, AMS testbeds such as San Mateo and San Diego formed some of the early examples where multiple DMA applications interact. Additionally, several DMA applications that were not prototyped before, such as EnableATIS, FRATIS, D-RIDE etc. were modeled with limited functionality so that their system-wide benefits could be measured.
6. Traditionally, modeling of transportation improvements utilized a single simulation tool with rarely any multi-resolution capability. All the AMS testbeds feature an integrated suite of simulation tools as demonstrated in Table 2-5. Testbeds such as Pasadena, even had multiple simulation tools such as Vissim and TRANSIMS constantly interacting and representing real-world performance and virtual world prediction.
7. Connected Vehicle applications such as Speed Harmonization and Intelligent Signal Control were previously evaluated using testbeds of limited geographic extent, whereas in the AMS testbeds, the models represented even metropolitan areas, with existing ITS infrastructure such as Ramp Meters, Dynamic Signal Control etc., when they were used for DMA application evaluation.

8. Additionally, the complex testbed set up that includes emulation of a traffic management center (such as in the Pasadena Testbed), could be used to replicate a real-time and predictive Decision Support System in which the operator can implement ATDM strategies based on what worked best in a predictive model.

The project also made significant advancements in the current modeling and simulation area for Connected Vehicles and active transportation management strategies at a testbed level. These are discussed below.

## 4.1 San Mateo Testbed

The San Mateo testbed was a DMA-centric testbed and brought in certain accomplishments of its own. The testbed, for example, was an expansion to the US-101 testbed that was used in FHWA INFLO impact assessment by adding El Camino Real parallel arterial. The merging of networks included developing certain niche techniques in calibration and utilized O-D merging as well as adding traffic sinks and sources to replicate physical connections between the networks.

Additionally, the calibration process included a network-wide cluster analysis using 2012 data that takes into account travel-time data from National Performance Management Research Data Set (NPMRDS), traffic demand data from California Performance Management System, weather data from National Weather Service and incident data from California Highway Patrol. This allowed, clustering of the days in 2012 based on a complex parametric relationship between traffic demand, transportation system performance, incidents and weather, helping the team choose the operational conditions (and representative days for each), that generally occur in the area.

The testbed integrated multiple DMA applications such as Queue Warning, Speed Harmonization, Incident Zone Alerts and Warnings and Intelligent Signal Control. To our knowledge, this was one of the first instances where multiple connected vehicle applications were modeled together, and required development of a unified simulation manager that manages the simulation, and distributes the data to multiple CV applications and implements the outcome in the simulation.

The testbed also integrated simplified communications modeling to assess the impact of different communication protocols, latencies and loss-rates on the CV applications. The Trajectory Conversion Algorithm (TCA) tool, that was developed by the Advanced Data Capture project by Noblis, was integrated with the simulation manager to perform this analysis.

The team also integrated the benefit and cost estimation tool developed by Booz Allen under National Impacts Assessment project, to analyze system-wide costs and benefits in the San Mateo region due to implementation of these CV applications.

Consequently, the San Mateo testbed was a non-traditional Software-in-the-Loop simulation system that integrated multiple tools developed by different teams into a unified testing interface that helped assess both synergies and conflicts between the applications, and impact of communication parameters.

## 4.2 Phoenix Testbed

The Phoenix Testbed was a DMA-ATDM testbed that aimed at modeling strategic DMA applications that relied on traveler-centric data. The testbed aimed at modeling strategic applications such as IDTO, FRATIS and EnableATIS. However, these applications were either not developed before, or developed as proprietary products. As part of this testbed, the team developed these applications and integrated them

to the modeling framework developed for Phoenix. Since the testbed was a traffic-assignment-based model, incorporating DMA applications included developing high-definition DTA tools, or HD-DTA.

The team also integrated ATDM strategies with the HD-DTA network. This included utilizing several external tools to set up a software-in-the-loop system. For example, RHODES traffic signal system was implemented as the Dynamic Signal Control system, which was implemented in Vissim using its inherent ASC/3 interface.

The testbed also included prediction-based traffic scheme implementation where prediction of link travel times was used to proactively implement ATDM strategies.

### **4.3 Pasadena Testbed**

The Pasadena Testbed was an ATDM-centric testbed that was primarily utilized to assess the impact of predictive Decision Support Systems. The testbed featured a prediction-in-the-loop system which included Vissim as the real-world transportation network and TRANSIMS macroscopic simulation as the virtual reality used for prediction. At specific intervals, TRANSIMS used the current network performance to advance its simulation to a prescribed prediction horizon, to return the predicted network performance.

As such, the testbed was a complex system of multiple software pieces and included Vissim (for its base simulation), a scenario manager (to control the simulations and data bus), TRANSIMS (for predicting future network performance), D4 controller (to simulate signal control behavior), GeoDyn (to control some of the ATDM features such as ramp metering) and other COM-based software (for ATDM strategies and performance measurement).

The use of a scenario manager as the data bus between the simulator and the predictor enabled testing of ATDM under different prediction parameters such as prediction horizon, prediction latency and prediction accuracy.

This first-of-its-kind software-integrated testbed could replicate a real-time Decision Support System at a Traffic Management Center (TMC)-level, by being able to assess different response plans in the TRANSIMS prediction tool and implement the one that is most system optimal.

Pasadena testbed was also one of the largest networks that is possible at a microscopic resolution and simulated around 100,000 vehicles each hour at 0.1-second resolution. The testbed geographic coverage was 11 square miles.

### **4.4 Dallas Testbed**

The Dallas Testbed utilized the ICM Dallas model developed using DIRECT. The ATDM-centric testbed model has been developed as an offline version of the ICM prediction tool and replicates several operational management strategies deployed as part of the ICM project. Like other testbeds, the Dallas testbed also underwent a data-centric approach to recognizing representative operational conditions. In addition to the operational conditions demonstrated through the cluster analysis, the team also evaluated the performance of ATDM strategies under two other operational conditions – inclement weather and evacuation.

The testbed also features advanced performance measurement which goes beyond mobility-based measures. While most ATDM strategies have been well recognized to improve operational efficiency of transportation systems, the Dallas testbed was able to provide quantitative impacts in terms of emissions, including carbon dioxide and nitrogen oxides and amount of fuel consumption.

As part of the Dallas testbed, the team also developed a Decision Support System in generating efficient traffic management schemes using a Genetic Algorithm, and using its DSS system, the emulated TMC could assess up to 45 different traffic management schemes to ensure the best performance.

While most other testbeds focused on Active Traffic Management and Active Demand Management strategies, the Dallas testbed also assessed the impact of Active Parking Management strategy, specifically, the Dynamically Priced Parking. By modeling traveler's departure, destination and mode choice, the testbed could quantify the impact of different parking prices on individuals' travel behavior.

## 4.5 Chicago Testbed

The Chicago Testbed was a later addition to the portfolio of AMS testbeds, and was selected due to its potential to assess the different weather-related strategies. Using the Chicago Testbed, four different weather-related strategies were evaluated, namely, Snow Emergency Parking Management, Traffic Signal Priority for Winter Maintenance Vehicles, Snowplow Routing, Anti-icing and Deicing Operations. This involved algorithm development, testing and integration of these strategies into the Chicago Testbed framework.

Additionally, this testbed was developed in DYNASMART, a (meso) simulation-based intelligent transportation network planning tool. This allowed testing of the impact of Connected Vehicle technology on the fundamental diagram of traffic flow, at different levels of market penetration.

The testbed also integrated DYNASMART-P, the network-state prediction module of DYNASMART. This enabled assessing different prediction parameters such as prediction horizon and latency.

The testbed also assessed the different ATDM strategies under multiple weather-based operational conditions chosen through a cluster analysis. Unlike other testbeds, the Chicago testbed used a 24-hour simulation cycle.

## 4.6 San Diego Testbed

The San Diego Testbed was a DMA-ATDM testbed that replicated the ICM San Diego system and was modeled using Aimsun simulation software. The testbed assessed combination of Cooperative Adaptive Cruise Control and Speed Harmonization applications. This included developing the CACC application for Aimsun as well as developing necessary wrappers for Speed Harmonization application that was previously only used with Vissim. In addition, the developed CACC application also featured a lane-changing behavior, which was not performed in the inherited TNO (Netherlands Organization for Applied Scientific Research, Toegepast Natuurwetenschappelijk Onderzoek) studies.

The testbed also included modeling response plans based on the ICM San Diego deployment which used Aimsun Online version as well as the following ITS systems: San Diego Ramp Metering System (SDRMS), Congestion Pricing System (CPS), Changeable Express Lane System (CELS).

San Diego Testbed was the only testbed which assessed the impacts of combining DMA applications and ATDM strategies.

# Chapter 5. Lessons Learned

The AMS project included development of six testbeds of varying size and resolution. The testbed size ranged from just a freeway-arterial corridor in case of San Mateo testbed to a major metropolitan area like Chicago. The project also included expanding existing applications and developing new models to replicate real-world transportation applications such as the DMA applications and ATDM strategies using traffic state prediction. Throughout this report, the team has specified gaps and challenges that the teams have faced during the AMS project as well as deviations from the original analysis vision. In this chapter, we briefly describe the different lessons learned throughout the course of the project. Please note that this report is not meant to be a guidance on how to perform AMS research, but rather pointing out the challenges that taught a lesson to the project team as well as considerations that would be made in future AMS research.

