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

Leveraging AMS Testbed Outputs for ATDM Analysis – A Primer

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16. Abstract

The primary objective of AMS Testbed project is to develop multiple simulation Testbeds/transportation models to evaluate the impacts of DMA connected vehicle applications and the active and dynamic transportation management (ATDM) strategies. Through this project, six virtual testbeds were developed and used for DMA and ATDM evaluation. The testbeds are diverse in terms of their geographic scope, modeling tools, modeled applications and strategies and answered research questions and produced over 24 deliverables to the USDOT.

The objective of this primer is to help public agencies understand how the portfolio of products developed under this project can be useful in conducting their own ATDM analysis.

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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 research questions surrounding the U.S. Department of Transportation's DMA and ATDM Programs.

The AMS Testbed project was a complex undertaking to develop and use simulation-based testbeds to assess the effectiveness of ATDM strategies and DMA applications on traffic network performance as well as to assess the factors and conditions amenable to several performance measures. By documenting every step of the project, the team produced 24 deliverables for public release throughout the course of this project. The objective of this primer is to summarize the entire project and highlight how the project's portfolio of products can help public agencies in conducting their own ATDM analysis. These AMS deliverables are:

1. Detailed AMS Requirements (FHWA-JPO-16-369)
2. AMS Testbed Selection Report (FHWA-JPO-16-355)
3. Testbed-specific Analysis Plans:
    a. San Mateo Testbed (FHWA-JPO-16-370)
    b. Pasadena Testbed (FHWA-JPO-16-371)
    c. Phoenix Testbed (FHWA-JPO-16-372)
    d. Dallas Testbed (FHWA-JPO-16-373)
    e. Chicago Testbed (FHWA-JPO-16-374)
    f. San Diego Testbed (FHWA-JPO-16-375)
4. AMS Testbed Evaluation Plan (FHWA-JPO-16-376)
5. Testbed-specific Calibration Reports:
    a. San Mateo Testbed (FHWA-JPO-16-377)
    b. Pasadena Testbed (FHWA-JPO-16-378)
    c. Phoenix Testbed (FHWA-JPO-16-379)
    d. Dallas Testbed (FHWA-JPO-16-380)
    e. Chicago Testbed (FHWA-JPO-16-381)
    f. San Diego Testbed (FHWA-JPO-16-382)
6. AMS Testbed Evaluation Reports and Summaries:
    a. DMA Program Evaluation Report (FHWA-JPO-16-383)
    b. DMA Program Evaluation Summary (FHWA-JPO-16-384)
    c. ATDM Program Evaluation Report (FHWA-JPO-16-385)
    d. ATDM Program Evaluation Summary (FHWA-JPO-16-386)
7. Testbed-specific Evaluation Reports and Summaries
    a. Chicago Testbed Evaluation Report (FHWA-JPO-16-387)

    b. Chicago Testbed Evaluation Summary (FHWA-JPO-16-388)
    c. San Diego Testbed Evaluation Report (FHWA-JPO-16-389)
    d. San Diego Testbed Evaluation Summary (FHWA-JPO-16-390)
8. Report on Gaps, Challenges and Future Research (FHWA-JPO-16-391)
9. Primer on Leveraging AMS Products for ATDM Analysis (FHWA-JPO-18-608)

The deliverables listed above are available in the National Transportation Library website at https://ntl.bts.gov/ and at FHWA's ATDM website at https://ops.fhwa.dot.gov/atdm/research/index.htm. In addition to these deliverables, all the project-related data and applications are shared with USDOT's Open Source Application Development Portal (https://itsforge.net/) and Research Data Exchange (https://www.its-rde.net/). The data and applications from each of the testbeds are highlighted below:

1. San Mateo Testbed:
    a. INFLO-AMS application.
    b. San Mateo RDE data environment.
2. Dallas Testbed:
    a. DIRECTView-AMS application.
    b. Dallas RDE data environment.
3. Pasadena Testbed:
    a. Pasadena RDE data environment.
4. Phoenix Testbed:
    a. DTALite Interface application
    b. D-RIDE application
    c. Phoenix RDE data environment
5. Chicago Testbed:
    a. Chicago RDE data environment, including the DYNASMART-executable.
6. San Diego Testbed:
    a. TCA-Aimsun application
    b. CACC-Aimsun application
    c. San Diego RDE data environment.

This primer aims at assisting agencies interested in conducting their own ATDM analysis and evaluation to understand the set of steps and considerations, as well as to utilizing the diverse set of deliverables that were developed for public release through the AMS Testbed project.

Chapter 1. Introduction and Background

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. This initiated the AMS Testbed project that aimed at developing six virtual computer-based simulation models to integrate different DMA applications and ATDM strategies and assess their impacts under varying operational and synthesized characteristics. The six testbeds were San Mateo, Pasadena, Dallas, Phoenix, Chicago and San Diego Testbeds. Figure 1-1 shows the six testbeds extending over the United States.

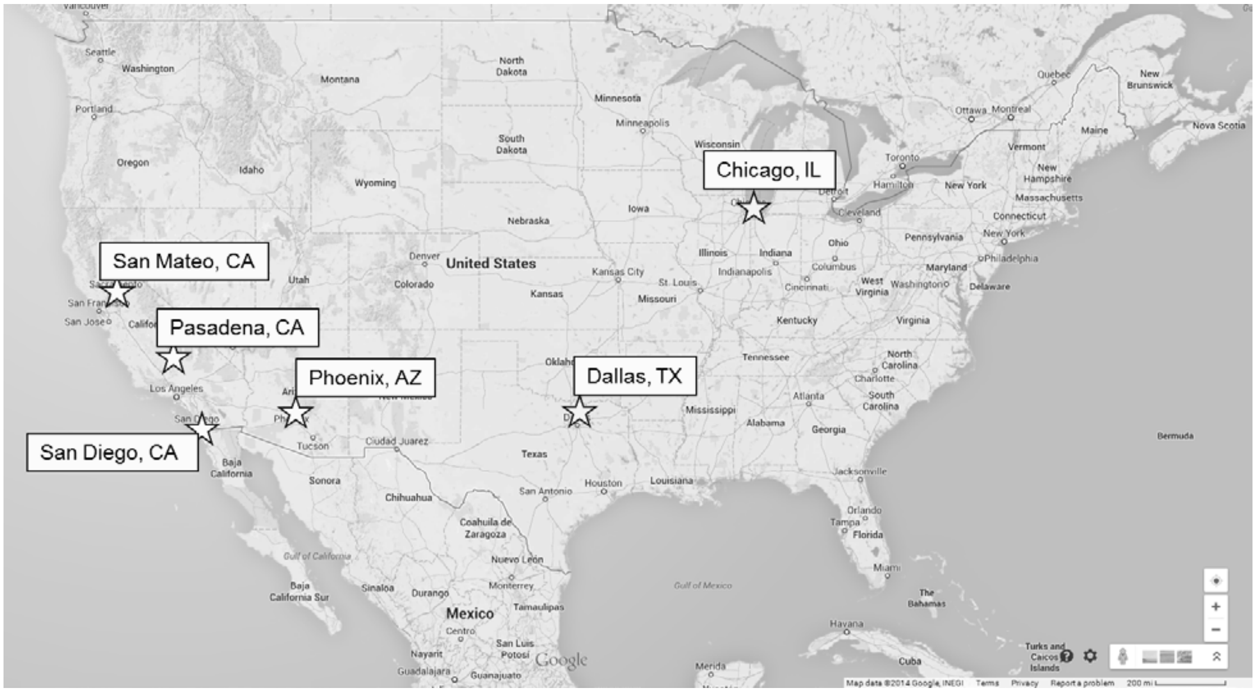

Figure 1-1. Testbeds Used for AMS Testbed project [Source: Booz Allen]

The AMS Testbed project was a complex undertaking to develop and use simulation-based testbeds to assess the effectiveness of ATDM strategies and DMA applications on traffic network performance as well as to assess the factors and conditions amenable to several performance measures. The objective of this primer is to assist agencies interested in conducting their own ATDM analysis and evaluation to understand the set of steps and considerations, as well as to utilize the diverse set of deliverables that were developed for public release through the AMS Testbed project. Throughout this document, we refer to sections and procedures adopted and documented in other deliverables made from the project so that the readers can refer to the relevant sections to understand each of the ATDM evaluation steps.

1.1 Project Overview

The AMS Testbed Project was a complex undertaking with several interconnected steps aiming at selecting testbed sites, developing the system of testbeds with integrated DMA and ATDM strategies, evaluation of response plans and DMA applications and eventually answering the research questions set forth by the AMS testbed. Figure 1-2 shows these steps.

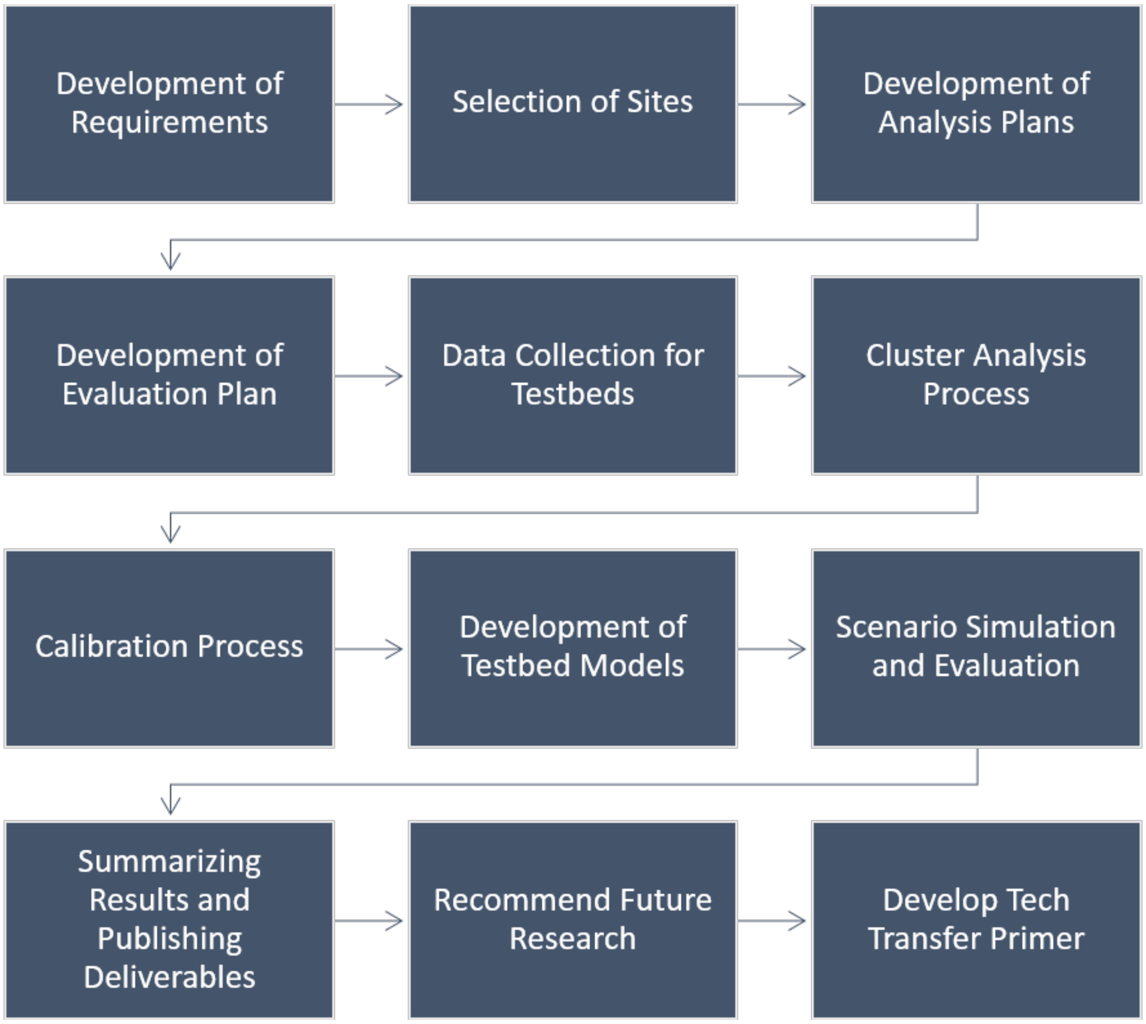

Figure 1-2. High-level AMS Process

As shown in the Figure, the following steps were adopted for achieving the AMS Testbed project objectives:

- Development of detailed AMS requirements to set as a base for the development of the AMS testbeds.
- Selection of sites to narrow down the number and scope of testbeds.
- Development of analysis plans to document the scope of each of the testbeds in terms of research questions that will be answered, as well as the DMA and ATDM strategies that will be integrated.

