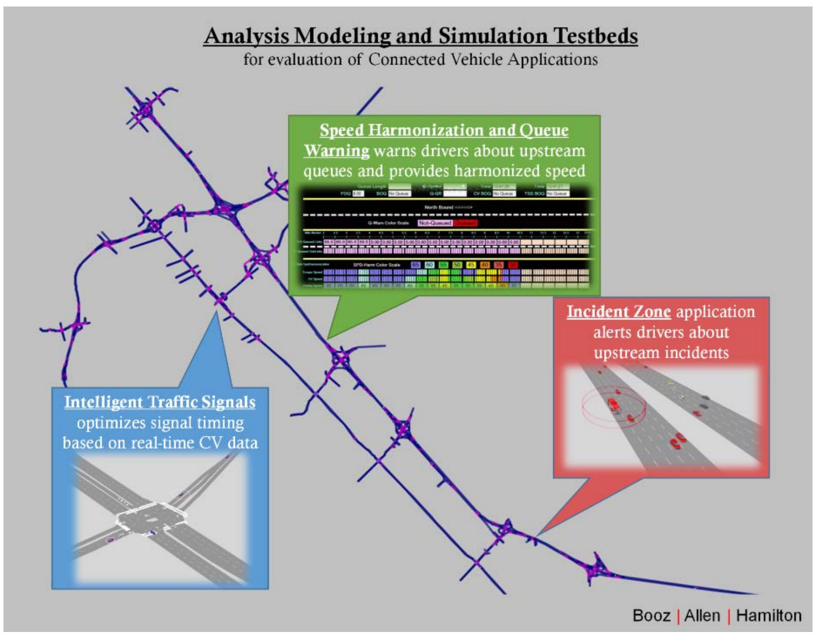
Analysis, Modeling, and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs

Evaluation Summary for ATDM Program

www.its.dot.gov/index.htm

Final Report — August 2017

FHWA-JPO-16-386



U.S. Department of Transportation

Produced by
Booz Allen Hamilton for

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

Notice

Cover Page by Booz Allen Hamilton

Technical Report Documentation Page

1. Report No. FHWA-JPO-16-386	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Analysis, Modeling, and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs — Evaluation Summary for ATDM Program		**5. Report Date** July 2017 **6. Performing Organization Code**
7. Author(s) Balaji Yelchuru and Raj Kamalanathsharma		**8. Performing Organization Report No.**
9. Performing Organization Name And Address Booz Allen Hamilton, 20 M Street SE, Suite 1000 Washington, DC – 20003		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** DTFH61-12-D-00041
12. Sponsoring Agency Name and Address U.S. Department of Transportation Intelligent Transportation Systems–Joint Program Office (ITS JPO) 1200 New Jersey Avenue, SE Washington, DC 20590		**13. Type of Report and Period Covered** Summary Report – Oct 2014 to Feb 2017 **14. Sponsoring Agency Code**

15. Supplementary Notes

FHWA Government Task Managers: James Colyar, Roemer Alfelor

16. Abstract

The primary objective of this project is to develop multiple simulation testbeds/transportation models to evaluate the impacts of Dynamic Mobility Application (DMA) connected vehicle applications and Active Transportation and Dynamic management (ATDM) strategies. While the project aims at evaluating both DMA applications and ATDM strategies, the primary purpose of this report is to summarize the evaluation done in terms of ATDM strategies using the AMS Testbeds. The full ATDM evaluation results are contained in the report entitled *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 ATDM Program* (FHWA-JPO-16-385). DMA evaluation results are documented in separate reports (FHWA-JPO-16-383 and FHWA-JPO-16-384). Dallas, Phoenix, Pasadena, Chicago and San Diego testbeds were used to assess the ATDM strategies under various scenarios of combinations of strategies, prediction attributes and evaluation attributes to answer a set of research questions set forth by the USDOT.