## 5.1 Scoping of Testbeds

During the development of testbed-specific analysis plans, the testbed teams evaluated the requirements of the AMS testbeds and assessed the realistic scope of each testbed that can be integrated within the given time-frame and resource availability. This includes geographic area and resolution of the testbeds, the communication features of the data bus and the software capabilities. Despite this scoping effort, some of the testbed architecture turned out to be too complex. One of the primary lessons learned when conducting in-depth review of the testbed architecture and tools while scoping the testbeds is to account for uncertainties that some tools might be more complex than imagined.

For Pasadena Testbed, the size and resolution of the testbed was too big to be computationally efficient to have a complex testbed architecture as shown in Figure 3-6. This caused computational issues as well as additional development requirements due to extensive debugging process that was required for each aspect of the testbed. Another example where scoping was affected was for the Phoenix Testbed, where the inconsistencies between the software requirements for the different parts of the testbed architecture affected the overall size of the network that was used for evaluation. For the Phoenix Testbed, integrating adaptive signal control strategy (RHODES in this case) and adaptive ramp metering encountered scalability issues which caused network downsizing for specific scenarios.

It is worth mentioning that the resources required for debugging and tool integration is exponential to the complexity of the model.

## 5.2 Data Availability and Calibration

Another major lesson learned was the impact of inconsistencies in data availability at certain locations in the same region. For example, most freeways are well-instrumented and collected high quality data on volumes, speeds, incidents etc. However, arterial instrumentation is sub-par at several locations with data only available for specific days or even typical days. Additionally, data sources for arterials relied on probe-vehicle data such as NPMRDS and Inrix, which caused inconsistencies during the calibration process. Microscopic simulation networks are meant to be calibrated for freeways and arterials for observed volumes, speeds and travel time. However, there were inconsistencies in the calibration of Pasadena, Phoenix and San Mateo.

For the Pasadena Testbed, the arterials were calibrated to a typical day, whereas freeways were calibrated to specific representative days for each cluster. Phoenix Testbed had varying data quality for arterials and freeways. Freeway data was obtained and maintained by Arizona Department of Transportation, whereas, arterial data was maintained by local agencies and are difficult to obtain. This inconsistency affected results of applications such as Dynamic Route Guidance or Advanced Traveler Information Systems in being overestimated. As far as the San Mateo testbed is concerned, both arterial data and freeway data available are from different time-periods. But the team conducted cluster analysis to select representative days corresponding to freeway data and used arterial data from days that had similar traffic performance. The lesson learned here is to perform additional data quality checks at the testbed selection stage itself.

Another aspect was the number of operational conditions identified. The number of operational conditions identified as a part of the cluster analysis was representative of the variability in conditions in each of the testbeds as well as the granularity in representing conditions by the selected clusters. Large number of clusters will result in each day being better represented by the clusters, whereas smaller number of cluster will result in more generalization of operational conditions. The selection of number of clusters was a trade-off between the resources required to perform calibration on each of the cluster and the representation of real-world data that was required.

### 5.3 Application Availability and Features

Understanding the limitations of applications and its features is also important prior to developing analysis plans. As demonstrated in Chapter 3, each of the Testbeds is a complex software system with multiple external software application, data systems as well as decision-making programs. Throughout the development phase, each of the components had to go through several rounds of debugging and testing prior to the integration in to the final testbed model. This includes external DMA applications, software that replicate ATDM strategies as well as system managers and performance measurement code base. During the start of the project, several of these applications were expected to be available to the project team and interact smoothly with each other.

During the testbed development phase, several of these applications that would have been developed under other contracts got downsized or delayed. Some of the software that were developed were unable to work with other software due to versioning issues, data type issues and other requirements. For example, San Mateo testbed had to integrate both INFLO application and MMITSS application to assess the interaction between the two. However, they both were designed for different versions of VISSIM and the team had to develop a third application to integrate the two. Similar issues happened to other testbeds such as Phoenix, Pasadena and San Diego. For San Diego for example the team didn't succeed in having a working local deployment of the MMITSS application: since the software is still in the research and development phase, it is very sensitive about the configuration of the computer used to run it, and there is no official technical support that can help solving this issue.

Additionally, there was little knowledge on the application availability, expandability and scalability when the analysis plan was being developed. For example, the INFLO application can have only one instance turned on at a time, which essentially limited the capability to run speed harmonization on both directions of a freeway, and it requires user interaction to be started, which didn't allow it to be interfaced with a simulation-based predictive framework.

The lesson learned here is that the scoping of modeling should articulate reviewing existing application algorithms in a detailed manner and should probably include engagement from stakeholders who were involved in the development of these application algorithms.

## 5.4 Computational and Software Requirements

Due to the size and resolution of the testbeds, the computational requirements to run simulations were quite high. Adding to this complexity was the Connected Vehicle emulation. Connected Vehicle emulation required data to be collected from each vehicle at 10<sup>th</sup> of a second, which contributed to over 10 trillion messages being generated by Pasadena Testbed alone in a 4-hour window. Since this was impossible to handle without cloud-based methods, the team only conducted CV emulation in smaller testbeds, such as San Mateo. Even for San Mateo testbeds, the team used a simplified Connected Vehicle emulator such as the Trajectory Converter Algorithm (TCA). Lack of cloud-based capability from VISSIM and TCA caused significantly high computation times which affected the number of random seeds simulations that are required for studying the statistical validity of the results. The lesson learned here is scoping the simulation process so as to reduce the number of scenarios that needs to be simulated to answer sets of research questions.

Additionally, there were instances that the software failed to properly function. Both VISSIM and VISTRO failed initially to process the Pasadena Model. VISUM was used to create the initial calibration and was then imported as a DTA model into VISSIM. To complete the calibration in VISSIM and to implement the ATDM strategies, the VISSIM model was converted from dynamic routing to static routing. The conversion process took upwards of four weeks working with PTV Support to successfully convert the dynamic routing to static routing. In this time, custom tools had to be created to manipulate the static routes. To generate dynamic timing plans, the traffic data from VISSIM was imported into VISTRO. However, due to software bugs in VISTRO, the dynamic timing plan creation was delayed by nearly two months. To implement a variety of strategies, traffic counts and speeds needed to be collected from numerous locations along the freeways. Initially, this was performed via detectors and COM functions that queried the detectors every second. However, vehicle counts and speed were missing data. The Pasadena Testbed found that by querying the detectors every tenth of a second all data was captured but the model was prohibitively slow. To increase the simulation speed, the detectors were replaced with VISSIM Data Collection Points and Vehicle Travel Time Measurements, which would automatically collect the relevant data. This allowed the Pasadena Testbed to query the data only when the data was needed instead of continually. Even with the testbed optimized, the complexity and size of the model still caused both hardware and software issues causing lost simulation runs. One such problem was that opening any dialog menu in VISSIM while the scenario manager was running caused VISSIM to crash immediately.

Another challenge for the Pasadena Testbed was creating the software interface between the Pasadena Scenario Manager, TRANSIMS, GeoDyn, and VISSIM. The communication between the Scenario Manager, GeoDyn, and VISSIM operated in Java, while the communication between the Scenario Manager and TRANSIMS operated in C#, which added to the complexity and difficult of integrating all the necessary systems. In addition, custom interfaces had to be designed to handle the communication between each part of the overall Testbed. The interfaces were also required to operate both offline and online to allow for testing of individual strategies.

## 5.5 Performance Measurement

As far as the performance measures were concerned, several lessons were learned during this project. Primarily, the ability for different tools to report certain performance measures varied across the tool sets that were used in building the AMS project. For example, the DTALite and HD-DTA simulation tool used for the Phoenix Testbed could not report performance measures that are related to environmental or safety measures, nor did it generate vehicle trajectory files which could be used for post-processing to compute those measures. Similarly, for reporting environmental performance measure, the vehicles have

to be calibrated to specific environmental models using tools such as CMEM or VT-Micro models. Due to lack of environmental data to calibrate at these testbed locations, generating model-specific parameters were not possible. In terms of travel-time reliability, the team utilized Travel Time Index over the course of simulation to identify worst and best travel times. However, in reality, the comparison should be made over an extended course of time, such as a year, which is not possible in a simulation environment.

The primary lesson learned here is that the tool selection process is a trade-off between its capabilities in modeling the new applications and its capacity to produce different performance measures.

## 5.6 Statistical Validity

As mentioned in Section 4.4, each of the AMS Testbeds were complex systems with several pieces of software interacting with each other. Owing to this complexity, most of the AMS testbeds that were microscopic in nature, had long runtimes. In addition, each of the AMS testbeds was used to simulate around 100 to 300 scenarios to answer the set of research questions that were set forth by the USDOT. This limited the team's ability to conduct multiple random seed runs to obtain statistically valid results. However, the team conducted at least 5 simulation runs (with the exception of the Pasadena Testbed) for each of the scenarios that were evaluated within the test environment. As with any other research, the statistical validity and the model complexity plays a trade-off role. Complex models are computationally complex to perform multiple repetitions.