- Development of evaluation plan which summarizes the evaluation approach for achieving the objectives of DMA and ATDM programs.
- Data collection for each of the testbeds to understand the current operational conditions and characteristics of the testbeds.
- Cluster analysis process to narrow down the number of operational conditions that need to be represented by each of the testbeds.
- Calibration process to adjust the testbed network performance to match real-world operations.
- Development of testbed models to integrate different tools and algorithms to the testbed model to emulate DMA applications, ATDM strategies, CV communication models, prediction models, system manager response plans etc.
- Summarizing the results and publishing deliverables, codes and data for use by the transportation community in conducting their own research.
- Recommend future research, as well as documenting gaps, challenges and lessons learned from this project.
- Development of a technology transfer primer to help the transportation community understand the different outputs from this project.

Each of these steps are described in detail, in the next chapter.

1.1.1 AMS Testbeds

This section presents a high-level overview of these AMS Testbeds, including their geographic details, description of the facility, as well as the primary applications/strategies type that were included in the Testbed.

Table 1-1 shows the overview of the testbeds. A more detailed description of the testbeds is provided in Appendix B.

Table 1-1. Overview of Testbeds

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

1.1.2 DMA Applications Modeled

The DMA program has developed six bundles of applications with three to six applications within each bundle. A description on these applications can be found in the USDOT's DMA website[1]. The AMS Testbed analysis includes all the six bundles. Table 1-2 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 1-2. DMA Application Mapping with Testbeds

DMA Application	*San Mateo*	*Pasadena*	*Dallas*	*Phoenix*	*Chicago*	*San Diego*
EnableATIS						
ATIS				●		
S-PARK						
T-MAP						
WX-INFO						
INFLO						
Q-WARN	●					●
SPD-HARM	●				●	●
CACC						●
MMITSS						
ISIG	●					●
TSP						
PED-SIG						
PREEMPT						
FSP						
IDTO						
T-CONNECT						
T-DISP				●		
D-RIDE				●		
FRATIS						
F-ATIS				●		
DR-OPT						
F-DRG				●		
R.E.S.C.U.M.E						
EVAC						
RESP-STG	●					
INC-ZONE	●					

1.1.3 ATDM Strategies Modeled

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. Unlike the traditional sense of traffic management, ATDM strategies are defined to be proactive in nature, where traffic state for a future time horizon is predicted and strategies are deployed based on simultaneous evaluations or historical knowledge. Hence modeling ATDM strategies generally

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[1] https://www.its.dot.gov/research_archives/dma/index.htm

include prediction-based strategy assessment. Further details on ATDM modeling is provided in the next chapter.

Table 1-3 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. The San Mateo Testbed was a DMA-centric Testbed.

Table 1-3. ATDM Strategy Mapping with Testbeds

ATDM Strategies	***San Mateo***	***Pasadena***	***Dallas***	***Phoenix***	***Chicago***	***San Diego***
Active Traffic Management						
Dynamic Shoulder Lanes		●	●		●	
Dynamic Lane Use Control		●			●	●
Dynamic Speed Limits		●			●	●
Queue Warning		●				
Adaptive Ramp Metering		●	●	●		
Dynamic Junction Control		●				
Dynamic Merge Control						●
Dynamic Traffic Signal Control		●	●	●	●	
Transit Signal Priority						
Dynamic Lane Reversal						
Active Demand Management						
Dynamic Ridesharing						
Dynamic Transit Capacity Assignment						
On-demand Transit						
Predictive Traveler Information			●	●	●	●
Dynamic Pricing						
Dynamic Fare Reduction						
Transfer Connection Protection						
Dynamic HOV/Managed Lanes						●
Dynamic Routing		●	●	●	●	●
Active Parking Management						
Dynamically Priced Parking			●			
Dynamic Parking Reservation						
Dynamic Wayfinding						
Dynamic Overflow Transit Parking						
Weather-Related Strategies						
Snow Emergency Parking					●	
Preemption for Winter Maintenance					●	
Snowplow Routing					●	
Anti-Icing and Deicing Operations					●	

1.2 Primer Overview

The layout of this primer is organized into four chapters with the following contents:

- Chapter 1 – Introduction and Background: This chapter introduces the report and identifies the purpose and overview of this document, and a brief description on the AMS Testbed Project.
- Chapter 2 – AMS Methodology: This chapter provides a detailed AMS methodology and the seven steps adopted by the AMS testbed team that are transferable to other similar analysis projects.
- Chapter 3 – AMS Testbed Project Outcomes: This chapter enlists the major outcomes from the project in terms of open source data, models, software and publications.
- Chapter 4 – ATDM Analysis Considerations: This chapter describes the different considerations that agencies should consider when conducting their own ATDM analysis.

Chapter 2. AMS Testbed Methodology

The AMS Testbed methodology used in this project represents a set of carefully crafted process with review gates throughout the process. This was necessary to satisfy the goals of a complex modeling-based project. While these steps are specific to AMS Testbed project, several of them are adaptable to agencies interested in modeling ATDM strategies and DMA applications. The process will help ease complexities that are involved with modeling ATDM strategies and a prediction-based decision support system that most of the ATDM-centric AMS testbeds adopted. While this chapter is meant to briefly describe the different steps in the AMS methodology used in the project, it also highlights the relevant documents that were generated during this project. This chapter also provides details on each of the documents and how agencies or researchers can adapt them to individual ATDM evaluation.

Figure 2-1 shows the overall process of the AMS testbed project and consists of several steps. The seven-step approach highlighted in this chapter includes:

1. Development of Detailed Requirements
2. Selection of Case Study Sites
3. Development of Analysis and Evaluation Plans
4. Data Collection and Cluster Analysis to Operational Conditions
5. Development and Calibration of Testbeds
6. Modeling and Simulation-based Evaluation
7. Documenting Gaps, Challenges and Future Research.

As shown, 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.

In the following sections, we briefly expand on the different steps and how they are adaptable to a generalized ATDM evaluation that is based on modeling and simulation as well as references that could be utilized for readers that were produced as a part of this project.

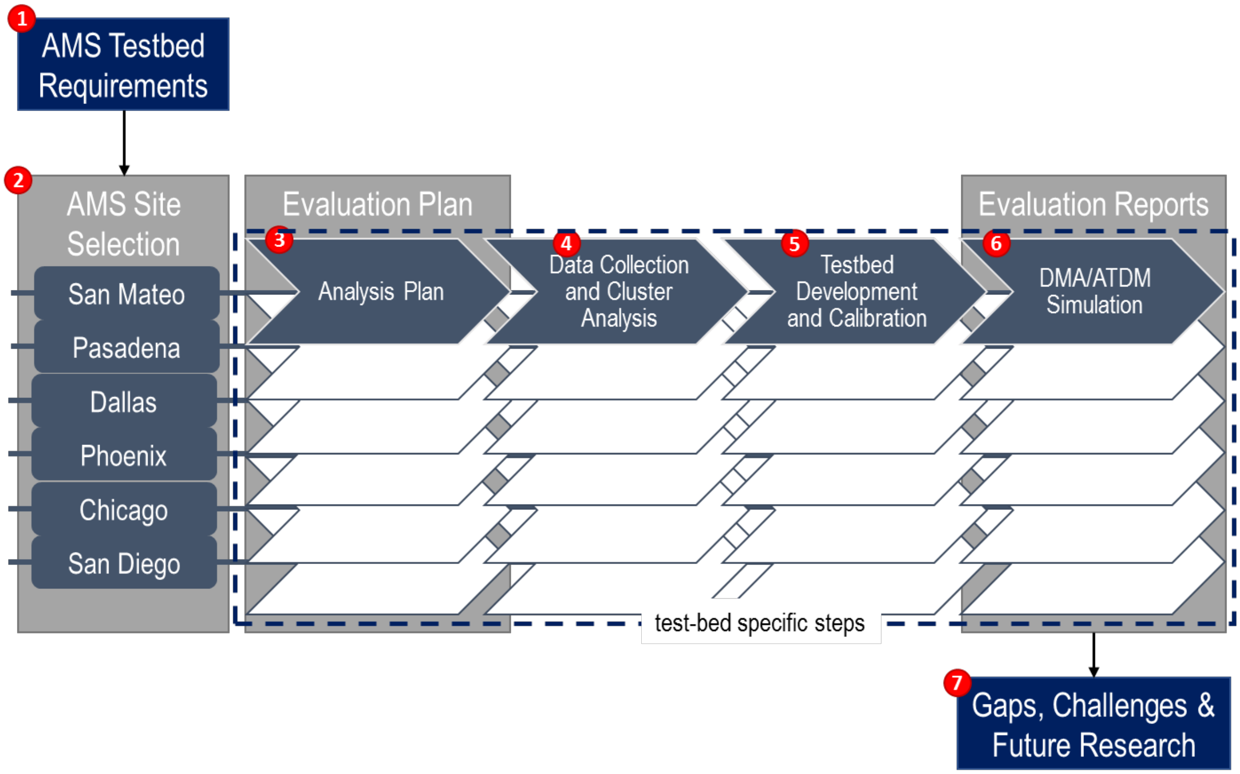


Figure 2-1. Process Flow of the AMS Testbed project

2.1 Development of Requirements

Development of detailed requirements is one of the first and important steps in an AMS evaluation. As an example of this project, the team identified seven sets of requirements that assisted the team in both selecting the appropriate case study sites, but also developing the appropriate software architecture that can support the evaluation. The different sets of requirements used were:

1. System User Requirements
2. Connected Vehicles and Connected Traveler Devices Requirements
3. Operational Data Environment Requirements
4. System Manager Requirements
5. Data and Information Flow Requirements
6. Operational Condition and System Performance Measurement Requirements
7. DMA Applications and ATDM Strategies Requirements

A full list of requirements is provided in **FHWA-JPO-16-369** (*AMS Testbed Development for DMA and ATDM Evaluation – Detailed AMS Requirements*) under each of these categories. While the document provides an exhaustive list of requirements, several of these could form the basis of future AMS Testbed projects that are required to evaluate ATDM and other innovative transportation technologies, such as data and information flow and performance measurement requirements.

2.2 Selection of Testbed Sites

Once the requirements were developed, the team conducted an in-depth testbed site selection to define the sites that will be used for DMA and ATDM evaluation. Instead of selecting one massive testbed that can fulfill all of the requirements, the team selected a portfolio of six sites, thereby distributing the risks across them, and to reduce complexity of individual testbeds. The site selection process is documented in **FHWA-JPO-16-355** (*AMS Testbed Development for DMA and ATDM Evaluation – AMS Testbed Selection Report*).

As described in the report, the team conducted a two-step process to narrow down a list of 14 testbeds to 6 testbeds. The candidate testbeds were identified based on nine factors such as geographic scope, temporal scope, temporal resolution, multi-modal capabilities, level of congestion, availability of multiple data sources, calibrated AMS models, ease of adaptability, and existing deployment or research environment. The first step of screening included qualitative and quantitative assessments based on preliminary screening criteria and the second step included a weighted scoring against the requirements that were developed in the previous steps. In the end, the following six testbeds were selected: San Mateo, Dallas, Pasadena, Phoenix, Chicago, and San Diego.