17. Key Words ATDM, Analysis Modeling and Simulation (AMS), Connected Vehicles, Pasadena, Phoenix, Chicago, San Diego, Dallas, ATM, ADM, Weather Management		**18. Distribution Statement**	
19. Security Class if. (of this report)	**20. Security Class if. (of this page)**	**21. No. of Pages** 22	**22. Price**

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

Table of Contents

AMS Testbed Project Overview

The United States Department of Transportation (USDOT) initiated the Active Transportation and Demand Management (ATDM) and the Dynamic Mobility Applications (DMA) programs to achieve transformative mobility, safety, and environmental benefits through enhanced, performance-driven operational practices in surface transportation systems management. In order to explore a potential transformation in the transportation system's performance, both programs require an Analysis, Modeling, and Simulation (AMS) capability. Effective and reliable AMS Testbeds provide valuable mechanisms to address this shared need by providing a laboratory to refine and integrate research concepts in virtual computer-based simulation environments prior to field deployments.

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

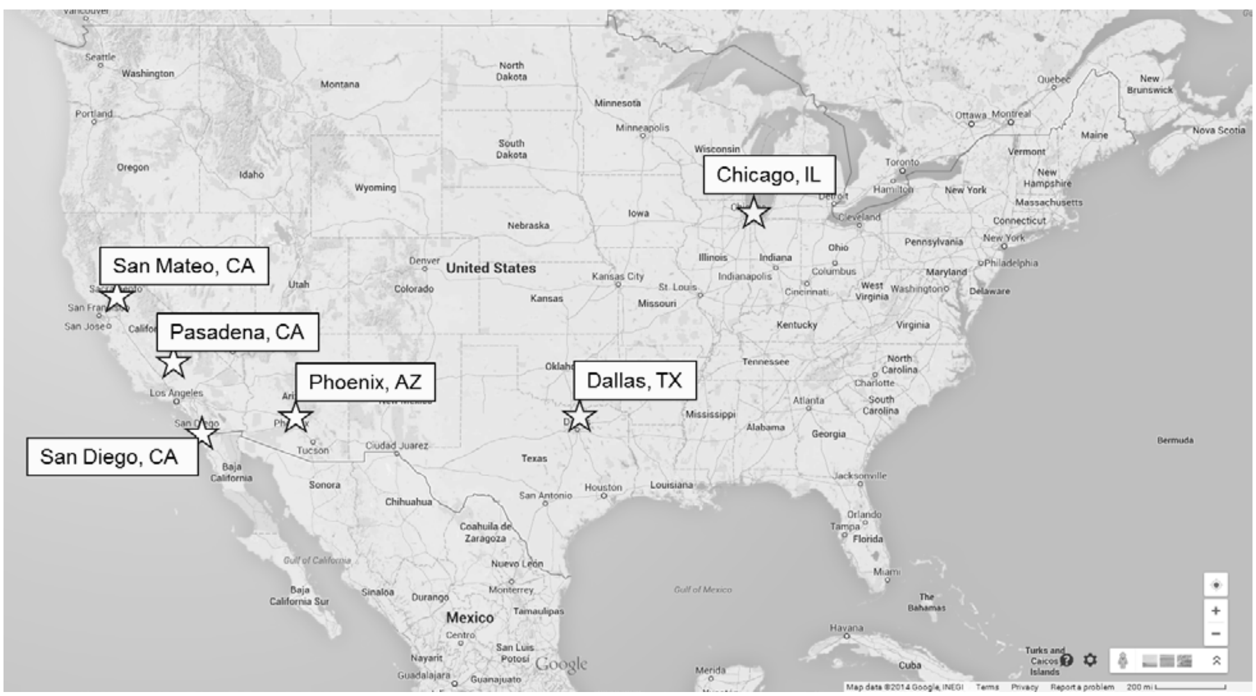


Figure 1. Testbeds Used for AMS Project [Source: Booz Allen]

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

Table 1. Overview of Testbeds

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

While the project aims to evaluate both DMA applications and ATDM strategies, the primary purpose of this report is to summarize the evaluation done in terms of ATDM strategies using the AMS Testbeds. DMA evaluation will be documented in a separate report. ATDM analysis was performed under various scenarios of combinations of strategies, prediction attributes and evaluation attributes to answer a set of research questions set forth by the USDOT using the following testbeds: Dallas, Phoenix, Chicago, San Diego and Pasadena. Through these research questions, the report is expected to provide additional insights to readers on the different ATDM strategies with respect to how they can be implemented and evaluated in a model-based simulation environment, synergies and conflicts between the strategies, favorable operational conditions, modes and facility types for the strategies as well as an evaluation of their sensitivity to different prediction attributes.