# Chapter 6. Gaps and Challenges in AMS Research

For executing the AMS project, each testbed underwent four major steps to execute the development of testbeds and using them to conduct DMA and ATDM evaluation. They are shown in Figure 6-1. Throughout these steps, there were challenges in performing the planned AMS research. These challenges left gaps in what the research team originally intended to do and the team could do, using the available resources. In this chapter, we discuss these gaps and challenges to help evaluate how they affected the overall project scope.



Figure 6-1. AMS Testbed Development and Evaluation Steps

## 6.1 Addressing AMS Requirements

At the onset of the project, the project team had developed detailed AMS requirements featuring a list of specific system requirements where each of the AMS testbeds should follow to achieve project objectives completely. These are available in Booz Allen Hamilton, *Analysis, Modeling, and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs – Detailed AMS Requirements*, FHWA-JPO-16-369, April 2016.

Considerable efforts were made for the development of each testbeds to address most of the project objectives. However, over the course of the project, certain requirements were eased and some others were not considered, owing to the additional level of effort and resources needed or the lack of a feasible modeling methodology. The following sub-sections summarize these gaps.

### 6.1.1 System User Requirements

As far as the system user requirements are concerned, the AMS requirements suggested emulating and tracking the movement of travelers using different modes of transport such as light duty vehicles, transit vehicles, trucks, emergency vehicles, as well as non-motorized modes such as pedestrians. While we had different modes of users in the AMS testbed framework, as shown in Table 2-4, non-motorized modes were not used in the project due to unavailability of data to calibrate the models as well as the complexity it would impart to these testbeds. For testbeds with transit modes, the transit vehicles and transit ridership were modeled in a separate network platform from conventional roadway traffic. For instance, Phoenix Testbed tested the IDTO applications T-DISP and D-RIDE using a subset of the network. T-DISP was assessed for the dynamic dispatch capability using a few transit routes and D-RIDE assessed the dynamic ridesharing functionality using 100 transit rides. The requirement to emulate

flexible route bus, rail transit and paratransit were not fully performed, except of the light-rail mode simulated as part of the Dallas Testbed.

As for the driver's decision making system, different testbeds considered individual driver's decision control systems in a different manner. For example, tactical driving decisions such as lane selection, lane changing, gap acceptance, following headway, speed, acceleration, deceleration etc. should be considered, as well as strategic driving decisions like way finding and mode choice. The current modeling framework only allowed some of the testbeds to emulate tactical driving decisions as well as strategic driving decisions, primarily due to the modeling structure. In general, macroscopic models are devoid of ability to emulate tactical driving decisions and microscopic models are too complex to emulate strategic driving decisions.

Another priority requirement that was simplified in this project was the need to emulate compliance rates of system users. While compliance rate was employed for ATDM evaluation, for DMA evaluation, the team used a combined compliance and market penetration rate. Hence the market penetration rate represented both. For example, a compliance rate of 50% and market penetration of 100% was considered to be same as a market penetration of 50%. This was done to reduce the degrees of freedom for analysis.

### **6.1.2 Connected Vehicles and Connected Traveler Requirements**

This project was envisioned to emulate mobile devices, carry-in devices and integrated devices separately. However, throughout the project, the team simplified these three types of devices to "equipped vehicles" and used a unified market penetration rate. Additionally, the communication modeling that assessed cellular and DSRC communication was distinguished only for San Mateo testbed, where a full communication emulation tool, such as the Trajectory Converter Algorithm (TCA) was used. However, TCA resulted in heavy computation requirements and therefore, modeling DMA applications with TCA was restricted to specific cases where impact of communications needed to be evaluated. In the San Diego testbed TCA was interfaced with the traffic simulator, but then coupling it with the INFLO application, which relies on a database for communication rather than a socket, was discarded for time constraints in favor of a simpler approach based on discarding records or applying a delay when reading and writing the database from Aimsun.

In the original proposal, the Phoenix Testbed team planned to insert a micro-scale, high-fidelity wireless simulator, OMNET++<sup>3</sup>, into the VISSIM and eventually become part of the multi-resolution simulation platform. However, soon after this project started, the microscopic simulator, VISSIM, experienced a major update by its vendor, PTV AG. This, in addition to resource limitations, caused the testbed team to scale-back on developing a fully functional communication model.

A full communication modeling was computationally and developmentally too complex to be integrated with larger models such as the Pasadena Testbed. For example, the Pasadena Testbed emulated over 70,000 vehicles in one hour, which in CV terms, will correspond to 2.5 trillion vehicle records in 1 hour at full market penetration. As such larger models were computationally too slow to simulate. Adding a CV communication layer would have made the models impossible to simulate using the current state-of-the-art machines. In addition to performance, the CV communication layer should fulfill the need of interoperability both with traffic simulators and with DMA applications, possibly with the definition of a standardized interface, to which any software that wants to rely on it should comply.

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<sup>3</sup> OMNeT++ is an extensible, modular, component-based C++ simulation library and framework, primarily for building network simulators. Accessed at: <https://omnetpp.org/intro>

The team recommends conducting a full-fledged communication modeling on smaller simulation testbeds since they are computationally possible, to elaborate on our understanding of how communication parameters would affect CV applications, and then supplement them with higher-level communication models for larger simulation testbeds, which simulates overall impacts and not packet-by-packet transactions.

Additional parameters with respect to connected vehicle devices such as their reliability in terms of local interference, device malfunction or user error were also not incorporated into the testbeds, due to lack of full communication modeling components in the testbeds such as radio-transmitter modules, discovery modules, packet loss models etc. This was primarily due to two factors: the computational complexity of doing a full communication modeling parallel to traffic modeling and unavailability of an integrated tool to perform such a modeling effort.

### **6.1.3 Operational Data Environment Requirements**

As far as the operational data environment is concerned, the primary requirements associated with the development of AMS testbeds were emulation of a quality control process for data from connected vehicles, mobile devices, detection systems as well as the prediction system. While some of the DMA-centric testbeds such as San Mateo, had components to emulate data capture and aggregation, a full quality control process was not emulated. For ATDM-centric testbeds like the Dallas, Pasadena, and Phoenix testbeds which have prediction capabilities; the data environment parameters such as prediction horizon, accuracy, latency, and geographic scope were emulated.

### **6.1.4 System Manager Requirements**

The team had identified 18 system manager requirements to be included in the AMS Testbeds and includes primarily the ability to emulate decision-making and decision-taking by various entities of traffic management operations such as freeway system and tollway manager, arterial manager, transit manager etc. All of the AMS testbeds emulated some form of system manager ranging from a simplified application manager for San Mateo Testbed to a full-fledged system manager who can use parallel predictions to emulate different response plans and pick the right one, as demonstrated by the Pasadena Testbed. However, the AMS testbeds simplified the system manager emulation to a unified model instead of separately emulating Arterial System Manager, Transit System Manager, Parking System Manager, Freight System Manager, Public Safety System Manager and Road Weather System Manager. None of the testbeds emulated Public Safety Systems and Freight Systems, whereas other systems were emulated by at least one Testbed. The focus of this study is on system-wide benefits and not user-centric benefits, hence the simplification by not modeling the system manager functions separately is irrelevant to the purpose of this study.

Another gap in system manager emulation is the emulation of system control by Information Service Providers using different types of broadcast media. For most of the ATDM-centric testbeds, the communication was simplified to be just from one module to another in a Software-in-the-Loop system. For San Mateo and San Diego Testbeds, communication aspects such as latency and losses were emulated for DMA evaluation.

### **6.1.5 Data and Information Flow Requirements**

Most of the data and information flow requirements have been satisfied by at least one of the testbeds. For example, the San Mateo testbed was designed to be a full Connected Vehicle emulation where the Simulation Manager queried information from the simulation and provided them to corresponding DMA applications. The queried information from vehicles include the major BSM parameters and the information from infrastructure represent standard ITS data and Signal Phasing and Timing information.

Additionally, scenarios for San Mateo testbed also included emulation of cellular-based and DSRC-based communication parameters.

### **6.1.6 Operational Condition and System Performance Measurement Requirements**

As far as the requirements for operational conditions are concerned, the AMS testbed could satisfy all the requirements including having calibrated and validated testbeds for multiple operational conditions identified via a clustering analysis. However, there were considerable challenges in using field data to identify prioritized operational conditions and to calibrate testbeds to be reflective of these conditions. These challenges are identified in Section 6.3.

The project teams envisioned demonstrating project results using three types of performance measures: (1) mobility, (2) safety and (3) environmental. Measure of effectiveness for each category were identified to demonstrate and compare their performances. However, as the project proceeded, several of these performance measures were not used in the final report. Mobility performance measures such as travel-time, average speeds etc. were used in demonstrating the performance of ATDM strategies, but for certain DMA applications, these MOEs were not statistically significant. Some tools such as DTALite could not report mobility-based measures such as travel time reliability.