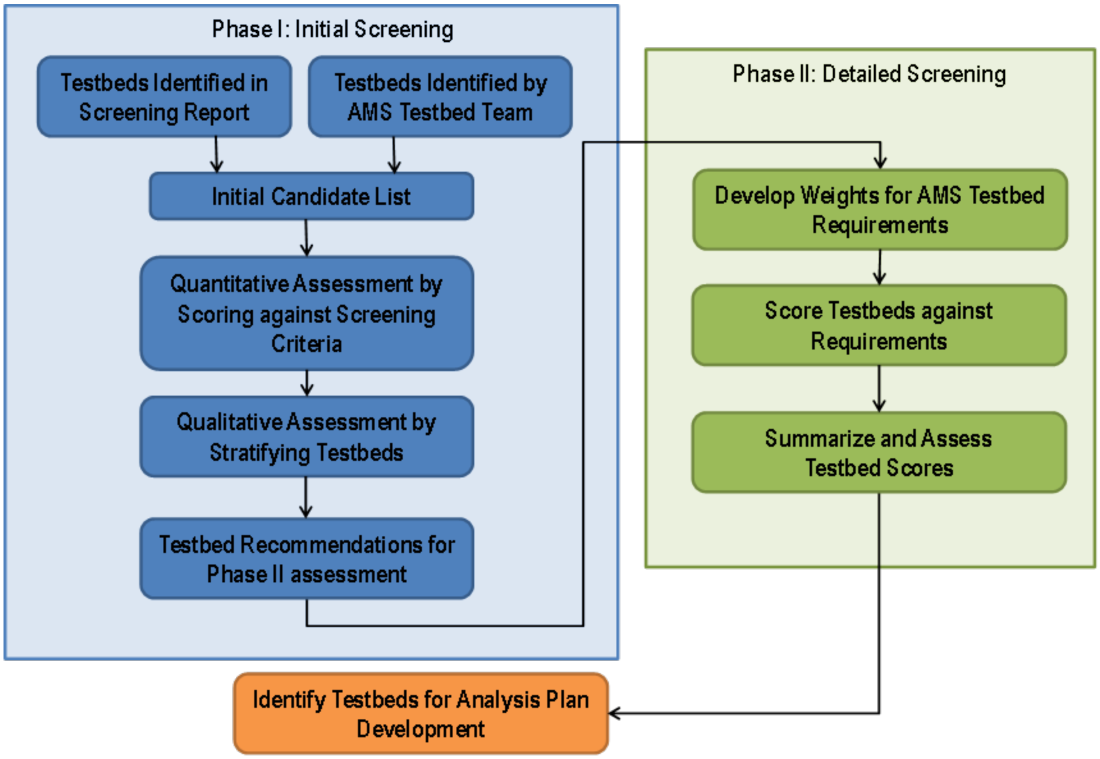


Figure 2-2. Two-step Case Study Site Process Adopted for the AMS Testbed Project [Source: Booz Allen]

This step is extremely important if agencies are considering the use of AMS tools to conduct ATDM evaluation, but not necessary if the evaluation should be for a specific geographic location.

2.3 Development of Analysis and Evaluation Plans

Once the sites have been identified, the project team developed tested-specific analysis plans for each of the six testbeds. Each of the analysis plans documented specifics on each of the testbed, including a description of the geographic conditions of the testbed, modeling and tool capabilities, analysis hypothesis and scenarios, DMA and ATDM strategies to be included in each of the testbeds, key assumptions, data needs and availability and a mapping of the AMS requirements that are met and unmet by the testbed. The analysis plan also documents the teams approach to conduct calibration and evaluation to answer the different research questions that were set forth by the USDOT.

Development of an analysis plan is vital for any AMS analysis since it helps in better scoping the activities to achieve realistic targets. Some of the activities associated with the analysis plan were to conduct research on the modeling tools and capabilities that are available and what needs to be built into the modeling framework. The project team developed DMA and ATDM Modeling Framework (Figure 2-3) for the AMS testbeds and adapted them to different testbeds based on the scope of each of them. In addition, the analysis plan identifies the research questions that are being answered through the modeling effort. The simulation scenarios are generated based on these research questions and the corresponding hypothesis.

Once the testbed sites are selected, the testbed team developed analysis plans that were specific to each testbed. Consequently, six analysis plans were developed:

1. **FHWA-JPO-16-370** (*AMS Testbed Development for DMA and ATDM Evaluation –Analysis Plan for San Mateo Testbed*)
2. **FHWA-JPO-16-371** (*AMS Testbed Development for DMA and ATDM Evaluation –Analysis Plan for Pasadena Testbed*)
3. **FHWA-JPO-16-372** (*AMS Testbed Development for DMA and ATDM Evaluation –Analysis Plan for Phoenix Testbed*)
4. **FHWA-JPO-16-373** (*AMS Testbed Development for DMA and ATDM Evaluation –Analysis Plan for Dallas Testbed*)
5. **FHWA-JPO-16-374** (*AMS Testbed Development for DMA and ATDM Evaluation –Analysis Plan for Chicago Testbed*)
6. **FHWA-JPO-16-375** (*AMS Testbed Development for DMA and ATDM Evaluation –Analysis Plan for San Diego Testbed*)

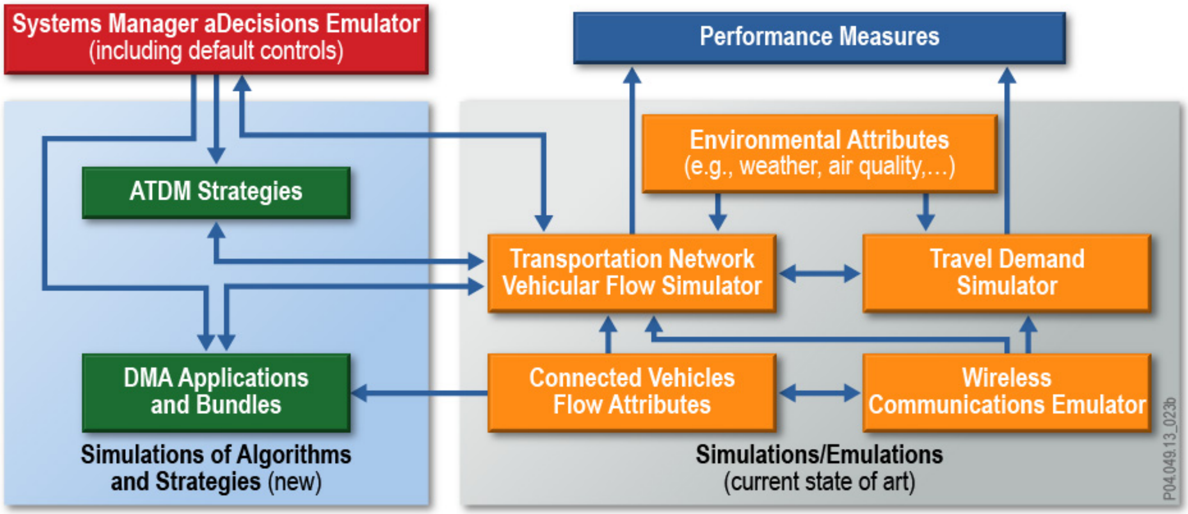


Figure 2-3: DMA ATDM Modeling Framework [Source: Booz Allen]

The project team also developed an overall evaluation plan **FHWA-JPO-16-376** (*AMS Testbed Development for DMA and ATDM Evaluation –AMS Evaluation Plan*) that documents all the analyses that will be included in the six testbeds. The objective of the evaluation plan was to get a high-level picture of what applications and strategies will be modeled as part of the project and what research questions will be answered throughout the entire evaluation period.

Development of analysis plans and an overall evaluation plan can help set up an initial approach to conducting the AMS analysis for interested agencies, as well as to identify initial gaps and risks and mitigation approaches. Hence development of these plans is encouraged for any large-scale simulation-based project.

2.4 Data Collection and Cluster Analysis

Once the analysis plans for individual testbeds were developed, the team proceeded into collecting the data for conducting cluster analysis. Traditionally, traffic simulation models have been using “typical” day models which are representative of an average weekday and in many cases, will normalize trends in traffic characteristics due to weather, congestion, incidents or other non-recurring events. To avoid this, the team decided to calibrate the network to a few real days that represent some of the common operational conditions that exist in the real-world. This was done using a cluster analysis procedure, that was recently added to the Traffic Analysis Toolbox. In fact, the AMS Testbed project was one of the early adopters of this process.

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.

Readers interested in our cluster analysis process can refer to each of our testbed’s calibration reports listed below:

1. **FHWA-JPO-16-377** (*AMS Testbed Development for DMA and ATDM Evaluation –Calibration Report for San Mateo Testbed*)
2. **FHWA-JPO-16-378** (*AMS Testbed Development for DMA and ATDM Evaluation –Calibration Report for Pasadena Testbed*)
3. **FHWA-JPO-16-379** (*AMS Testbed Development for DMA and ATDM Evaluation –Calibration Report for Phoenix Testbed*)
4. **FHWA-JPO-16-380** (*AMS Testbed Development for DMA and ATDM Evaluation –Calibration Report for Dallas Testbed*)
5. **FHWA-JPO-16-381** (*AMS Testbed Development for DMA and ATDM Evaluation –Calibration Report for Chicago Testbed*)
6. **FHWA-JPO-16-382** (*AMS Testbed Development for DMA and ATDM Evaluation –Calibration Report for San Diego Testbed*)

Each of the calibration reports give details on the cluster analysis process and identification of representative days.

2.5 Testbed Development and Calibration

The testbed development encompassed three stages: (a) development of the geographic testbed model structure, (b) calibration of the model and (c) integration of DMA applications and ATDM strategies.

2.5.1 Development of the Testbed

In most cases, the AMS testbed team started off with an existing testbed network for use in this project. Enhancements to the models were made to update the geometry, number of lanes, HOV/SOV restrictions, updating the signal control methods and timings etc. The testbed selection process described in Section 2.2 aimed at reducing this scope by selecting testbeds that are existing and can be readily used for the AMS project.

2.5.2 Testbed Calibration

For each of the selected operational conditions, the team also selected a “representative day” for which data is available to calibrate the model. In most cases, the calibration was done to match field collected data for demand (volumes) and performance (travel time and speed), and the team utilized USDOT guidance to achieve the required calibration targets. Reference to the testbed-specific calibration reports are provided in Section 2.4.

2.5.3 Integration of DMA/ATDM and other Tools

Once the calibrated testbeds were developed, each of the testbed teams integrated internal and external applications to replicate DMA and ATDM strategies. In addition, modules that emulate communication and data transfer layers, prediction managers, system manager, decision support systems, and performance measurement were integrated to these systems. The six testbeds were a complex suite of software and the simulation piece was just one of the component. Table 2-1 shows a listing of the different modeling tools integrated for each of the testbeds in this project.

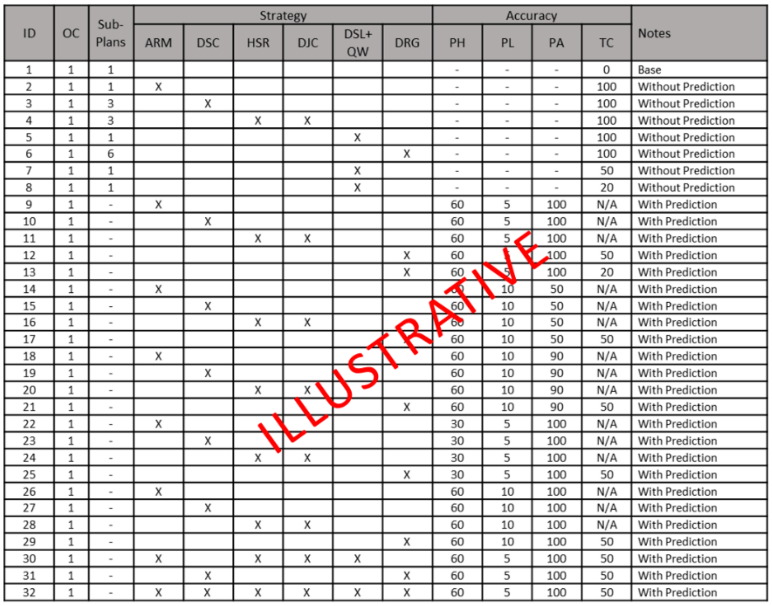
Table 2-1. Modeling Tools Used for Testbeds

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

The development of testbed models requires a lot of debugging and in some instance, readjusting some of the calibration from the previous step. The team has made several of these models and software available for use on USDOT's Research Data Exchange and Open Source Application Development Portal. Details on these are provided in the next chapter.

2.6 DMA/ATDM Simulation and Evaluation

Once fully-functional testbed models are developed, the next step is to emulate the different scenarios to develop test data for evaluation of DMA and ATDM strategies. The first step in this is to develop a scenario table that enlists the different scenarios that need to be simulated to answer the different sets of research questions. This could be either part of the analysis plan development or just prior to running the simulations. Running simulations are resource and time intensive and one of the major criteria while developing the scenarios are to reduce the number of scenarios while maximizing the results that can be achieved from them. An illustrative example is provided in Figure 2-4. Additional examples of scenario listing can be found in the analysis plan documents listed in Section 3.3.