The study addressed important research questions regarding the effectiveness of specific ATDM strategies under different operational conditions in a simulated testbed environment. The research questions fall under the following categories: (1) synergies and conflicts among ATDM strategies, (2) impact on strategy performance of different facility types under varied operational conditions, (3) impact of prediction parameters such as prediction accuracy, prediction horizon, prediction coverage etc. on the ATDM benefits.

ATDM-specific Testbeds Overview

The AMS testbed project spans over six testbeds, namely – San Mateo, Phoenix, Dallas, Pasadena, Chicago, and San Diego. However, Dallas and Pasadena were the ATDM-specific testbeds while Phoenix, San Diego and Chicago also modeled DMA applications, in addition to ATDM strategies. These five testbeds are covered in this report.

The Dallas Testbed consists of the US-75 freeway and all associated arterial roadways. 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. The corridor is equipped with 13 Dynamic Message Signs (DMSs) and numerous cameras that cover all critical sections of the US-75 freeway. The US-75 corridor is a multimodal corridor where travelers can use the following mode options: a) private car; b) transit; c) park-and-ride; and d) carpooling. Transit and park-and-ride travelers are estimated to represent less than 2% of the traveler population. The freeway consists of four lanes per direction for most of its sections with the exception of the section at the interchange with I-635 freeway which consists of three lanes only. This lane reduction creates a major bottleneck during the morning and afternoon peak periods.

The Phoenix Testbed covers the entire Maricopa Association of Governments (MAG) which is home to more than 1.5 million households and 4.2 million inhabitants. This multi-resolution simulation model takes multiple modes into account such as single/high occupancy vehicles, transit buses and light-rail and freight vehicles. The region covers an area of 9,200 square miles and is characterized by a low-density development pattern with population density of 253 people per square mile. The region has one city with more than 1 million people (Phoenix) and eight cities/towns with more than 100,000 people each. The region has experienced dramatic population growth in the past two decades, with the pace of growth slowing rather significantly in 2008-2012 period in the wake of the economic downturn. The region is home to the nation’s largest university (Arizona State University with more than 73,000 students), several special events centers and sports arenas, recreational opportunities, a 20-mile light rail line, and a large seasonal resident population. The focus of the Testbed is Tempe area which covers an area of 40 square miles. This testbed considers PM peak traffic between 3PM and 7PM.

The Pasadena Testbed models the roadway network of the City of Pasadena in Los Angeles County, California. This testbed network was derived from the regional travel model shown in Figure ES-2 that had been developed under US DOT contract DTFH6111C00038, which is publicly accessible through the Research Data Exchange portal (https://www.its-rde.net/). Primarily covering the City of Pasadena, the network also includes unincorporated area of Altadena to the north, part of the Cities of Arcadia to the east, Alhambra to the south and Glendale and Northeast Los Angles to the west. The total area is 44.36 square miles.