Assessment of safety-based performance measures using Surrogate Safety Assessment Models (SSAM) such as post-encroachment time could not be used for mesoscopic and macroscopic simulation models. For testbeds such as San Mateo and Pasadena, the vehicle trajectory data was unmanageably big to conduct such analysis. SSAM, being an older software, was not designed with parallel multi-core computing in mind and was designed to assess safety at a single corridor level or for a single intersection. Hence, safety-based performance measurement was utilized only for specific DMA applications such as speed harmonization to assess the impact on shockwaves. Environmental measures such as fuel-consumption and emissions require specifically calibrated energy/emissions model to be incorporated into the testbeds, such as MOVES. Extending these models into state-of-the-art traffic models require large amounts of operational data on energy and emissions which were not available to the testbed team. Therefore, such measures were only reported to testbeds with inherent capability. For example, Dallas testbed did report performance in terms of fuel consumption and greenhouse gas emissions. Lack of calibrating data and the resources required to add energy/emission models hindered coding other testbeds to report such performance measures.

### **6.1.7 DMA Application and ATDM Strategy Requirements**

As far as the requirements for DMA applications and ATDM strategies are concerned, the team had limitations due to availability of application source-code or ATDM response strategies for certain applications and strategies.

## **6.2 Addressing Research Questions**

The USDOT put forward a list of research questions for the project team to answer through the AMS project. This includes 29 questions from the DMA program and 18 questions from the ATDM program. Using a combination of qualitative and quantitative analysis, the team was able to successfully answer most of these research questions. However, some of the questions were not possible to be answered with the current evaluation framework and modeling capabilities. These are discussed in this section.

As far as the DMA-related research questions are concerned, there were significant limitations in modeling certain policy aspects of the applications. For instance, policy implications such as the impact of

availability of Personally Identifiable Information could not be modeled with the current testing framework. For example, applications are not prototyped with behavioral parameters to be able to assess the impact of certain policy aspects. Additionally, several of the policy-related questions including agency participation, user opt-in, availability of data etc. were assessed using the market penetration aspect of the CV modeling.

As far as the ATDM-related research questions are concerned, the major gaps in answering were with respect to conducting a benefit-cost analysis. This is due to lack of robust benefit-cost analysis models that the team could utilize to conduct this analysis and the development of a full BCA model was beyond the resource availability in this project. For instance, the team performed benefit-cost analysis for the DMA applications using one of the models that was acquired from the DMA program's National Impact Assessment team which performed benefit cost analysis focusing on travel time savings. This model did not quantify savings due to travel time reliability or environmental sustainability. Such a model did not exist for the ATDM program. The other major gap in ATDM research was the impact of short-term versus long-term behavior of travelers under active management. Under the current modeling framework, each of the simulations are independent of each other and there is no learning associated with traveler path or mode selection. This limited our ability to conduct analysis surrounding comparison of short-term versus long-term traveler behavior.

### **6.3 Operational Conditions, Cluster Analysis and Calibration**

The AMS project team identified representative operational conditions via a cluster analysis procedure. Cluster analysis identified scenarios from traffic data records that represent the majority of the field scenarios. However, during the cluster analysis procedure, days with the shortest Euclidean distance that are clustered together may not have been chosen for implementation in the analysis due to inadequate representation of the total field scenario. Hence, another cluster with the next shortest Euclidean distance is assessed for its representation of field scenario before a decision is made to adopt. Additionally, if the selected representative day's data is unavailable, the next closest day was chosen.

A hierarchical agglomerative clustering analysis framework was utilized for Phoenix testbed in which hour-by-hour data structure was used to identify the four most representative clusters for a whole year. Nonetheless, the gap mainly exists in the availability of datasets, in terms of types of data, amount of data, duration of data as well as resolution of data. These data attributes changed from region to region and time-period to time-period. One of the gap due to this restriction is the reduction in analysis scope. The original scope of Phoenix testbed was to model the entire metropolitan region, but was subsequently reduced to City of Tempe since the demand for data in cluster analysis was tremendous. Not all the data were available to the ASU project team. For example, the lane-by-lane freeway counts are being collected every 20 seconds in Phoenix by the Arizona Department of Transportation whereas collecting traffic counts on arterials is in the charge of municipal agencies and were unavailable to the project team. In addition, the resolutions and fidelities of weather conditions and incidents on freeways and arterials were also quite different.

The cluster analysis data included only freeway performance since arterial data is either unavailable or only available for a typical day operation. In such cases, even the arterial calibration is made only for that specific day. For example, in Pasadena testbed, the freeways are calibrated for three different operational conditions, whereas the arterials are calibrated to a typical day. San Mateo testbed had lack of arterial data for the year 2012, for which the cluster analysis was performed. However, the testbed team identified representative days from 2013 for the selected clusters and used the arterial data from that year for calibration.

## 6.4 Modeling DMA Applications

Six bundles of applications were envisioned by the DMA program, each containing around three to six applications. Several of these applications were, however, not prototyped previously. Hence the project team did not have an open-source usable code to deploy into the testbeds. Additionally, some of the prototyped applications had limitations such as the need for coupling with proprietary third-party applications or inability to port to a simulation interface. These restrictions did not allow the project team to simulate the following applications (See Section 3.1 for specific reasons on each of these applications):

1. S-PARK, T-MAP and WX-INFO of the EnableATIS bundle.
2. TSP, PED-SIG, PREEMPT and FSP of the MMITSS bundle.
3. T-CONNECT of the IDTO bundle.
4. DR-OPT of the FRATIS bundle.
5. EVAC of the R.E.S.C.U.M.E. bundle.

Despite non-existence of an open-source DMA application codebase, the Phoenix Testbed integrated simplified versions of three of the application bundles in to the modeling framework – EnableATIS, FRATIS and IDTO which replicate some of the functionalities of the original DMA’s vision for the applications. Additional gaps exist in the ability to integrate multiple DMA applications to the same testbed and conduct sensitivity analyses with combinations of the applications. For example, the Phoenix Testbed team had difficulties in combining DMA application algorithms together because of the scalability limit of the current simulation technologies. Thus, FRATIS, T-DISP and D-RIDE had to be evaluated in an “offline” manner given the background traffic. [Offline manner represents a post-processing based approach where the simulation was first performed to get time-based link-specific travel times. This data was used to reoptimize the user paths and used it in the subsequent simulation until equilibrium is achieved.]

Another major gap in modeling DMA applications is the model calibration, both for the baseline model, as well as for the applications. For example, the Phoenix Testbed experienced significant imbalance of traffic data on freeways and on arterials in the calibration efforts. Freeway data were more comprehensive and detailed compared to arterials data. The imbalance in data quality and resolution caused the calibration emphasis substantially more focused on the traffic along freeways. Simulated arterials traffic were significantly underestimated compared to field arterial traffic. This problem propagated to all the DMA application evaluations.

Other challenges in modeling DMA applications include creating data-sockets from the application to the testbed and vice-versa, supporting the additional option of interposing a communication emulator like TCA, producing application-output as vehicle-based commands for the simulation etc. Other challenges include versioning, data-bus resolution, time-synchronization etc. Additionally, the prototyped DMA applications lacked parallel or distributing computing capabilities which created scalability issues in certain deployments.

Additionally, there were disparity in the way each of the applications were modeled. For example, INFLO and MMITSS are the two DMA applications that were implemented in the San Mateo Testbed. INFLO application require vehicle inputs at a 20-second interval input into an access database whereas MMITSS require real-time vehicle inputs at 1-second interval derived from the driver-behavior model in VISSIM. The need for an Access database made VISSIM 5.40 and 7.00, the only feasible candidates to run INFLO, whereas the driver-model-based BSM (Basic Safety Message) generator makes VISSIM 6.00, the only feasible candidate to run MMITSS. The team overcame this challenge by redesigning INFLO’s input output sockets to match VISSIM 6’s COM API. Additionally, the team created a time-synchronization function to enable simulations at real-time operation. Similar issues also run in implementing USDOT’s

TCA Communication Emulator with INFLO. TCA require VISSIM to produce vehicle information at a decisecond 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. The team overcame this issue by only using TCA for communication-specific scenarios.

The San Diego Testbed team also faced challenges in incorporating certain DMA applications within the network. The open-source version of MMITSS application was developed for VISSIM simulation platform that uses Econolite controllers. The San Diego testbed that is based on Aimsun uses McCain 170-type controllers. The team developed a translator to accommodate this change. Additionally, when running the INFLO's speed harmonization application, the application can only exist in one direction of the freeway using one-instance of the application. For implementing CACC application, the team used open-source CACC version that was developed for VISSIM as a Driver Behavior Model. The team utilized this code to rebuild CACC for Aimsun, since it had to be redesigned into specific car-following and lane-changing codes.

The Phoenix testbed had similar issues in modeling DMA applications. For instance, a high-fidelity CV communication emulator had been tested on an older VISSIM platform prior to the project proposal. The network files and CV emulators could not be migrated into the newer version of the simulation platform. This inability to migrate the network and emulators resulted in most research questions related to wireless communication latencies limited to being evaluated and addressed at high and aggregate level. Although the evaluation results answered the research questions to some degree, they didn't reach the level of the original expectations. On the side of simulation platform development, it turned out that developing the simulation platform as in the original proposal needed tremendous efforts to make the proposed simulation platform stable and scalable. There are also limitations in the simulation technologies. After early efforts to integrate travel demand forecast (Open-AMOS), DTA-Lite and VISSIM, the Phoenix Testbed team concluded that the needed computing time was unacceptable when the three layers of transportation simulators were running together. Therefore, the team decided to focus on a two-layer simulation platform development.