ID	OC	Sub-Plans	Strategy						Accuracy				Notes
			ARM	DSC	HSR	DJC	DSL+ QW	DRG	PH	PL	PA	TC	
1	1	1							-	-	-	0	Base
2	1	1	X						-	-	-	100	Without Prediction
3	1	3		X					-	-	-	100	Without Prediction
4	1	3			X	X			-	-	-	100	Without Prediction
5	1	1					X		-	-	-	100	Without Prediction
6	1	6						X	-	-	-	100	Without Prediction
7	1	1					X		-	-	-	50	Without Prediction
8	1	1					X		-	-	-	20	Without Prediction
9	1	-	X						60	5	100	N/A	With Prediction
10	1	-		X					60	5	100	N/A	With Prediction
11	1	-			X	X			60	5	100	N/A	With Prediction
12	1	-						X	60	5	100	50	With Prediction
13	1	-						X	60	5	100	20	With Prediction
14	1	-	X						60	10	50	N/A	With Prediction
15	1	-		X					60	10	50	N/A	With Prediction
16	1	-			X	X			60	10	50	N/A	With Prediction
17	1	-							60	10	50	50	With Prediction
18	1	-	X						60	10	90	N/A	With Prediction
19	1	-		X					60	10	90	N/A	With Prediction
20	1	-			X	X			60	10	90	N/A	With Prediction
21	1	-						X	60	10	90	50	With Prediction
22	1	-	X						30	5	100	N/A	With Prediction
23	1	-		X					30	5	100	N/A	With Prediction
24	1	-			X	X			30	5	100	N/A	With Prediction
25	1	-						X	30	5	100	50	With Prediction
26	1	-	X						60	10	100	N/A	With Prediction
27	1	-		X					60	10	100	N/A	With Prediction
28	1	-			X	X			60	10	100	N/A	With Prediction
29	1	-						X	60	10	100	50	With Prediction
30	1	-	X		X	X	X		60	5	100	50	With Prediction
31	1	-		X				X	60	5	100	50	With Prediction
32	1	-	X	X	X	X	X	X	60	5	100	50	With Prediction

Figure 2-4. Illustrative Example of Scenario List

Once the simulations are performed and raw data is collected, the next step is to analyze the data to produce meaningful interpretation of results. Typically, simulations are performed in batches to collect statistically significant amount of data for each scenarios that are averaged to assess performance. Results analysis incorporate comparing "test" data with "base" data and conducting statistical testing to understand the confidence interval and significance of interested variables. For the AMS Testbed project, the following documents expands on our analysis procedure and results:

1. **FHWA-JPO-16-383** (*AMS Testbed Development for DMA and ATDM Evaluation –Evaluation Report for the DMA Program*)
2. **FHWA-JPO-16-385** (*AMS Testbed Development for DMA and ATDM Evaluation –Evaluation Report for the ATDM Program*)
3. **FHWA-JPO-16-387** (*AMS Testbed Development for DMA and ATDM Evaluation –Evaluation Report for Chicago Testbed*)
4. **FHWA-JPO-16-389** (*AMS Testbed Development for DMA and ATDM Evaluation –Evaluation Report for San Diego Testbed*)

Please note that two of the testbeds have their specific evaluation reports, but are also included in the DMA and ATDM-specific evaluation reports. Specifically, these reports expand on each of the categories of research questions and how they are answered by each of the different testbeds. Not all testbeds were used in answering all the research questions. For readers interested in obtaining a summary of the analysis, the following documents would be of interest:

1. **FHWA-JPO-16-384** (*AMS Testbed Development for DMA and ATDM Evaluation –Evaluation Summary for the DMA Program*)
2. **FHWA-JPO-16-386** (*AMS Testbed Development for DMA and ATDM Evaluation –Evaluation Summary for the ATDM Program*)
3. **FHWA-JPO-16-388** (*AMS Testbed Development for DMA and ATDM Evaluation –Evaluation Summary for Chicago Testbed*)
4. **FHWA-JPO-16-390** (*AMS Testbed Development for DMA and ATDM Evaluation –Evaluation Summary for San Diego Testbed*)

2.7 Documenting Limitations, Gaps and Future Research Directions

The final AMS step was to document the limitations, gaps and our recommendations for future research to help understand the complexity of the project as well as to guide future researchers in AMS-based projects. As a result, the team developed **FHWA-JPO-16-391** (*AMS Testbed Development for DMA and ATDM Evaluation – Gaps, Challenges and Future Research*). 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 when developing 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.

Chapter 3. AMS Testbed Project Outcomes

Through the modeling of DMA applications and ATDM strategies efforts across the six testbeds, the project team has created a wealth of data, models and software for use by the transportation community in subsequent projects. Hence, all the shareable data, models, and software have been released for open-source usage though USDOT's application and data sharing portals. These are elaborated below.

3.1 Review of Open Source Software

The project team integrated several existing applications within the testbeds either using "wrapper" software or using customized software-in-the-loop applications. Additionally, the team also developed several applications based on existing algorithm definitions for some of the testbeds. The software and source code that were developed under this contract and that does not use proprietary licenses have been uploaded to the USDOT's application sharing platform, Open-Source Application Development Portal (OSADP). The website is accessible at www.itsforge.net (as of July 2017). Each of the software is accompanied by user notes and guidance on how to integrate it with other simulation models and/or a user guide with instructions. Table 3-1 shows a list of applications that are shared on the open source portal. Please note that several other applications and modules were developed during the project, but were not shared due to the usage of licensed or proprietary components.

Table 3-1. List of Applications Developed for Open Source Sharing

Application	*Testbed*	*Description*
INFLO-AMS	San Mateo	Consists of the enhanced Vissim to INFLO interface that is coded in Python.
DIRECTView-AMS	Dallas	A visualization application designed to visualize the performance measures generated during simulations using DIRECT software with options to turn on and turn off scenarios
TRANSIMS-v7	Pasadena	An integrated system of travel forecasting tools for modeling regional transport systems.
DTALite Interface	Phoenix	This repository contains the DTALite source-code, executable files, user's guide, and NEXTA graphical user interface (GUI).
D-RIDE-AMS	Phoenix	A car-sharing application that provides drivers and riders with information which supports them making decisions on the model and route to complete their trip
TCA-Aimsun	San Diego	Utilizes Aimsun API to gather realtime simulation information to transmit CV information.
CACC-Aimsun	San Diego	CACC for Aimsun is designed to simulate Cooperative Adaptive Cruise Control platoons in Aimsun via a custom behavioral model developed with microSDK.

3.2 Review of Public Use Data

The project team has submitted all the data that are used and produced in the six testbeds to the USDOT's data sharing platform, Research Data Exchange (RDE). The website is accessible at www.its-rde.net (as of July 2017). The data from each testbed has been organized into a data environment that consists of typically four datasets. They are:

1. Cluster Analysis Data – This dataset consists of the data that was used to conduct the cluster analysis for each testbed and generally include three types of data:
    a. 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.
    b. 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.
    c. 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.

    The cluster analyses were done to identify commonly occurring operational conditions by finding out representative days using historical data.

2. Calibration Data – This dataset consists of the data that is used for calibrating the simulated network's performance to the performance of the actual network on the selected operational conditions' representative day. This dataset generally includes three types of data:
    a. Observed and simulated travel-time data.
    b. Observed and simulated temporal and spatial distribution of network speeds
    c. Observed and simulated temporal and spatial distribution of network demand or volumes.

    Please note that the type of calibration and the data used to perform calibration vary across the testbeds due to differences in model type (micro- versus meso-) and availability of data.

3. Network Files – This dataset consists of the network files that are calibrated to the field conditions for the selected representative days. The dataset documentation describes the type of tool that is required to use and modify the network files. For example, San Mateo datasets include Vissim files, whereas San Diego datasets include Aimsun files.
4. Simulation Data – This dataset consists of the output of simulations that are performed for this project and are generally accompanied by a table of scenarios that represent each simulation runs. Due to large number of runs and the complexity of testbeds, only aggregate data are provided for all the scenarios. However, a representative dataset that shows raw data is also provided with each of the testbed's data environment.

Figure 3-1 shows the setup of the different data environments on RDE, and the documentation associated with each layer. An overview document is available for each of the data environment, in addition to metadata documentation, included with each of the datasets. Table 3-2 provides a list of the data environments that were created as part of this project and the included datasets, per the aforementioned numbering. While the team tried to provide all of the data that was used in this project, the data that were part of use-only agreements were not made available in the RDE. For example, the cluster analysis data that was performed under a different contract for San Diego Testbed.

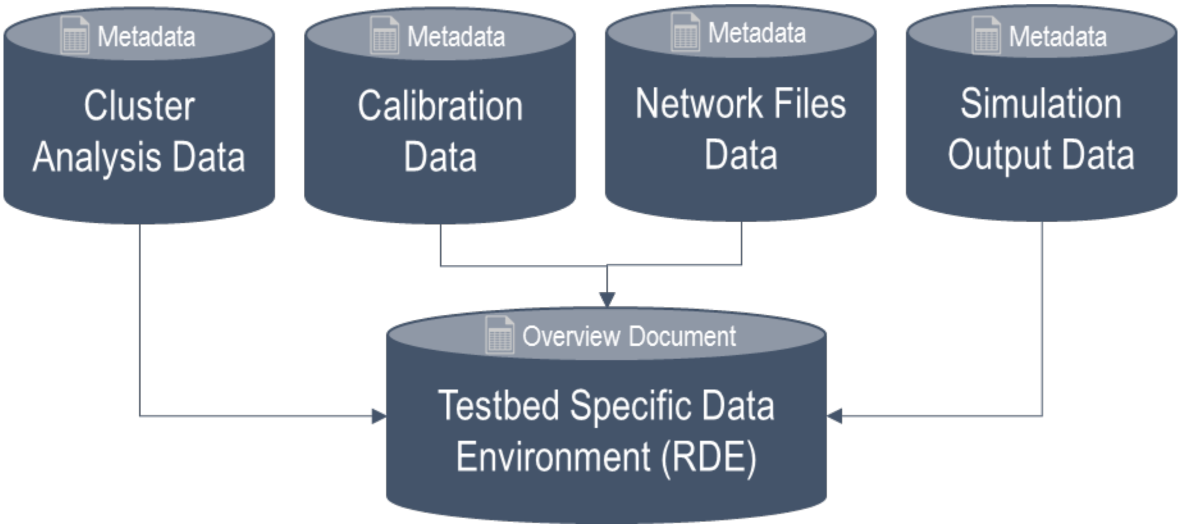


Figure 3-1. Overview of Data Environment Setup in RDE

Table 3-2. Accessible Links to Different AMS Data Environments

Data Environment	*Cluster Analysis Data*	*Calibration Data*	*Network Files*	*Simulation Output Data Files*
San Mateo	✓	✓	✓	✓
Dallas	✓	✓	✓	✓
Pasadena	✓	✓	✓	✓
Phoenix	✓	✓	✓	✓
Chicago	✓	✓		✓
San Diego		✓	✓	✓

3.3 Project Deliverables and Descriptions

Due to the extensive scope of this project, the project team utilized a carefully crafted set of steps to achieve the project objectives. Each of these steps have been documented descriptively throughout the project and gave rise to 24 deliverables spanning the six testbeds. These publications are available for download at USDOT's National Transportation Library (accessible at www.ntl.bts.gov as of July 2017) and the FHWA ATDM website (https://ops.fhwa.dot.gov/atdm/). Table 3-3 shows a list of the publications from this project. In the next chapter, the AMS steps and the reference to each of them in the listed publications are discussed.