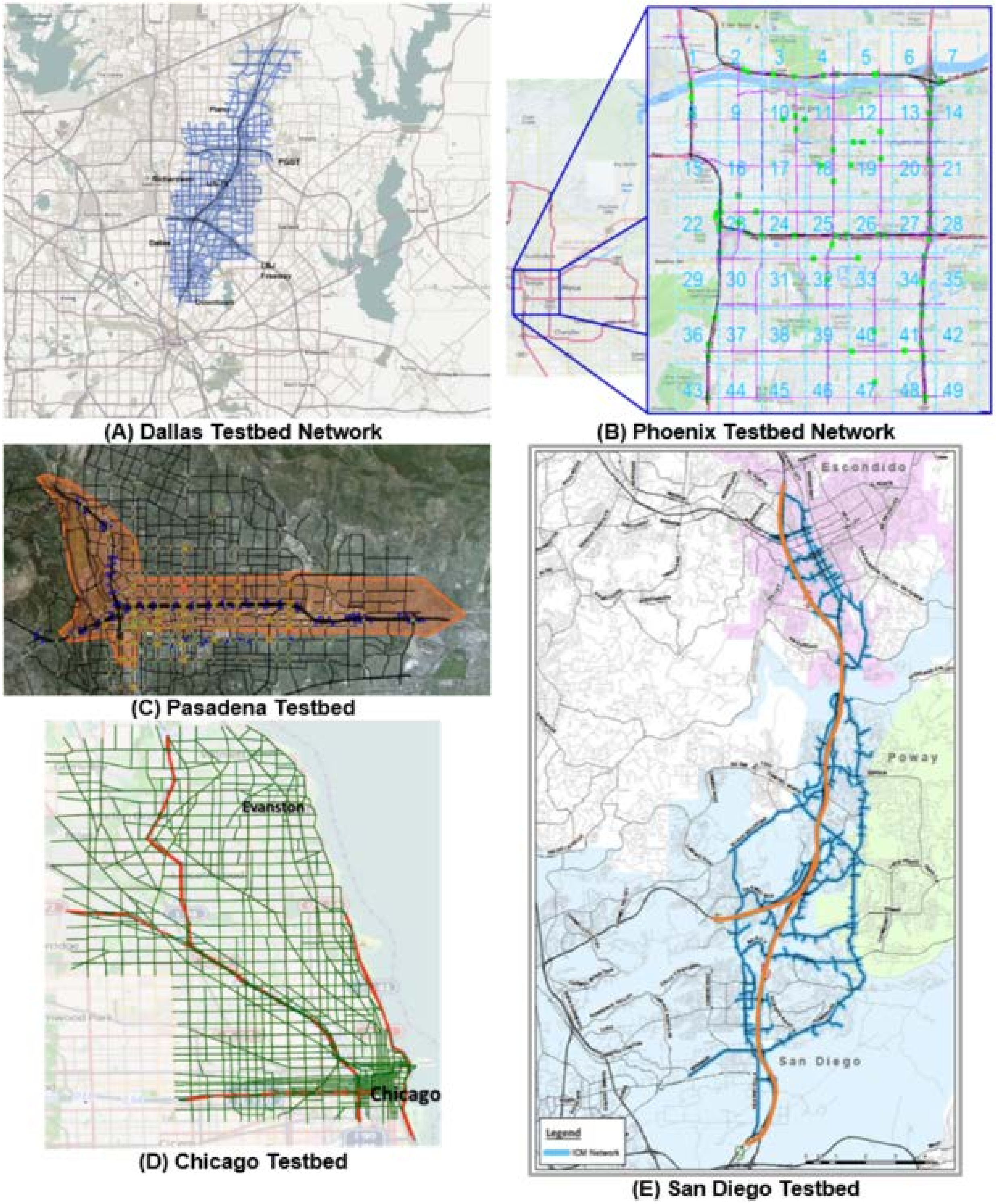


Figure 2: Pasadena, San Diego and Chicago Testbeds Used for ATDM Evaluation [Source: SMU, ASU, BAH, HBA, NWU]

The Chicago Testbed network includes Chicago downtown area located in the central part of the network, Kennedy Expressway of I-90, Edens 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 bound the Testbed network from south and north, respectively. This network was extracted from the entire Chicago Metropolitan Area Network to enhance the estimation and prediction performance during the implementation procedure. The testbed, modeled in DYNASMART, a (meso) simulation-based intelligent transportation network planning tool, consist of over 4800 links and 1500 nodes, with over 500 signalized intersections, nearly 250 metered and non-metered ramps. The network demand is coded for 24 hours at 5-minute intervals with over a million vehicles simulated.