The Phoenix Testbed had additional challenges in modeling DMA applications including the requirement for network fidelity and details which are different between mesoscopic simulation and microscopic simulation. For instance, most mesoscopic traffic networks were derived from shape files and they are low resolution for microscopic simulation. To address this issue, the project team used a software tool developed in a parallel project to convert the microscopic network to a link-based DTA network. While the EnableATIS application was quite ready on the project start, the first step to evaluate T-DISP, D-RIDE and FRATIS for the ASU project team was to develop the core algorithms. This turned out to be very challenging to integrate the newly developed algorithms with DTALite causing several scalability and traceability issues. Consequently, the applications were tested in an off-line manner. The necessary data to evaluate T-DISP, D-RIDE and FRATIS were proprietary and hence the project team had to use empirical approximations for some of the analysis involving these applications. For example, the transit data from transit agencies, freight data from companies such as USPS, UPS etc., and ride-sharing data from Transportation Network Companies (TNCs) such as Lyft and Uber could not be acquired by the team due to their private nature.

## 6.5 Modeling ATDM Strategies

Similar to the DMA program, a number of ATDM strategies have been envisioned by the ATDM program, but not all of them were evaluated in the AMS project. The ATDM strategies that are not evaluated are listed below:

1. Transit Signal Priority and Dynamic Lane Reversal (Active Traffic Management)

2. Dynamic Ridesharing, Dynamic Transit Capacity Assignment, On-demand Transit, Dynamic Pricing, Dynamic Fare Reduction and Transfer Connection Protection (Active Demand Management).
3. Dynamic Parking Reservation, Dynamic Wayfinding and Dynamic Overflow Transit Parking (Active Parking Management).

Each of the ATDM applications, although well-defined by the ATDM program, did not have any industry-standard logic or pseudo code associated with it. Therefore, the teams had to use data from local agencies to help them develop the associated pseudo code (Eg: Chicago Testbed). In some other testbeds, the teams used an existing state-of-the-art commercial ATM tool such as GeoDyn for Pasadena Testbed to model such strategies. This procedure was time-consuming and involved a lot of trial-and-error procedure, especially if the strategy is not existent in the real-world. For example, for the Phoenix Testbed, setting up RHODES at intersections required setting up a small DTA-type network structure. Additionally, the limitation of communication protocols between VISSIM and RHODES in its current form prohibited city-wide evaluations of adaptive signal control. Consequently, the team downsized the scope of ATDM evaluations to three signalized intersections plus three ramps. Integrating adaptive signal control strategy (RHODES in this case) and adaptive ramp metering also encountered certain scalability issue. To make the simulation platform implementable, the ASU project team had to downsize the scope of network.

As for the Pasadena testbed, the challenge was to integrate various off-the-shelf commercial software packages into a single system. The testbed did not have an existing ATDM system or model in place and thus closely represented real-world conditions of having to design and implement an ATDM system from scratch. As a result, the team looked to virtually implement off-the-shelf commercial tools as much as possible. However, that became a challenge for the selection of the prediction tool, a critical component of any ATDM system. Over the course of the project, the team evaluated and conceptually designed the integration of three different prediction tools, finally settling on a new custom-modified version of TRANSIMS. Another challenge resulting from this overall testbed architecture objective was the requirement of having to develop a project specific run-time environment that wraps the individual commercial software tools. Additionally, after the system had been integrated, it mimicked a black box system that became increasingly difficult to test, verify, and debug. For example, when either Dynamic Shoulder Lanes or Dynamic Speed Limits were turned on, the system functioned as expected, but when both ATDM Strategies were turned on, the model reached network-wide congestion. This problem alone required a couple weeks of simulation runs and analysis to determine the cause of the conflict.

Developing individual strategies also proved challenging. The development of individual strategies, particularly the geographical placement of each strategy, required multiple simulation runs to evaluate the effect of each individual strategy to ensure the strategy improved the model as expected. Numerous simulations were run to evaluate and understand each of the individual strategies and their interaction with one another.

In the San Diego testbed, the lack of a standard Dynamic Speed Limit logic made the team decide to deploy the same pseudo-code developed for a variable speed limit evaluation in Europe several years ago. The results of the evaluation may be different if using another logic.

## 6.6 Testbed Development and System Manager Emulation

The dominant challenge for the Pasadena Testbed was allowing the scope to increase. The modeling framework as well as the geographic region modeled, was too complex and large to allow easier model testing, updates, and scenario assessment. Adding to this, the selected VISSIM software had limitations on performing parallel processing to some of its older processes such as route computations etc. which

not only increased the startup and runtime of the simulations, but the ease of quickly running model queries.

For the Chicago testbed, 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.

As for the Phoenix Testbed, in the original proposal, the project team planned to set up a true multi-resolution city-wide simulation platform to evaluate multiple ATDM applications. Although the early development went smoothly and the team successfully set up an identical microscopic and mesoscopic city-wide simulation network, the testbed team ran into several main issues:

1. **Model calibration:** The team had developed mature and widely accepted calibration module for the mesoscopic simulator, DTALite, prior to this project that aimed at minimizing the difference between the simulated outputs and field observations. This approach was very data-demanding and to calibrate a city-wide simulation model precisely, it needed data from freeways as well as from arterials with equivalent quantity and quality. While freeway data was available from the Arizona DOT at high resolution, arterial data quality and resolution was low and was only available from local agencies. Thus, the calibration algorithm strongly favored the freeways while it significantly underestimated the traffic volumes along arterials. This bias not only affected the mesoscopic simulation but also affected the microscopic simulation eventually.
2. **Path generation and synchronization between mesoscopic simulation and microscopic simulation:** To have a true multi-resolution simulation platform, it is necessary to synchronize the path and path flows between DTALite and VISSIM. While path generation is very natural and easy in DTALite, it is much more difficult to replicate those paths in VISSIM. To achieve that goal, the testbed team developed a special parsing tool to be able to replicate 95% of the path and path flows generated from DTALite to VISSIM. Nonetheless, it turned out difficult to keep moving vehicles' original paths between VISSIM and DTALite.
3. **Fundamental difference of traffic dynamics in mesoscopic simulation and microscopic simulation:** As originally proposed, the multi-resolution simulation platform allowed both link-based traffic flow in DTALite and lane-based traffic in VISSIM to run at the same time. However, it turned out the resulting traffic dynamics in both simulators were fundamentally different. For instance, most freeway segments in Phoenix testbed have 4+ lanes which affected smoother lane changes causing lane blockage at several points. However, such phenomenon does not exist in DTALite because there are no lane-changing behaviors in link-based traffic flows. Such difference eventually generated a huge difference of traffic performance in two simulators even though they had the same traffic conditions. The testbed team attempted several approaches to mitigate this problem but could not fully resolve at a city-wide scale. Consequently, the Phoenix team decided only to take the DTALite traffic flow and use the VISSIM to implement high-fidelity traffic signal control mechanism and adaptive ramp metering algorithms.

For the Pasadena testbed, a major challenge was the lack of an existing ATDM system. Evaluating ATDM measures requires not only a functioning simulation testbed that integrates emulators of each of the ATDM system components and strategy controls, it also requires the design of such system in the field. This means determining how each strategy should function in the specific project area including placing of all field devices and careful selection of all control parameters. Furthermore, it includes the development

of strategy management business rules that clearly specify under which conditions strategies are to be deployed. In summary, this process is comparable to the CONOPS phase of the systems engineering process, a major undertaking for a complex and large project area such as covered by the Pasadena testbed. Even though this task could have easily constituted its own project of similar time and budget, the project team had to accommodate it within a subtask.

Microscopic simulators like Vissim are high fidelity that are powerful enough to model ATDM or DMA strategies, yet come at the cost of exponentially growing calibration difficulties when the network size becomes large. Much of the calibration efforts were spent on adjusting driving behavior at local streets that are of little concern to the overall project objectives, yet must be resolved before the simulated traffic flow could be realistic representations of the real world operations, e.g., free from artificial gridlocks.

Designing individual ATDM or DMA strategy action plans must see their consistencies across all off-the-shelf platforms, such as TRANSIMS, GeoDyn and Vissim. The typical engineering tools for designing, evaluating and finalizing such strategies and plans are not suited especially for cross-platform data transfers, as in the case of Pasadena testbed. For example, the signal timing plan optimization for Dynamic Signal Control (DSC) strategies were held up by the commercial software and thus custom solutions had to be developed to merge the plans for testbed use cases. Due to the high CPU and RAM needs of micro simulations, the runtime performance of the testbed was not as desired to be faster than real-time so that more evaluation runs can be performed. Calibration of large networks in microsimulation suffers from the complexity of entangled parameters, i.e., network coding errors, traffic controls, driving behavior parameters, demand estimation, route choice behavior assumptions. A streamlined process has been proven effective and used in the Pasadena testbed calibration, i.e. to decouple the demand estimation and route choice behavior calibration from others by multi-resolution modeling techniques, yet simply the network size had made model calibration itself a major obstacle to achieve the testbed development goal.

# Chapter 7. Future Research Directions

In this chapter, specific future research directions with respect to modeling DMA and ATDM to fully understand the applications are provided.