Table 3-3. Publications from the AMS Testbed project

No.	*Document Title*	*JPO Publication #*
1	ATDM-DMA AMS Testbed Project: Detailed AMS Requirements	FHWA-JPO-16-369
2	ATDM-DMA AMS Testbed Project: AMS Testbed Selection Report	FHWA-JPO-16-355
3	ATDM-DMA AMS Testbed Project: Analysis Plan for San Mateo Testbed	FHWA-JPO-16-370
4	ATDM-DMA AMS Testbed Project: Analysis Plan for Pasadena Testbed	FHWA-JPO-16-371
5	ATDM-DMA AMS Testbed Project: Analysis Plan for Phoenix Testbed	FHWA-JPO-16-372
6	ATDM-DMA AMS Testbed Project: Analysis Plan for Dallas Testbed	FHWA-JPO-16-373

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

Chapter 4. ATDM Analysis Considerations

Active Transportation and Demand Management (ATDM) represents the concepts and strategies put in place by an agency to improve trip reliability, safety, and throughput of the surface transportation system by dynamically managing and controlling travel and traffic demand, and available capacity, based on prevailing and anticipated conditions, using one or a combination of real-time operational strategies. Through the use of available tools and assets, traffic flow is managed and traveler behavior is influenced in real-time to achieve operational objectives, such as preventing or delaying breakdown conditions, improving safety, promoting sustainable travel modes, reducing emissions, or maximizing system efficiency. Under an ATDM approach, the transportation system is continuously monitored and requires a performance- or objectives-driven approach. As described earlier, under an ATDM approach, the transportation system is continuously monitored. Using both archived and real-time data and predictive methods, actions are performed in real time to achieve or maintain a system performance level.

Figure 4-1 shows the generic ATDM implementation steps and includes continuous monitoring of the system, assessing system performance at specific intervals, evaluating dynamic actions and recommending the best set of strategies and implementing the best set.

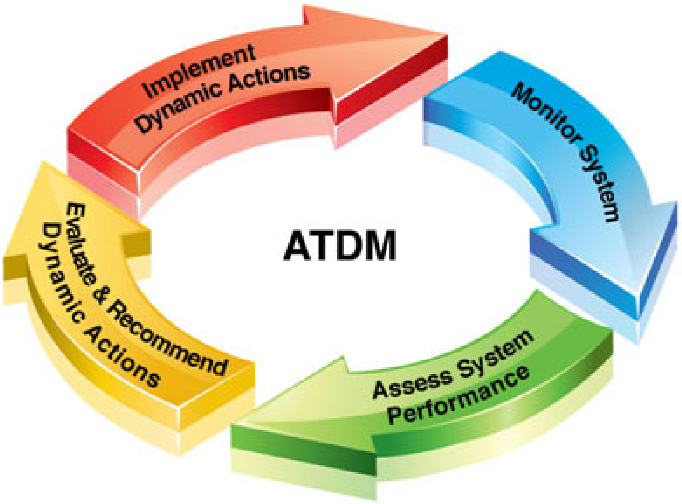


Figure 4-1. ATDM Concept Diagram [Source: USDOT]

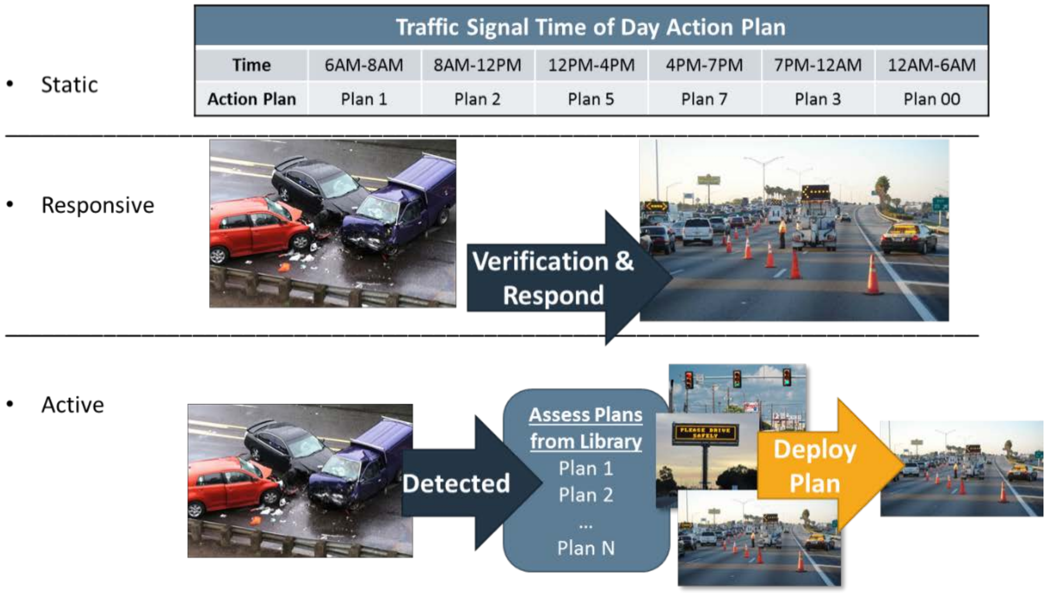
Each of them are summarized below:

1. **Monitor System:** The system is monitored continuously using real-time and historical data and analysis tools. AMS tools and methods are necessary to process the collected data and analyze the information to monitor the system in real time.
2. **Assess System Performance:** Analysis using a continuously moving time-window is performed to predict future conditions, and predicted conditions and established system-level performance targets are compared at the current time step. AMS tools and methods are necessary to predict future performance based on existing and anticipated changes to network demand and supply. The duration of the prediction window depends on the agency preference and control strategies

of interest. Predictions can be made by analytical methods or by using detailed simulation and modeling tools.

3. **Evaluate and Recommend Dynamic Actions:** If system performance does not meet the established targets, AMS tools are needed to evaluate and recommend dynamic actions. AMS tools are also needed to identify and recommend ATDM strategies to implement based on predicted improvement in performance.
4. **Implement Dynamic Actions:** Dynamic actions are then implemented based on the recommendations that the ATDM decision support tools recommend.

As shown in Figure 4-2, active management sets itself apart from static and responsive traffic management by proactively implementing strategies to manage traffic on a facility (Active Traffic Management), reduce or redistribute travel demand by providing alternate routes (Active Demand Management) or alter the demand on parking capacities (Active Parking Management). Table 4-1 shows some examples of strategies that are used by agencies to achieve this goal.



Traffic Signal Time of Day Action Plan

Time	6AM-8AM	8AM-12PM	12PM-4PM	4PM-7PM	7PM-12AM	12AM-6AM
Action Plan	Plan 1	Plan 2	Plan 5	Plan 7	Plan 3	Plan 00

Figure 4-2. Active Management comparison with Static and Responsive Management [Source: Booz Allen]

Table 4-1. Examples of ATDM Strategies

Active Demand Management	*Active Traffic Management*	*Active Parking Management*
Dynamic Ridesharing	Dynamic Lane Use/Shoulder Control	Dynamically Priced Parking
On-Demand Transit	Dynamic Speed Limits	Dynamic Parking Reservation
Dynamic Pricing	Queue Warning	Dynamic Way-Finding
Predictive Traveler Information	Adaptive Ramp Metering	Dynamic Parking Capacity

As demonstrated before, ATDM strategies aim at influencing traveler behavior and traffic flow in real-time and hence use archived data and/or predictive methods to assess performance in real-time to achieve or maintain system performance. Therefore, modeling ATDM strategies is a complex process, unlike traditional traffic modeling or modeling of traffic management strategies on a static or responsive approach. In this chapter, we aim to provide high-level considerations to agencies interested in conducting ATDM analysis.

Readers are encouraged to refer to FHWA-JPO-16-371 (AMS Testbed Development for DMA and ATDM Evaluation –Analysis Plan for Pasadena Testbed) or FHWA-JPO-16-375 (AMS Testbed Development for DMA and ATDM Evaluation –Analysis Plan for San Diego Testbed) for examples of such ATDM analysis.

> *Modeling ATDM strategies should include emulation of the overall ATDM process, including continuous monitoring of the system, assessing system performance, evaluating response plans and making recommendations and implementing recommended response plans based on anticipated future conditions/performance.*

4.1 Designing and Setting up ATDM Analysis

Modeling active management strategies in a simulated environment is complex as it is essential to emulate real-world implementation within the modeling framework. For properly designing and setting up an ATDM testbed, the AMS project team utilized a software-in-the-loop modularized set up as shown in Figure 4-2 which assumes a ***Monitor -> Assess -> Evaluate -> Implement*** cycle that is repeated every time-step that represents the ATDM update frequency.

As shown in the figure, the set up consists of a calibrated testbed model as a base-layer. At every time-step of the ATDM update frequency, the ATDM system manager reads simulation data (**Monitor**), and runs a moving-horizon prediction loop. Under this prediction loop, multiple ATDM strategy combinations are assessed for the system performance in the future (**Assess**). Based on the assessment results, the best strategy, or a combination of strategy is selected (**Evaluate**). The ATDM system manager, then implements the recommendation in the simulation (**Implement**). This cycle is repeated every time-step. A performance log will document the system-wide impacts of deploying each strategy so that the analyst can compare the results at the end of the analysis.

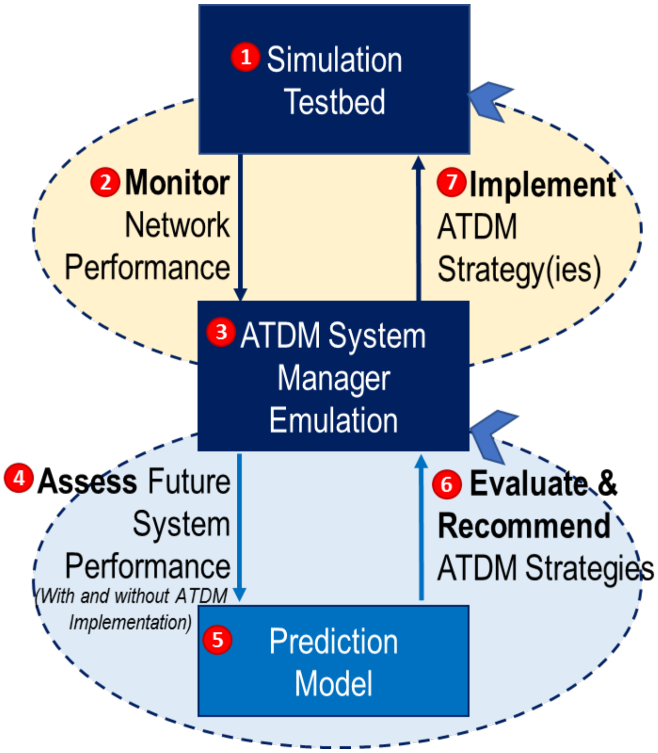


Figure 4-3. Generic ATDM Simulation Setup

Each of the modules within an ATDM Simulation Set up is described below.

4.1.1 Simulation Testbed Model

The testbed model is the base model up on which all evaluations are performed and represents the real-world transportation operations. Through proper use of cluster analysis and calibration process described in Chapter 2, the testbed model will ensure that it is representative of the real-world transportation network performance. In an ATDM evaluation, the microscopic model should also have the ability to implement traffic and demand management strategies that the agencies are interested in assessing. For example, if the agency wants to assess Adaptive Ramp Metering and Adaptive Signal Control, the testbed model should incorporate these strategies either internally or externally. For example, in the AMS Pasadena Testbed modeled in Vissim, the project team incorporated two external applications to the microscopic model to emulate these strategies. GeoDyne was utilized to integrate ramp metering and D4 software controller was used to emulate adaptive signal control.

4.1.2 System Manager Emulation

The system manager, in this context, is representative of a Traffic Management Center, and is the brain of the active management implementation in the testbed model. The system manager conducts the four steps of *Monitor -> Assess -> Evaluate -> Implement* and receives instantaneous system performance data (or simulation data) from the testbed model, and has the ability to control different ATDM strategies.

A high-level list of duties performed by the system manager are provided below:

1. Monitor the testbed network, and receive data. This includes logging the system performance for post-simulation analysis.
2. Assess different combinations of active management strategies to be deployed in the testbed. This can be done using prediction-based methods or using archived data.
3. Evaluate the different strategy combinations based on the prediction results and create the best set of action plans.
4. Implement the best set of active management strategies in the testbed network.

The **update frequency** of ATDM implementation, and receiving data by the system manager is of specific importance in an ATDM context, and should be representative of the field. Having longer update frequency may reduce the effectiveness of ATDM strategies (due to delayed implementation or dis-implementation) and shorter updates may be unrealistic in real-life.

ATDM analysis could also entail additional complexities to improve the granularity of ATDM implementation. For example, agencies could also emulate communication models when receiving data or providing the data.