The San Diego Testbed facility comprises of a 22-mile stretch of interstate I-15 and associated parallel arterials and extends from the interchange with SR 78 in the north to the interchange with SR-163 in the south. The current I-15 corridor operates with both general-purpose (GP) lanes and four express lanes from the Beethoven Drive DAR to the southern extent of the model. These lanes currently run with two northbound lanes and two southbound lanes and are free to vehicles travelling with two or more passengers in the car (High-Occupancy Vehicles, or HOVs); they also allow Single Occupancy Vehicles (SOV) to use the lanes for a fee, using a variable toll price scheme making them High Occupancy Tolled (HOT) lanes. In addition, it is possible to change the lane configuration of the express lanes with the use of barrier transfer (zipper) vehicles and the Reversible Lane Changing System (RLCS). The network was coded in Aimsun microsimulation software and was calibrated to four different operational conditions.

Full details on the evaluation approach, modeling methodology, and evaluation results 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.

Summary of Operational Conditions

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

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

Table 2. Operational Conditions for Each Testbed

Op. Con.	Pasadena	Dallas	Phoenix	Chicago	San Diego
OC-1	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
OC-2	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
OC-3	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
OC-4		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
OC-5				Medium to High Demand, No Incidents, Snowy Weather Conditions.	
HO-1*		Low Demand, Major Incidents and Adverse Weather Conditions.		Medium to High Demand, Minor Incidents, Snowy Weather Conditions	
HO-2*		High Demand, No Incidents, Contra-flow Operations, Wet Weather Conditions.			

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

Table 3. Operational Conditions Attributes Across Testbeds

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

ATDM Strategies Modeled

The ATDM strategies that are evaluated in the AMS project include Active Traffic Management (ATM) strategies, Active Demand Management (ADM) strategies and (Active Parking Management (APM) strategies. In addition, Chicago testbed also assessed several weather-related strategies. Table 4 shows a mapping of different ATDM strategies to the different testbeds.

Active Traffic Management (ATM) is the ability to dynamically manage recurrent and non-recurrent congestion based on prevailing and predicted traffic conditions[1]. Focusing on trip reliability, it maximizes the effectiveness and efficiency of the facility. It increases throughput and safety through the use of integrated systems with new technology, including the automation of dynamic deployment to optimize performance quickly and without delay that occurs when operators must deploy operational strategies manually. Some of the examples of Active Traffic Management strategies are listed below:

1. **Dynamic Shoulder Lanes:** This strategy enables the use of the shoulder as a travel lane(s), known as Hard Shoulder Running (HSR) or temporary shoulder use, based on congestion levels during peak periods and in response to incidents or other conditions as warranted during non-peak periods.
2. **Dynamic Lane Use Control:** This strategy involves dynamically closing or opening of individual traffic lanes as warranted and providing advanced warning of the closure(s) (typically through dynamic lane control signs), in order to safely merge traffic into adjoining lanes.
3. **Dynamic Speed Limits[2]:** This strategy adjusts speed limits based on real-time traffic, roadway, and/or weather conditions. Dynamic speed limits can either be enforceable (regulatory) speed limits or recommended speed advisories, and they can be applied to an entire roadway segment or individual lanes.

[1] FHWA Active Traffic Management Website at http://www.ops.fhwa.dot.gov/atdm/approaches/atm.htm
[2] FHWA Variable Speed Limit website at http://safety.fhwa.dot.gov/speedmgt/vslimits/

4. **Adaptive Ramp Metering[3]:** This strategy consists of deploying traffic signal(s) on ramps to dynamically control the rate vehicles enter a freeway facility. This, in essence, smoothens the flow of traffic onto the mainline, allowing efficient use of existing freeway capacity.
5. **Dynamic Junction Control:** This strategy consists of dynamically allocating lane access on mainline and ramp lanes in interchange areas where high traffic volumes are present and the relative demand on the mainline and ramps change throughout the day.
6. **Dynamic Merge Control:** This strategy (also known as dynamic late merge or dynamic early merge) consists of dynamically managing the entry of vehicles into merge areas with a series of advisory messages (e.g., displayed on a dynamic message sign [DMS] or lane control sign) approaching the merge point that prepare motorists for an upcoming merge and encouraging or directing a consistent merging behavior.
7. **Adaptive Traffic Signal Control[4]:** This strategy continuously monitors arterial traffic conditions and the queuing at intersections and dynamically adjusts the signal timing to optimize one or more operational objectives (such as minimize overall delays).