## 7.1 Unaddressed Research Questions

The array of testbed selection was made with the goal of best evaluating DMA and ATDM strategies. However, as with any experimental design, there were some risks inherent in the approach that not all of the questions that this research set out to answer would be satisfactorily answered. The future directions of this research should primarily aim at answering the full suite of questions that the project set out to answer. Section 5.2 gives a summary of the unanswered research questions.

## 7.2 Future DMA AMS Research

It is necessary to continue the research momentum in developing new DMA core algorithms, primarily because several DMA applications have not been prototyped before. For example, applications under EnableATIS bundle have not been developed in a full-fledged manner, either for field deployment or for modeling and simulation. Additional DMA research directions are listed below:

### 7.2.1 Development of a DMA Interface

While it is necessary to answer research questions like the joint impact of multiple DMA deployments in the same region, integrating currently available applications within the same modeling framework has been generally challenging. It is critical to eventually integrate various core algorithms of DMA application into the next generation of traffic simulation platform. To this end, developing a DMA interface which can read trajectory information from state-of-the-art simulation tools and apply the DMA methodology would be a good option. The interface would allow data sharing between applications as well as applying specific vehicle commands back to the simulation in the intended way.

### 7.2.2 Development of a Performance Measurement Interface

The team had significant challenges in expanding the performance measurement interface available with the current AMS testbeds to include safety and energy/emissions. One of the potential research directions to this end is development of a performance measurement interface which is like SSAM, but more advanced. The envisioned interface would have parallel processing capabilities which can import trajectory data from simulations (as \*.trj files) and utilize it to measure different mobility, safety and environmental performance measures. This interface will not only make comparing scenarios easy, but also standardize the performance measurement across different modeling projects. In addition, new performance measures can be developed since finer-grained data will be provided in short intervals using Connected Vehicle technology.

## 7.3 Future ATDM AMS Research

The testbeds, individually and collectively, enabled the testing of a wide array of measures and interventions, providing estimates of the expected benefits and impacts, as well as helping to identify conditions and factors that influence their respective effectiveness. By using state of the art modeling technology, and conducting extensive sensitivity analyses vis-à-vis quantities and parameters for which no reliable observations are available, the study provided a solid foundational body of knowledge to advance the state of the practice in ATDM design and application. It also helped identify important areas in need of additional attention. Some of these future directions identified by the project team are listed below:

### 7.3.1 Improving Prediction Accuracy for ATDM Applications

ATDM is envisioned to provide traffic network managers with the capabilities to predict the traffic network conditions and to develop proactive traffic management schemes to cope with these conditions. However, the effectiveness of the generated schemes in alleviating the congestion is expected to depend primarily on the level of accuracy of the network state prediction. As illustrated in this study, a discrepancy between the predicted and the actual network conditions has been shown to diminish the effectiveness of the generated schemes. As such, it is crucial to enhance existing capabilities related to traffic network state prediction. It requires accurate prediction of the dynamic travel demand, network supply and their interactions. Thus, more research effort is required to develop a) efficient tools for real-time origin-destination traffic demand estimation and prediction; b) accurate models that capture travelers route, mode and departure time choice decisions under different recurrent and non-recurrent congestion situation, and c) models that captures the traffic demand and capacity interactions considering a wide variety of control schemes and able to produce of meaningful measures of performance to support decision making.

### 7.3.2 Lack of Multi-resolution Integrated Modeling Framework for ATDM and DMA

The evolution of connected vehicles (CV) technologies is expected to significantly change the current traffic network management practice. CV technologies will provide richer data sources that can be fused with traditional real-time data sources to achieve more accurate traffic network state estimation and prediction. In addition, new traffic control strategies are expected to evolve based on these technologies. While this study has addressed both DMA and ATDM applications, most of the effort was devoted to evaluating their effectiveness separately. One main reason for not being able to study both technologies simultaneously is that most existing modeling frameworks have focused on representing either ATDM or DMA. For example, models developed to evaluate ATDM strategies are developed at the macroscopic or the mesoscopic levels. On the other hand, models used to evaluate DMA are at the microscopic level and require additional capabilities for representing V2V and V2I messaging. Research effort devoted to developing a multi-resolution modeling framework that can be used to study both ATDM and DMA in an integrated fashion is still in its infancy.

### 7.3.3 Online Calibration Capabilities of Traffic Network Models for Real-Time Operations

Developing well-calibrated models is crucial for providing high-fidelity traffic network state estimation and prediction capabilities which are the core functionalities of ATDM systems. In most proposed ATDM system implementations, a network model is configured to run in real-time to provide a minute-by-minute estimation of the current network conditions. The model defines the prevailing network conditions and is used to provide prediction of the network congestion dynamics. The model also is used to evaluate the

different proposed traffic management schemes before recommendation for deployment in the real-world network. Before using the model in the on-line mode, a comprehensive off-line model calibration is usually performed to ensure that the model accurately represents a typical day of operation. This initial calibration effort involves estimating the dynamic origin-destination (OD) demand table, travelers' route-mode choice behavior during normal and congested situations, traffic flow models for the different highways, and any other parameters specific to the model used. Nonetheless, considering the limited data that is usually available for off-line calibration, this effort could result in inaccurate estimate of the model parameters, which limits the model's ability to provide estimation results that are consistent with the observed real-world conditions. In addition, actual operational conditions could significantly vary from the one used in off-line calibration. Therefore, developing online calibration capabilities that take advantage of the availability of real-time data feeds will ensure consistency between the model estimation and the observed real-world conditions. Estimating the network's current conditions at high accuracy enhances the quality of the network state prediction and the effectiveness of the generated traffic management schemes.

### **7.3.4 Need for Real-Time Decision Support Capabilities for ATDM Applications**

The AMS project primarily focused on either developing the architecture of real-time traffic management systems, or examining the effectiveness of different traffic management strategies under different operation conditions in offline simulation environments. Studies that focus on developing active decision support capabilities in the context of real-time traffic network management are infrequent in the literature. In addition, limited effort is devoted to testing the effectiveness of traffic network strategies when integrated as part of decision support capabilities for real-time traffic network management systems. To our knowledge, research effort that is devoted to a) developing real-time traffic management systems that can generate integrated traffic management schemes that combines a wide variety of ATDM strategies and DMA; and b) evaluating the performance of these systems for calibrated networks with reasonable sizes and for extended horizons has not been thoroughly presented in the literature.

### **7.3.5 Robust ATDM for Operational Conditions Uncertainty**

As concluded in this project, one of the main ATDM system functionalities is to accurately predict the network conditions to generate proactive traffic management schemes that cope with the evolving network conditions. Failing to provide such accurate prediction has shown to significantly impact the effectiveness of the generated schemes. However, it is unrealistic to assume the ability to obtain perfect network state prediction. It requires accurate prediction of the dynamic travel demand, network supply and their interactions which is typically a very challenging task. Thus, it is idealistic to assume that traffic network state conditions can be predicted with perfect accuracy, and that traffic management schemes generated based on such prediction optimally manage the network. Alternatively, ATDM systems should be designed to explicitly consider the uncertain nature of traffic networks and inability to accurately predict their conditions. One plausible approach is to develop robust traffic network management schemes that account for uncertainty in the network operational conditions. These robust traffic schemes are designed such that they consider the possible variation in the operational conditions. In other words, the approach develops robust traffic management schemes such that the system performance remains "close" to optimal for any realization of the operational conditions.

### 7.3.6 Maintaining Operational and Environmental Equity Constraints in ATDM Applications

It is generally assumed that all agencies fully collaborate to improve the overall performance of the region (corridor) irrespective of the performance of the local jurisdictions. In other words, traffic management schemes are generated to improve the overall traffic network performance. However, in most cases; agencies/municipalities could require the generated schemes to maintain a pre-defined level of service for a certain jurisdiction or a facility. For instance, frequent traffic diversion from the freeway facility to a city's local streets could result in high level of congestion followed by complaints of the residents. To avoid such complaints, the amount of traffic to be diverted must be constrained to ensure that the congestion along these local streets is tolerable. Thus, the generated ATDM schemes should make sure that different jurisdictions or subareas are maintaining comparable level of service. Considering the performance equity among local jurisdictions in ATDM applications is another important research extension that has not been covered under this or the ICM evaluation.

### 7.3.7 Modeling Behavioral Responses to ATDM Strategies

Traveler choice behavior, and particularly the dynamics of this behavior in interaction with ATDM and DMA interventions, remains a challenging but critical area for investigation to ensure the success of these program areas. Simply stated, the ultimate effectiveness of many of these strategies depends critically on how users understand and respond to these strategies, not only once but over time. In this study, the relevant behavioral dimensions were identified and integrated into a modeling framework that captures the interaction of these dimensions with the relevant supply-side elements. Where available, data is compiled to characterize these behaviors, and in selected cases to develop and calibrate new models and specifications. In other cases, sensitivity tests to various underlying behavioral parameters are conducted, which allows us to address the study objectives. However, the limitations in modeling such behavioral responses are well documented<sup>4</sup>, and additional effort in this regard is essential, as outlined in a recent FHWA study, which suggested several possible directions to address this important gap<sup>5</sup>.