4.1.3 Traffic/Demand Prediction

Traffic-state or demand prediction is one of the methods to assess and deploy ATM/ADM strategies in the real-world. Typically, this entails a prediction system that can run multiple predictive scenarios in very short time. Agencies predict the system performance without any ATDM strategy as well as with different sets of strategies. The resulting performance measures will be used to pick whether to implement a new strategy, keep the previously implemented strategy or not to implement any strategies. Different types of prediction tools can be used to perform this. For example, in the AMS Dallas Testbed, the team implemented a moving horizon prediction system that conducts additional parallel simulations to estimate future states under different strategy conditions. AMS Pasadena Testbed used a similar system where predictions were conducted by macroscopic simulations (to reduce computation time and to enable demand predictions) using TRANSIMS. AMS Chicago and AMS San Diego testbed also utilized similar approaches.

Figure 4-4 demonstrates the moving-horizon prediction window, when coupled with continuous system monitoring by the system manager. At every Δt, the system manager initiates a prediction-based assessment to predict the traffic state and/or demand to a fixed time interval in the future (typically 30-minutes or 60-minutes into future).

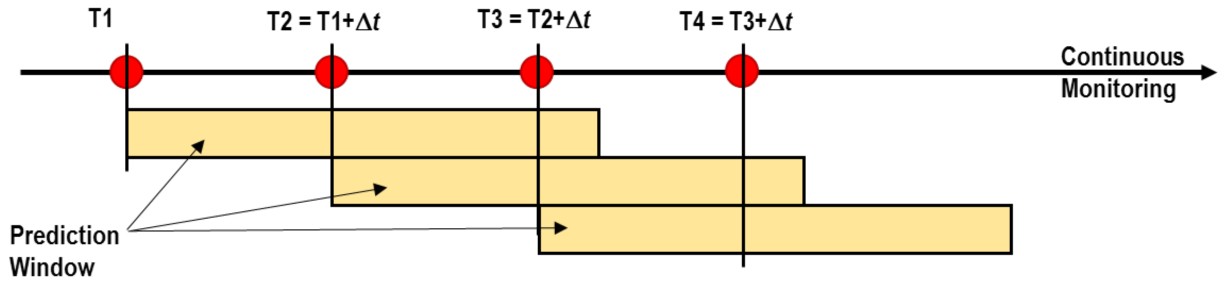


Figure 4-4. Demonstration of Moving-Horizon Prediction Loop [Source: Booz Allen]

An example of the moving horizon prediction system is provided below:

AMS Dallas Testbed's Real-time Network State Estimation and Prediction System

The AMS Dallas Testbed's prediction-based active management system, emulated using DIRECT (Dynamic Intermodal Routing Environment for Control and Telematics) integrates 1) network state estimation module; 2) a network state prediction module; 3) demand estimation and prediction module; 4) consistency checking module; and 5) decision support subsystem (scheme generator) and is shown in Figure 4-5.

The network state estimation module is synchronized with the real clock and provides an estimate of the current network conditions at any point in time. It consists of a real-time simulation-based macroscopic model capable of capturing the network congestion dynamics resulting from the network's demand-supply interaction. This DTA simulation-based model is used as the basis for the estimation and the prediction modules. DIRECT consists of several interconnected components including: (a) demand generation; (b) travel behavior; (c) shortest path algorithm; (d) vehicle simulation; and (e) statistics collection.

The network prediction module is periodically activated (e.g., every 5 to 10 minutes) to predict the network conditions over a predefined horizon (30 minutes to 1 hour). The prediction module consists of another instance of the network simulation model running faster than real-time. The initial conditions for each prediction horizon are obtained from the estimation module which provides a snapshot of the network conditions at the start time of each prediction horizon. This snapshot defines the current location, speed, and assigned route for all travelers in the network. The new vehicles to be loaded during the prediction horizon are obtained through activating the online dynamic demand estimation and prediction module for the prediction horizon, which is described in more details in the next section. The system also allows the use of demand data that are estimated offline.

To ensure consistency between the simulation and the real network, the simulation model receives continuous data feeds in the form of speed and flow rate observations for roadway links equipped with surveillance devices. These observations can be used to adjust the model parameters in real-time to achieve better estimation results. The DIRECT framework is ready to integrate correction algorithms to any of its parameters. In the current implementation, as the model is fully calibrated off-line, no online model adjustment modules are activated to adjust any of the model parameters.

As illustrated in the figure, the estimation module implements a moving horizon approach to report the estimated measures of performance. Following this approach, statistics that covers a pre-defined horizon (e.g., 30 minutes) are continuously collected and reported at each roll (e.g., 5 minutes). Such approach is more suitable for real-time applications as it continuously monitors the time-varying network performance associated with any emerging congestion and the implemented response plans. Readers are encouraged to refer FHWA-JPO-16-385 (AMS Testbed Development for DMA and ATDM Evaluation – Evaluation Report for the ATDM Program) for more information and examples from other testbeds.

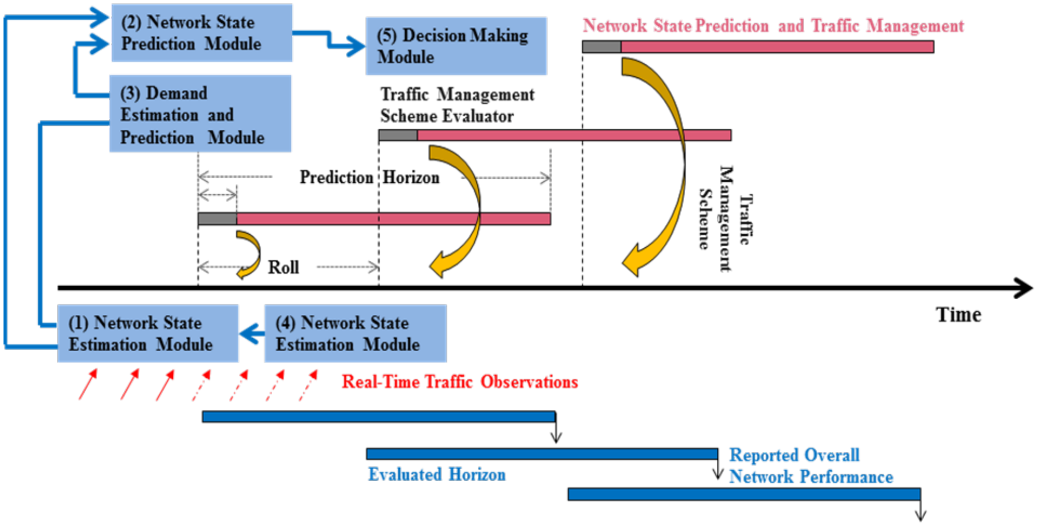


Figure 4-5: DIRECT-based prediction model used in the AMS Dallas Testbed [Source: SMU]

There is another approach to active management, where advanced analytics and business intelligence is used to mine through structured historic performance data. When active management relies of archived data, at every time-step, the system manager compares the system performance for a prescribed period to similar performance in the archived data when a strategy was deployed to understand its impacts. By comparing multiple such past deployments, the system manager will be able to pick the best-performing strategy. This approach relies on large-amount of highly granular data and will be useful for agencies with a long and continuous history of performance data collection. Please note that all the AMS testbeds utilized prediction-based approach to conducting ATDM evaluation.

4.2 Conducting Effective ATDM Analysis

Once the ATDM analysis testbed is set up, the next step is to conduct the analysis using the software-in-the-loop set up described in the previous subsection. This subsection provides some considerations to include in conducting effective ATDM analysis. Effective ATDM analysis should integrate well-defined sets of ATDM strategies, Response Plans, Business Rules as well as ATDM Parameters. The analyst should identify a proper set of ATDM strategies to include in the evaluation and as described in section 4.1.1, the emulation of these strategies should be included in the microscopic simulation model. The FHWA ATDM website (https://ops.fhwa.dot.gov/atdm/approaches/index.htm) lists and describes an exhaustive list of ATDM strategies and their descriptions as well as examples of their deployment.

4.2.1 Response Plans

In an ATDM context, the traffic management schemes deployed or evaluated for deployment are called response plans. Response plans include specific deployment characteristics of a specific ATDM strategy or a combination of strategies. During ATDM analysis, the analysts should provide potential combinations of response plans to the system manager, so that a comparative prediction-based analysis can be conducted at the ATDM update frequency to select and deploy the best ATDM strategies (or response plans).

4.2.2 Business Rules

Since ATDM strategies are implemented throughout the network, in order to reduce variability of traveler compliance, it is important for the system manager to consider business rules when assessing and implementing ATDM response plans. Business rules denote a set of rules that govern transition from one response plan to the other. For example, AMS Pasadena Testbed used a response plan frequency of 5-minutes. But implementing and removing hard-shoulder running (HSR) strategy from a freeway cannot be made in 5-minutes. Hence a business rule was set that once an HSR strategy is implemented, it cannot be removed for 30 minutes. Implementing such business rules are very important in making the ATDM analysis system realistic. Typically, TMC policies should be used to develop these business rules.

4.2.3 ATDM Parameters

In addition, several prediction parameters and ATDM parameters need to be considered in deploying ATDM strategies in a simulated testbed. Some of them are defined below:

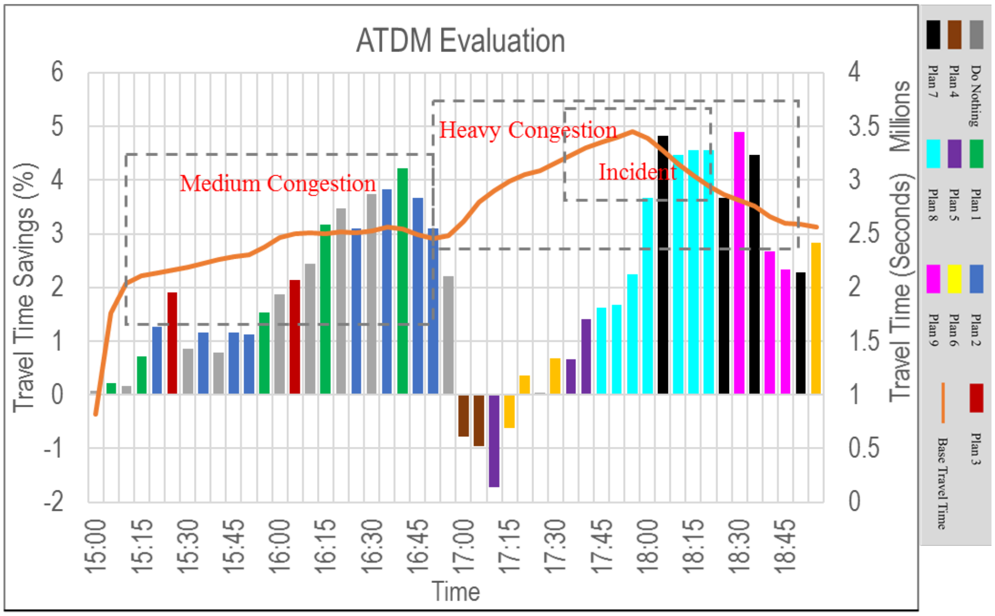
- **Prediction Accuracy** – The percentage of accuracy in predicting the future conditions. This relies on several factors, such as the accuracy of the data from the field that is provided to the ATDM system manager, or the methodology used to conduct the prediction.
- **Prediction Horizon** – The length of time into the future when the prediction model will assess traffic performance and state.
- **Prediction Latency** – The time difference between when the field data is received for predicting and assessing different response plans and when the recommended strategies are applied to the transportation network
- **Geographic Coverage** – The geographic area which is used as an input data for the system manager to assess possible response plans.
- **Traveler Compliance** – The portion of travelers that will deviate from their current state and adhere to strategies recommended

Realistically defining these parameters in the ATDM framework and set up is of importance when developing credible ATDM analysis decisions. For example, prediction latency not only involves communication latency, but the time it takes for the prediction system to run multiple simulations with different response plans and the time it takes for the system manager to decide on the best plan and implement it in the testbed.

Lastly, effective ATDM analysis involves a set of carefully developed simulation scenarios to match the research questions an agency is trying to answer.