Table 4: ATDM Strategies Implemented in Different Testbeds

Bundle	*ATDM Strategies*	*Pasadena*	*Dallas*	*Phoenix*	*Chicago*	*San Diego*
Active Traffic Management	Dynamic Shoulder Lanes	●	●		●	
	Dynamic Lane Use Control	●			●	●
	Dynamic Speed Limits	●			●	●
	Adaptive Ramp Metering	●	●	●		
	Dynamic Junction Control	●				
	Dynamic Merge Control					●
	Adaptive Traffic Signal Control	●	●	●	●	
Active Demand Management	Predictive Traveler Information		●	●	●	●
	Dynamic HOV/Managed Lanes					●
	Dynamic Routing	●	●	●	●	●
Active Parking Management	Dynamically Priced Parking		●			
Weather Related Strategies	Snow Emergency Parking				●	
	Preemption for Winter Maintenance				●	
	Snowplow Routing				●	
	Anti-Icing and Deicing Operations				●	

Active Demand Management (ADM) uses information and technology to dynamically manage demand, which could include redistributing travel to less congested times of day or routes, or reducing overall

[3] FHWA Ramp Metering website at http://www.ops.fhwa.dot.gov/freewaymgmt/ramp_metering/index.htm
[4] FHWA EDC-1 Adaptive Traffic Signal Control website at https://www.fhwa.dot.gov/innovation/everydaycounts/edc-1/asct.cfm

vehicle trips by influencing a mode choice[5]. ADM seeks to influence more fluid, daily travel choices to support more traditional, regular mode choice changes. The ADM strategies included in AMS project are:

1. **Predictive Traveler Information:** This strategy involves using a combination of real-time and historical transportation data to predict upcoming travel conditions and convey that information to traveler's pre-trip and en-route (such as in advance of strategic route choice locations) in an effort to influence travel behavior.
2. **Dynamic HOV/Managed Lanes[6]:** This strategy involves dynamically changing the qualifications for driving in a high-occupancy vehicle (HOV) lane(s). HOV lanes (also known as carpool lanes or diamond lanes) are restricted traffic lanes reserved at peak travel times or longer for exclusive use of vehicles with a driver and one or more passengers, including carpools, vanpools and transit buses.
3. **Dynamic Routing:** This strategy uses variable destination messaging to disseminate information to make better use of roadway capacity by directing motorists to less congested facilities.

Active Parking Management (APM) is the dynamic management of parking facilities in a region to optimize performance and utilization of those facilities while influencing travel behavior at various stages along the trip making process: i.e., from origin to destination[7]. Dynamically Priced Parking[8] was the APM strategy evaluated using Dallas Testbed. This strategy involves parking fees that are dynamically varied based on demand and availability to influence trip timing choice and parking facility or location choice in an effort to more efficiently balance parking supply and demand, reduce the negative impacts of travelers searching for parking, or to reduce traffic impacts associated with peak period trip making.

For details on how the applications are modeled, along with the full ATDM evaluation results, readers are encouraged to refer to 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.

[5] FHWA Active Demand Management website at http://www.ops.fhwa.dot.gov/atdm/approaches/adm.htm
[6] http://ops.fhwa.dot.gov/freewaymgmt/hov.htm
[7] FHWA Active Parking Management website at http://www.ops.fhwa.dot.gov/atdm/approaches/apm.htm
[8] http://www.ops.fhwa.dot.gov/congestionpricing/strategies/not_involving_tolls/parking_pricing.htm

Summary of Findings and Conclusions

In this section, the major findings and conclusions, with respect to ATDM evaluation, are summarized. The results are summarized and categorized according to the different types of research questions that were set forth by the USDOT. As mentioned, the full ATDM evaluation results are contained 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.