- a. *Behavioral research before/during/after projects*, combining use of both passive tracking technologies to measure behavior, along with personal surveys to query respondents on their motivations, intentions, willingness to change behavior and to track actual behavior into management and infrastructure projects.
- b. *Virtual experimentation* has a role to play as well; technology-facilitated ATDM and DMA interventions create new situations that may not yet have real-world counterparts<sup>6</sup>. Therefore, there may not be opportunities to observe traveler behavioral responses to such interventions. Furthermore, a real-world demonstration project can generally only implement one version among several competing designs. Laboratory experiments provide an approach to learn about user behavior in controlled settings. Improvements in simulated worlds and

<sup>4</sup> Mahmassani, H.S., Koppelman, F., Frei, C., Frei, A. and Haas, R., 2013. Synthesis of Traveler Choice Research: Improving Modeling Accuracy for Better Transportation Decisionmaking (No. FHWA-HRT-13-022). <https://www.fhwa.dot.gov/publications/research/operations/13022/13022.pdf>

<sup>5</sup> Mahmassani, H.S., Frei, C., Frei, A., Story, J., Lem, L., Talebpour, A., Chen, Y., Zockaie, A., Saberi, M., Halat, H. and Haas, R., 2014. *Analysis of Network and Non-network Factors on Traveler Choice Toward Improving Modeling Accuracy for Better Transportation Decisionmaking* (No. FHWA-HRT-13-097). <https://www.fhwa.dot.gov/publications/research/operations/13097/13097.pdf>

<sup>6</sup> Mahmassani, H.S., 2009. Learning from interactive experiments: travel behavior and complex system dynamics. *The expanding sphere of travel behavior research*. Emerald Group Publishing, Bingley, UK, pp.131-158.

gaming technology provide an entirely new level of possibilities to learn about user behavior in a variety of environments under different types of interventions.

However, no matter how rich and complete our models are, the behavior of users will remain a moving target for many interventions. People by their very nature adapt, and change, due to both external factors (the economy, lifestyles, shifting preferences) as well as factors internal to the transportation system (including the kinds of dynamically changing interventions motivating the present study, e.g. information, prices, controls, etc.). While modeling the mechanisms underlying such behavioral adaptation remains an important part of the research agenda for the travel behavior community, it is important to recognize such adaptation and evolution in the very design of the interventions. This calls for a new paradigm in designing and implementing interventions, in which learning about user behavior becomes an integral element of the system, and adapting and fine-tuning the policies are considered by design<sup>7</sup>.

### 7.3.8 Logic Design for ATDM Measures

The ATDM and DMA measures tested in this study all required a certain logic for applying the intervention—generally relying on predictive control principles, whereby online measurements of the system state feed predictions of future evolution, triggering application of different displays and information to users to improve conditions for the users and the system. For instance, in the Chicago Testbed, speed harmonization was applied in certain instances when a propagating shockwave was detected; snow plows were triggered when predicted snow accumulation levels exceeded a certain threshold; and so on. In this study, researchers adopted best state of the art or state of practice for the logic of these interventions. However, these are all candidates for additional research as both sensing and predictive capabilities are improving, and computational capabilities are also improving, enabling faster online computation of optimal solutions for larger geographic areas over longer time horizons.

Three main drivers thus exist for improving the logic of the interventions:

- a. Advances in sensing, information and computing technologies, as noted above.
- b. Experience arising from field deployments and implementations, as these strategies are applied and their impact monitored.
- c. Integration of behavioral responses into the very design of the strategies, towards making them more robust vis-à-vis changes and adaptation in user behavior.

The AMS testbeds developed in this study already provide a ready environment in which to test improved logic and the strategies generated by alternative control rules and formulations.

### 7.3.9 Prediction Logic, Pattern Matching and Machine Learning

Expanding upon the previous point, additional opportunities exist in the predictive logic used to drive the various strategies. In other words, this does not pertain directly to the controls and interventions, but rather to the prediction engines used to predict demand and traffic patterns in the rolling horizon framework. The project featured different prediction approaches in the various testbeds, and all performed extensive simulation experiments on the sensitivity to different dimensions of the prediction, such as quality, latency, and so on. However, this is currently an area where considerable effort is being deployed, in light of emergence of new techniques driven by the availability of considerably more data (“Big Data”) from a variety of sensors including individual particle (vehicle or traveler) tracking.

<sup>7</sup> Mahmassani, H.S., Frei, C., Frei, A., Story, J., Lem, L., Talebpour, A., Chen, Y., Zockaie, A., Saberi, M., Halat, H. and Haas, R., 2014. Analysis of Network and Non-network Factors on Traveler Choice Toward Improving Modeling Accuracy for Better Transportation Decisionmaking (No. FHWA-HRT-13-097). <https://www.fhwa.dot.gov/publications/research/operations/13097/13097.pdf>

Advances in data mining techniques, machine learning, and hybrid inference engines that combine statistical concepts with computer science are largely untested in the traffic realm. Limited experiments have shown promise when conditions are largely stationary or conform to historically observed scenarios, but do not perform so well when there are disruptions such as crashes, surges or even severe weather. Hence the potential for hybrid techniques that combine data-driven machine learning with approaches that explicitly model the system dynamics, such as simulation-based methods used in several of the testbeds.

In conjunction with any prediction technique, starting points are usually influential in the accuracy of the predicted conditions. Hence the reliance of pattern matching techniques that retrieve most similar conditions from historically occurring libraries have a role to play in this context. This is particularly effective during weather-related events. Research on predictive methods for use in conjunction with field-deployable ATDM and DMA strategies is needed to take advantage of these important opportunities.

### **7.3.10 Field Deployment of Operator Support Systems**

While most of the ATDM and DMA measures can be implemented in an automated manner, with clear decision logic delineating when to apply certain interventions, and checking for safety and other considerations in a data-driven manner, actual field deployment often still requires the expert judgment of an experienced human operator. Our experience in developing and deploying such advanced traffic management software and tools is that most public-affecting interventions will not be implemented by agencies unless checked and approved by a responsible human engineer or technician.

This places new challenges for the development of decision support tools that can communicate the impact of the predictive strategies before these are implemented, enable some online testing, and provide intuitive interfaces to approve and implement these strategies. This would include components for scenario retrieval from historical information, strategy configuration from available libraries, decision recommendation interfaces and post-implementation monitoring and tracking. This work entails interdisciplinary perspectives from human factors, management decision support systems, visualization and communications, in addition to transportation operations engineering. While this aspect was outside the scope of the project, it is nonetheless an important, and missing, link in translating the findings and recommendations of the study into actual deployment in practice.

## **7.4 Future Road-weather AMS Research**

An especially important feature of the Chicago testbed was its explicit consideration of weather impacts on network performance, and the testing of targeted interventions during such events (WRTM, or weather-related traffic management). The science and applications of WRTM has advanced considerably over the past 5 years, largely through the efforts of the US DOT's Road Weather Program. The Chicago testbed demonstrates some of these advances particularly regarding capturing the impact of precipitation and visibility on traffic performance, during both rain and snow events. Additional advances in this study include integration of snow plow operations in both the ATDM operational strategies as well as in modeling the impacts of these actions on network conditions. In the latter aspects (snowplow routing, snow accumulation), we found serious gaps in the literature and in documents used in practice, e.g. regarding snow accumulation modeling, and the impact of different depths of snow on traffic performance along different types of roadway facilities.

Similarly, user behavior under severe weather, with and without advance information, as well as in response to the various ATDM interventions, remains an important gap. While we noted this aspect in connection with all the testbeds and strategies, it is singularly different in the context of severe weather because the main concern is not only being late or getting stuck in traffic, but also much higher risk of

crashes associated with slipping and sliding on icy pavements or inexperienced driver maneuvers, as well as concerns about personal physical safety associated with long exposures to freezing temperatures. There is virtually no research on these aspects, which are essential to developing a full-fledged decision support capability for ATDM and DMA. Severe weather, while frequent enough to warrant special traffic management interventions, is also rare enough from the standpoint of timing its study and tracking behavior. It is also salient enough in people's memory that the use of retrospective surveys, where people are asked to recall their latest experiences with the conditions of interest, can be conducted with much higher fidelity than typically associated with such recall for more routine events.

# Chapter 8. Summary

The primary purpose of this report is to document the gaps and challenges identified by the testbed team and some of the future research directions for the U.S. Department of Transportation. Specifically, the report lists the different gaps and limitations in evaluating ATDM strategies and DMA applications using AMS Testbeds in this project with respect to modeling, calibration, performance measurement, tools development and benefit-cost analysis. The report also lists the numerous challenges faced by the testbed team to develop modeling tools, integrate them with existing tools and use them to effectively evaluate the research questions put forth by the USDOT. Finally, the report suggests future research directions based on the project.

The DMA applications emulated in this project include: Speed Harmonization, Queue Warning, Cooperative Adaptive Cruise Control, Incident Zone Alerts, Intelligent Traffic Signal, Advanced Traveler Information, Freight Advanced Traveler Information, Dynamic Transit Dispatch, Dynamic Ride-sharing, and Freight Dynamic Route Guidance. The ATDM strategies emulated in this project include Dynamic Shoulder Lanes, Dynamic Speed Limits, Queue Warning, Adaptive Ramp Metering, Dynamic Junction Control, Dynamic Traffic Signal Control, Predictive Traveler Information, Dynamic HOV, Dynamic Managed Lanes, Dynamic Routing, Dynamically Priced Parking as well as certain weather-related strategies such as Shown Emergency Parking, Preemption for Winter Maintenance, Snowplow Routing, Anti-icing and Deicing Operations.