4.3 Reporting ATDM Results for Decision-Making

Once the ATDM evaluation is performed, ATDM results should be reported in a detailed manner to help agency decision-making. This includes reporting clarifying assumptions regarding the ATDM and prediction set up, parameters etc. Unlike traditional simulations, ATDM analysis reporting also entails combining performance measures with the implemented strategies. For example, when demonstrating the effectiveness of ATDM implementation, when compared to individual strategies, the reports should also show the exact temporal distribution when a strategy was implemented. An example from the AMS Pasadena Testbed is shown in Figure 4-6 which shows the travel time savings when ATDM implementation was made. As shown in the figure, multiple action plans including combinations of dynamic route guidance and dynamic signal control were utilized based on instantaneous network congestion. The performance of ATDM was demonstrated as travel time savings, and bar-graphs were colored based on the strategy that was implemented.



Trigger	Action Plans
Medium Congestion	1. DRG Plan 1 2. DRG Plan 2 3. DRG Plan 3
Heavy Congestion	4. DRG Plan 1 + DSC Plan 1 5. DRG Plan 2 + DSC Plan 1 6. DRG Plan 3 + DSC Plan 1
Incident	7. DRG Plan 4 + DSC Plan 2 8. DRG Plan 5 + DSC Plan 2 9. DRG Plan 6 + DSC Plan 2

Figure 4-6. Demonstration of Performance Measures with Deployment

APPENDIX A. List of Acronyms

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

Table A-1. List of Acronyms

Acronym	Description
AMS	Analysis, Modeling and Simulation
API	Application Programming Interface
ASC	Adaptive Signal Control
ATDM	Active Transportation and Demand Management
ATIS	Advanced Traveler Information System
CACC	Cooperative Adaptive Cruise Control
COM	Component Object Model
CV	Connected Vehicle
DIRECT	Dynamic Intermodal Routing Environment for Control and Telematics
DMA	Dynamic Mobility Applications
D-RIDE	Dynamic Ridesharing
DR-OPT	Drayage Optimization
DTA	Dynamic Traffic Assignment
DYNASMART	Dynamic Network Assignment-Simulation Model for Advanced Road Telematics
EnableATIS	Enable Advanced Traveler Information System
EVAC	Emergency Communications and Evaluation
F-ATIS	Freight Real-Time Traveler Information with Performance Monitoring
F-DRG	Freight Dynamic Route Guidance
FRATIS	Freight Advanced Traveler Information System
FSP	Freight Signal Priority
HD-DTA	High Definition Dynamic Traffic Assignment
HOV	High Occupancy Vehicles
ICM	Integrated Corridor Management
IDTO	Integrated Dynamic Transit Operations
INC-ZONE	Incident Scene Pre-Arrival Staging Guidance for Emergency Responders
INFLO	Intelligent Network Flow Optimization
I-SIG	Intelligent Traffic Signal Control
ITS	Intelligent Transportation Systems

Acronym	Description
MAG	Maricopa Association of Governments
MMITSS	Multi-Modal Intelligent Traffic Signal Systems
OSADP	Open Source Application Development Portal
P-DYNA	Predictive Dynamic Network Assignment
PED-SIG	Mobile Accessible Pedestrian Signal System
PREEMPT	Emergency Vehicle Preemption
Q-WARN	Queue Warning
RDE	Research Data Exchange
RESCUME	Response, Emergency Staging and Communications, Uniform Management, and Evacuation
RESP-STG	Responder Staging
SOV	Single Occupancy Vehicle
SPD-HARM	Dynamic Speed Harmonization
TCA	Trajectory Conversion Algorithm
T-CONNECT	Connection Protection
T-DISP	Dynamic Transit Operations
TRANSIMS	Transportation Analysis Simulation System
TSP	Transit Signal Priority
TSS	Transport Simulation Systems
USDOT	United States Department of Transportation

APPENDIX B. AMS Testbed Descriptions

San Mateo Testbed

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). Figure A-1 shows the geographic overlay map of the Testbed.

The testbed was primarily utilized to evaluate DMA applications and was modeled using Vissim microscopic simulation. A system manager was used to develop a software-in-the-loop system to replicate DMA applications outside of the Vissim platform and to recreate its impacts in real-time in the network. This module also 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. A high-level software architecture is shown in Figure A-2.

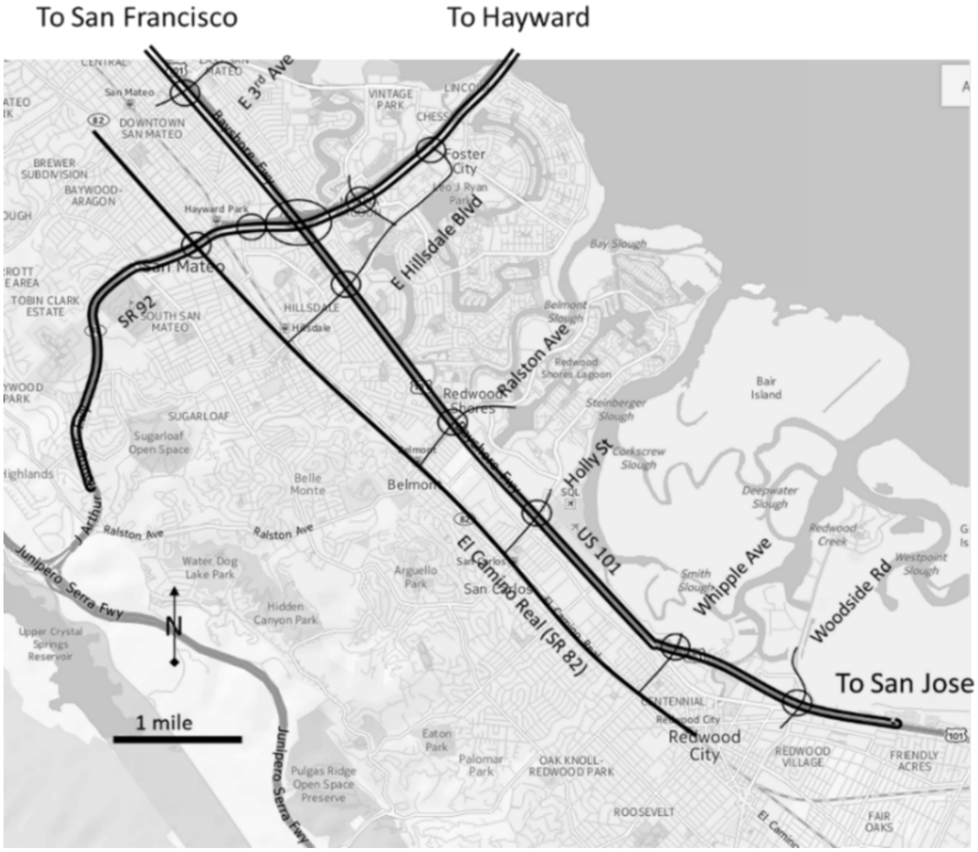


Figure A-1 San Mateo Testbed [Source: Booz Allen]

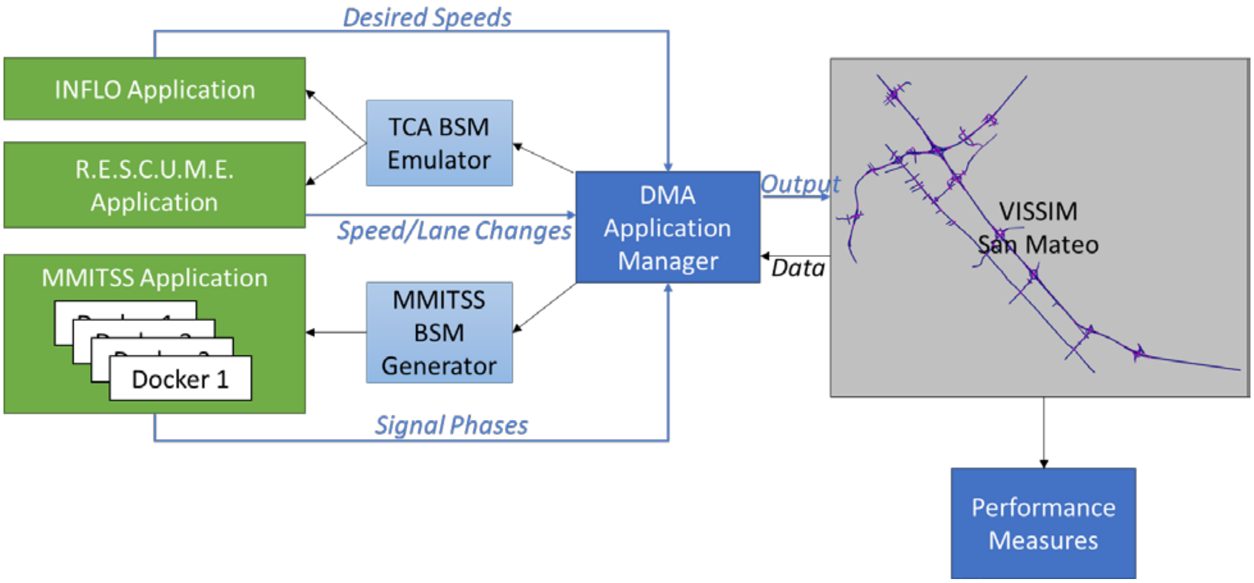


Figure A-2. San Mateo Testbed Modeling Framework [Source: Booz Allen]

The testbed was used to model four different operational conditions which accounted for non-holiday 5-hour PM peak period between 2:30PM and 7:30PM and represented combinations of medium to heavy traffic demand, minor to major incidents and dry and wet weather conditions. Further details on the testbed, its calibration and evaluation architecture 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
3. FHWA-JPO-16-383, Evaluation Report for the DMA Program

Pasadena

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

The Pasadena Testbed was an ATDM-centric testbed that was utilized to evaluate the impact of prediction-based decision support systems on traffic management. the modeling framework (Figure A-4) 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.

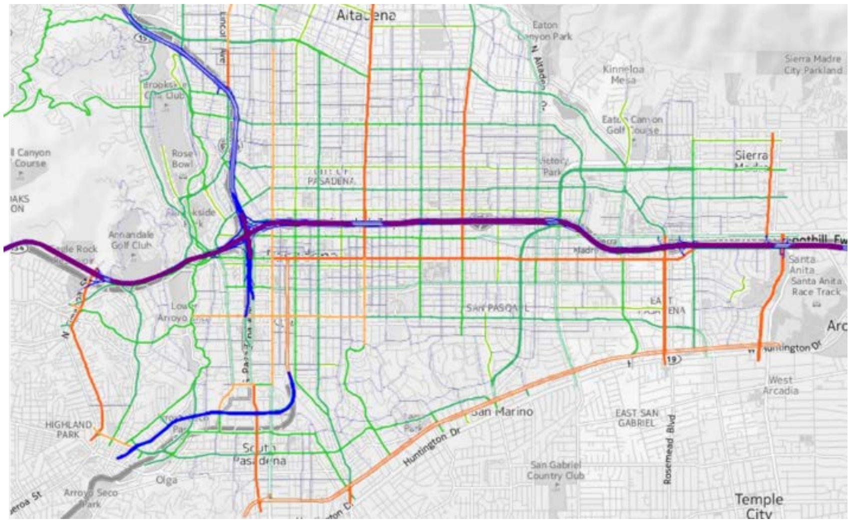


Figure A-3. Pasadena Testbed [Source: Booz Allen]

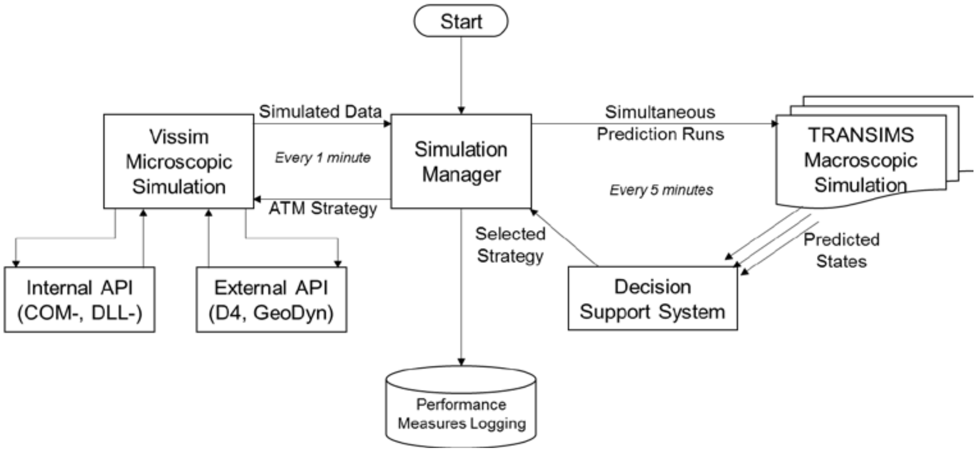


Figure A-4. Pasadena Testbed Modeling Framework [Source: Booz Allen]

The testbed was used to model three different operational conditions which accounted for non-holiday 4-hour PM peak period between 3PM and 7PM and represented combinations of medium to high traffic demand, minor to major incidents and dry weather conditions. Further details on the testbed, its calibration and evaluation architecture 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
3. FHWA-JPO-16-385, Evaluation Report for the ATDM Program

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. Figure A-5 shows the geographic overlay map of the Testbed.

The Dallas testbed was also an ATDM-centric testbed which used a rolling horizon-based prediction method, similar to Pasadena, in its evaluation. At the core, the simulations were done using DIRECT (Dynamic Intermodal Routing Environment for Control and Telematics) software which includes a network-state prediction and estimation modules to replicate prediction and deployment of ATDM-based response plans. This rolling prediction process is shown in Figure A-6.

Figure A-5. Dallas Testbed [Source: USDOT]

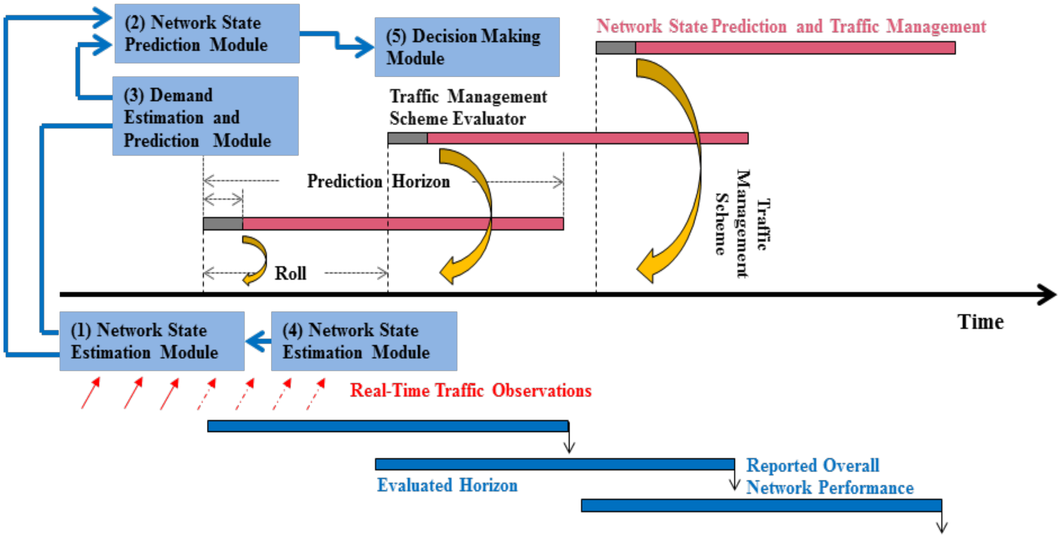


Figure A-6. Dallas Testbed Modeling Framework with Rolling Prediction Horizon [Source: SMU]

The testbed was used to model four different operational conditions which accounted for PM peak periods and represented combinations of medium to high traffic demand, minor to major incidents and dry weather conditions. Additionally, the testbed was also calibrated to one AM peak condition and two hypothetical conditions that represent adverse weather conditions and an evacuation-based demand pattern. Further details on the testbed, its calibration and evaluation architecture 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.
3. FHWA-JPO-16-385, Evaluation Report for the ATDM Program

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. Figure A-7 shows the geographic overlay map of the Testbed.

The Phoenix testbed was used for evaluation of both DMA and ATDM applications. Using a variety of tools to model different aspects of the testbed. The DMA applications were modeled using HD-DTA where link-travel times were used for application modeling. ATDM strategies were modeled using a combination of HD-DTA and DTA-Lite which had an integrated Vissim microscopic simulation to adapt the signal control strategies. The testbed was used to model four different operational conditions which accounted for AM+PM peak periods and represented combinations of low to high traffic demand, minor to major incidents and dry and wet weather conditions. Further details on the testbed, its calibration and evaluation architecture 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.
3. FHWA-JPO-16-383, Evaluation Report for the DMA Program
4. FHWA-JPO-16-385, Evaluation Report for the ATDM Program

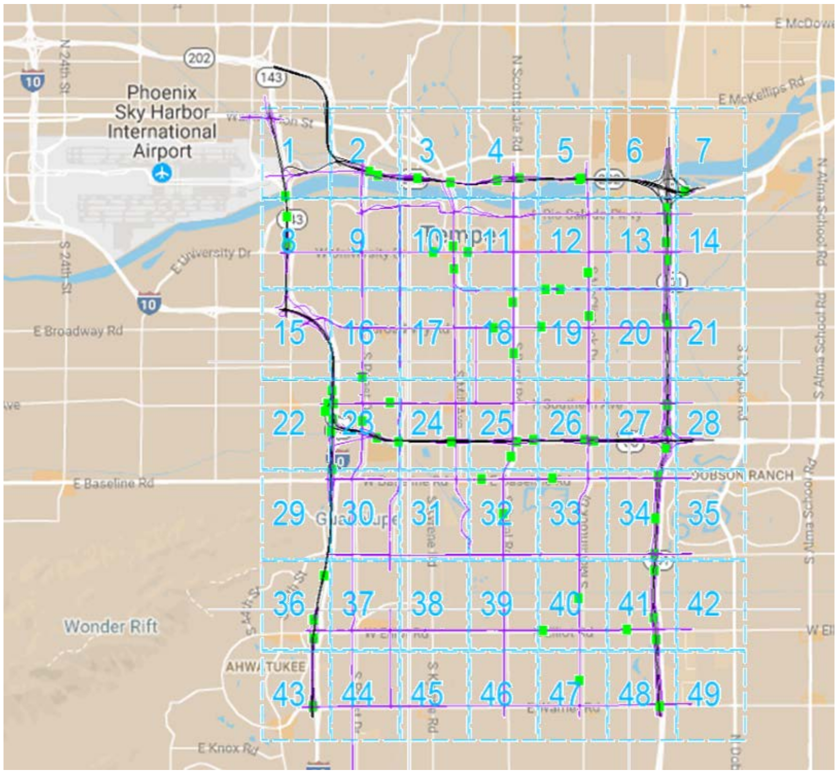


Figure A-7. Phoenix Testbed [Source: Booz Allen]

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. Figure A-8 shows the geographic overlay map of the Testbed.

The Chicago testbed was primarily used for weather-related traffic management strategies and ATDM strategies. However, limited DMA evaluation was also performed to understand the impact of DMA applications under snow-weather conditions. This testbed adopted a software architecture similar to the Dallas using DYNASMART (Dynamic Network Assignment-Simulation Model for Advanced Road Telematics) simulation platform and integrated rolling-horizon based prediction systems to compare and adapt different response plans.

The testbed was used to model six different operational conditions which accounted for 24-hour network behavior and represented combinations of low to high traffic demand, minor to major incidents and dry to wet to snowy weather conditions. Further details on the testbed, its calibration and evaluation architecture 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
3. FHWA-JPO-16-387, Evaluation Report for Chicago Testbed

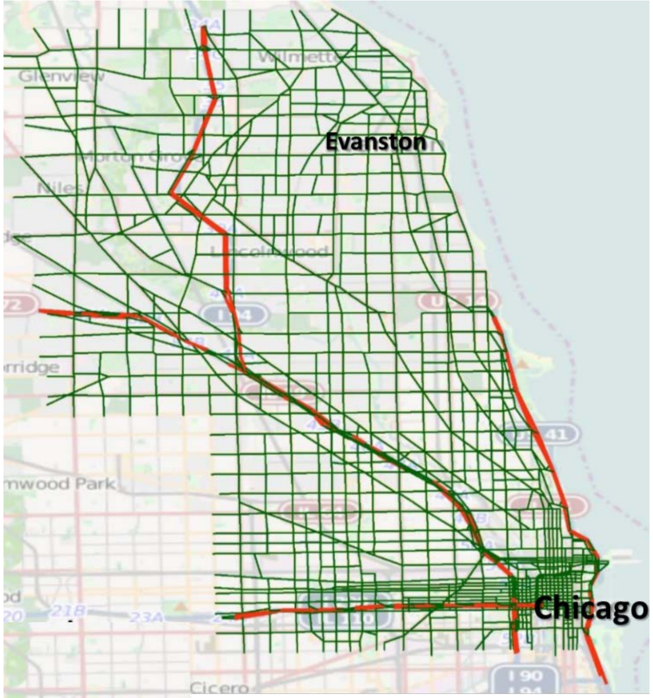


Figure A-8: Chicago Testbed [Source: NWU]

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 Figure A-9. The express lanes are currently under construction from Beethoven Drive to SR-78 and will only be included in the future models. These lanes currently run with two northbound lanes and two southbound lanes and are free to vehicles travelling with two or more passengers in the car (High-Occupancy Vehicles, or HOVs); they also allow Single Occupancy Vehicles (SOV) to use the lanes for a fee, using a variable toll price scheme making them High Occupancy Tolled (HOT) lanes.

The modeling framework for the San Diego testbed is similar to the one deployed in San Mateo. 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.

The testbed was used to model four different operational conditions which accounted for two of AM and PM peak-hour network behavior and represented combinations of medium to high traffic demand, medium to major incidents and dry weather conditions. Further details on the testbed, its calibration and evaluation architecture 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.
3. FHWA-JPO-16-389, Evaluation Report for San Diego Testbed

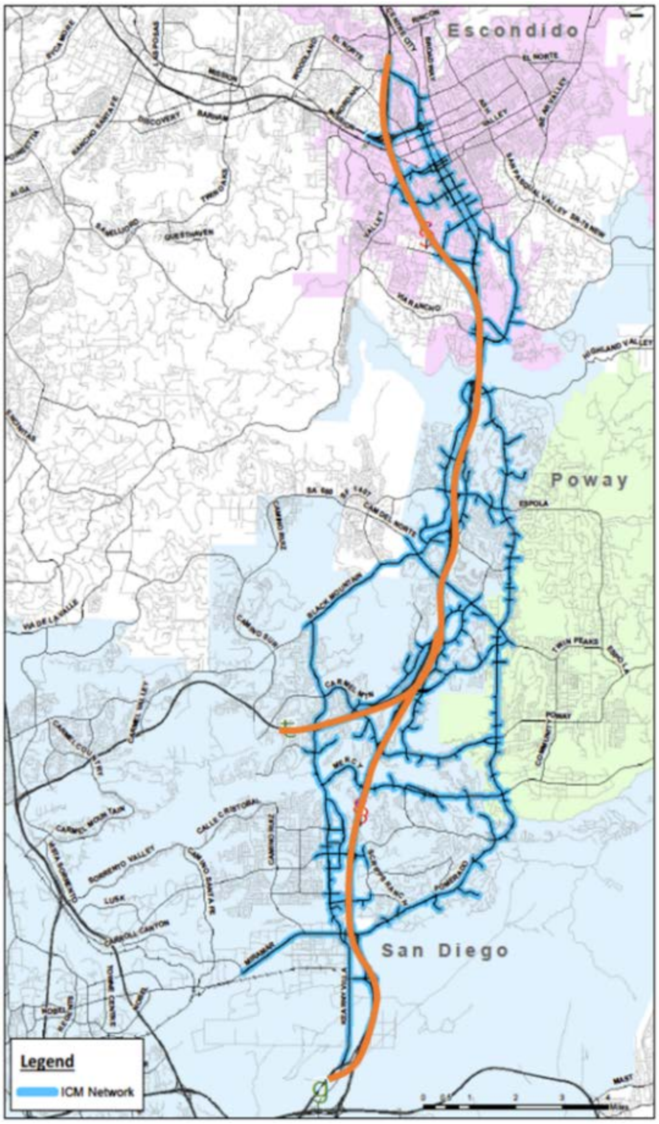


Figure A-9. San Diego Testbed [Source: TSS]

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