As far as the major lessons learned are concerned, the team primarily identified the following lessons learned:

1. Since each of the AMS testbeds are a system of multiple software pieces, scoping should include additional cost contingency when allocating resources, selecting tools and techniques and considering the overall range of scenarios. As the scope and complexity of the testbed increase, the resources required for development and testing increased exponentially.
2. Not all regions and not all roadways have traffic data available at the same accuracy, quality and resolution, which could lead to differences in quality of calibration.
3. Throughout the AMS project, the project team integrated applications built by other teams to these testbeds. Our ability to include and exclude applications from our scope dependent on application availability and features that exist in other applications.
4. The AMS testbeds were envisioned to be complex systems of multiple software-in-the-loop systems that communicate via a data bus. Depending on the original architecture of each of these software pieces, computationally complexity of the testbeds varied across the six AMS testbeds.
5. Performance measurement capability of different simulation tools varied across the six testbeds. However, tool-selection was a trade-off that prioritized which one is the best for sets of applications or strategies and the performance measures it produced.
6. The team tried getting statistical valid results through multiple repetitions of each of the simulation runs. Despite these efforts, some of the more complex simulations could not be tested for statistical validity owing to longer computation times.

The team also identified gaps and challenges with respect to the following:

1. The AMS requirements which could not be met completely consisted primarily of different factors that were specific to a user-type or facility-type. The team focused more on system-wide impacts.

2. DMA and ATDM research questions that remained unanswered consists primarily of policy-based questions for DMA and benefit-cost analysis questions for ATDM.
3. With respect to operational conditions, cluster analysis and calibration, the team had to make use of available data, which in some cases had gaps. Additionally, the teams had to prioritize certain operational conditions based on their number of instances in the model year.
4. The team had lot of technical challenges in modeling DMA applications and ATDM strategies, primarily due to (i) unavailability of robust existing applications, and (ii) increasing scope of testbeds.
5. As far as testbed development and system manager emulation is concerned, team had to make certain assumptions and simplifications to prevent scope creep.

The project team also identified several future directions for the AMS research in terms of addressing unanswered research questions from this project as well as DMA and ATDM research.

## Appendix A. List of Acronyms

Given below is a list of acronyms used in this report.

**Table A-1. List of Acronyms**

<b>Acronym</b>	<b>Description</b>
<b>AMOS</b>	Activity Mobility Simulator
<b>AMS</b>	Analysis, Modeling and Simulation
<b>API</b>	Application Programming Interface
<b>ASC</b>	Adaptive Signal Control
<b>ATDM</b>	Active Transportation and Demand Management
<b>ATIS</b>	Advanced Traveler Information System
<b>CACC</b>	Cooperative Adaptive Cruise Control
<b>CMEM</b>	Comprehensive Modal Emission Model
<b>COM</b>	Component Object Model
<b>CV</b>	Connected Vehicle
<b>DIRECT</b>	Dynamic Intermodal Routing Environment for Control and Telematics
<b>DMA</b>	Dynamic Mobility Applications
<b>D-RIDE</b>	Dynamic Ridesharing
<b>DR-OPT</b>	Drayage Optimization
<b>DTA</b>	Dynamic Traffic Assignment
<b>DYNASMART</b>	Dynamic Network Assignment-Simulation Model for Advanced Road Telematics
<b>EnableATIS</b>	Enable Advanced Traveler Information System
<b>EVAC</b>	Emergency Communications and Evaluation
<b>F-ATIS</b>	Freight Real-Time Traveler Information with Performance Monitoring
<b>F-DRG</b>	Freight Dynamic Route Guidance
<b>FRATIS</b>	Freight Advanced Traveler Information System
<b>FSP</b>	Freight Signal Priority
<b>HD-DTA</b>	High Definition Dynamic Traffic Assignment
<b>HO</b>	Hypothetical Operational Condition
<b>HOV</b>	High Occupancy Vehicles
<b>ICM</b>	Integrated Corridor Management
<b>IDTO</b>	Integrated Dynamic Transit Operations

<b>Acronym</b>	<b>Description</b>
<b>INC-ZONE</b>	Incident Scene Pre-Arrival Staging Guidance for Emergency Responders
<b>INFLO</b>	Intelligent Network Flow Optimization
<b>I-SIG</b>	Intelligent Traffic Signal Control
<b>ITS</b>	Intelligent Transportation Systems
<b>MAG</b>	Maricopa Association of Governments
<b>MMITSS</b>	Multi-Modal Intelligent Traffic Signal Systems
<b>OC</b>	Operational Conditions
<b>OD</b>	Origin Destination
<b>OMNET++</b>	Objective Modular Network Testbed in C++
<b>OSADP</b>	Open Source Application Development Portal
<b>P-DYNA</b>	Predictive Dynamic Network Assignment
<b>PED-SIG</b>	Mobile Accessible Pedestrian Signal System
<b>PREEMPT</b>	Emergency Vehicle Preemption
<b>Q-WARN</b>	Queue Warning
<b>RDE</b>	Research Data Exchange
<b>RESCUME</b>	Response, Emergency Staging and Communications, Uniform Management, and Evacuation
<b>RESP-STG</b>	Responder Staging
<b>RHODES</b>	Real-time Hierarchical Optimizing Distributed Effective System
<b>SOV</b>	Single Occupancy Vehicle
<b>SPD-HARM</b>	Dynamic Speed Harmonization
<b>SSAM</b>	Surrogate Safety Assessment Model
<b>TCA</b>	Trajectory Conversion Algorithm
<b>T-CONNECT</b>	Connection Protection
<b>T-DISP</b>	Dynamic Transit Operations
<b>TRANSIMS</b>	Transportation Analysis Simulation System
<b>TSP</b>	Transit Signal Priority
<b>TSS</b>	Transport Simulation Systems
<b>USDOT</b>	United States Department of Transportation

## Appendix B. List of Publications

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

**Table B-1: AMS Project Publications**

<b>No.</b>	<b>Document Title</b>	<b>JPO Publication #</b>
1	ATDM-DMA AMS Testbed Project: Detailed AMS Requirements	FHWA-JPO-16-369
2	ATDM-DMA AMS Testbed Project: AMS Testbed Selection Report	FHWA-JPO-16-355
3	ATDM-DMA AMS Testbed Project: Analysis Plan for San Mateo Testbed	FHWA-JPO-16-370
4	ATDM-DMA AMS Testbed Project: Analysis Plan for Pasadena Testbed	FHWA-JPO-16-371
5	ATDM-DMA AMS Testbed Project: Analysis Plan for Phoenix Testbed	FHWA-JPO-16-372
6	ATDM-DMA AMS Testbed Project: Analysis Plan for Dallas Testbed	FHWA-JPO-16-373
7	ATDM-DMA AMS Testbed Project: Analysis Plan for Chicago Testbed	FHWA-JPO-16-374
8	ATDM-DMA AMS Testbed Project: Analysis Plan for San Diego Testbed	FHWA-JPO-16-375
9	ATDM-DMA AMS Testbed Project: AMS Evaluation Plan	FHWA-JPO-16-376
10	ATDM-DMA AMS Testbed Project: Calibration Report for San Mateo Testbed	FHWA-JPO-16-377
11	ATDM-DMA AMS Testbed Project: Calibration Report for Pasadena Testbed	FHWA-JPO-16-378
12	ATDM-DMA AMS Testbed Project: Calibration Report for Phoenix Testbed	FHWA-JPO-16-379
13	ATDM-DMA AMS Testbed Project: Calibration Report for Dallas Testbed	FHWA-JPO-16-380
14	ATDM-DMA AMS Testbed Project: Calibration Report for Chicago Testbed	FHWA-JPO-16-381
15	ATDM-DMA AMS Testbed Project: Calibration Report for San Diego Testbed	FHWA-JPO-16-382
16	ATDM-DMA AMS Testbed Project: Evaluation Report for DMA Program	FHWA-JPO-16-383
17	ATDM-DMA AMS Testbed Project: Evaluation Summary for DMA Program	FHWA-JPO-16-384
18	ATDM-DMA AMS Testbed Project: Evaluation Report for ATDM Program	FHWA-JPO-16-385
19	ATDM-DMA AMS Testbed Project: Evaluation Summary for ATDM Program	FHWA-JPO-16-386
20	ATDM-DMA AMS Testbed Project: Evaluation Report for Chicago Testbed	FHWA-JPO-16-387

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<b>No.</b>	<b>Document Title</b>	<b>JPO Publication #</b>
<b>21</b>	ATDM-DMA AMS Testbed Project: Evaluation Summary for Chicago Testbed	FHWA-JPO-16-388
<b>22</b>	ATDM-DMA AMS Testbed Project: Evaluation Report for San Diego Testbed	FHWA-JPO-16-389
<b>23</b>	ATDM-DMA AMS Testbed Project: Evaluation Summary for San Diego Testbed	FHWA-JPO-16-390
<b>24</b>	ATDM-DMA AMS Testbed Project: AMS Gaps, Challenges, and Future Research	FHWA-JPO-16-391

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