Synergies and Conflicts between ATDM Strategies

In this category, research questions evaluating the benefits of implementing ATDM strategies under combination or isolation are assessed for the different operational conditions to understand their synergistic pairs and conflicting pairs. The project team analyzed the impact of combining different strategies and implementing them together in an Active Traffic Management context and to find out synergistic and conflicting strategies. In order to assess the impact of combination of different ATDM strategies, the proposed strategies were assessed in isolation and in combination. It was found that these strategies are synergistic in nature, with combination of strategies showing better performance measures than isolation.

The results from the Dallas Testbed shows that all of the ATDM strategies improve the overall network performance during non-recurrent congestion scenario. Integrated ATDM strategies such as Dynamic Signal Timing, Dynamic Routing, Adaptive Ramp Metering and Dynamic Shoulder Lane could have significant benefits in terms of congestion reduction. All the applications are synergistic with each other with the exception of Dynamic Shoulder Lanes and Dynamic Routing, where we have seen a reduction in benefits provided by Dynamic Shoulder Lanes when implemented with Dynamic Routing. According to Table 5, Dynamic Shoulder Lanes strategy contributed to the highest benefits, in isolation and in combination. Most of the strategies were synergistic.

Table 5. Deploying Different ATDM Strategies on Dallas Testbed under Medium Demand and Low Incident Severity

Dynamic Signal Timing	***Dynamic Shoulder Lanes***	***Dynamic Ramp Metering***	***Dynamic Routing***	***Total Network Travel Time Savings (minutes) per Simulation Hour***
✓				223
	✓			48,630
		✓		10,923
	✓		✓	44,210
✓			✓	15,125
✓	✓		✓	53,871
✓		✓	✓	22,926
✓	✓	✓	✓	75,304

Based on the Phoenix Testbed analysis, it was seen that Adaptive Ramp Metering and Adaptive Signal Control was synergistic in the sense that together, they were able to reduce travel time on freeways as well as arterials. Dynamic Routing/Predictive Traveler Information System was shown to help travelers avoid bottlenecks and therefore considerably reduce their overall travel delays. Table 6 demonstrates the combined travel time savings when compared to individual strategies. Please note that an average of all operational conditions was used in this table for comparison.

Table 6. Deploying Different ATDM Strategies on the Phoenix Testbed

Oper. Cond.	*Adaptive Signal Control*	*Predictive Traveler Information*	*Adaptive Ramp Metering*	*Dynamic Route Guidance*	*Total Network Travel Time Savings (%)*
Average of all operational conditions	✓				15 %
			✓		14 %
	✓		✓		17 %
		✓		✓	45 %

Results from the Pasadena testbed indicates that Dynamic Speed Limit (DSL) and Queue Warn (QW) causes negative operational impact. These operational results are also reflected in the combination scenarios that include the DSL + QW strategy. In the later sections of this report, DSL + QW demonstrates significant safety improvement along the freeway where the strategy is used to distribute the isolated congestions and reducing any abrupt speed changes. Other strategy combinations without DSL + QW demonstrate synergy performance. Although the summary results shown in Table 7 below shows the isolated Hard Shoulder Running (HSR) and Dynamic Junction Control (DJC) operates with the best travel time savings when deployed in isolation, a more detailed analysis in the later sections show that under combination, the ATDM performances can yield almost similar travel time savings with only a fraction of the HSR + DJC activation time. Most travel time savings are shown from the freeway focused strategies compared to the arterial focused strategies.

Table 7. Deploying Different ATDM Strategies on the Pasadena Testbed

ARM	*DSC*	*HSR + DJC*	*DSL + QW*	*DRG*	*Network Travel Time Savings (Seconds)*	*Network Travel Time Savings (Percent)*
✓					64,663	2.45
	✓				20,322	0.77
		✓			205,075	7.77
			✓		-187,920	-7.12
				✓	55,425	2.10
	✓			✓	55,689	2.11
✓		✓			175,251	6.64
✓	✓	✓		✓	176,370	6.68
✓		✓	✓		-118,769	-4.50
✓	✓	✓	✓	✓	-105,573	-4.00

From the Chicago Testbed results, we can conclude that the low-medium penetration rate yields the most benefits for system performance, while the high penetration rate requires coordination in vehicle routing to achieve benefits. Therefore, for the ADM involved scenarios, we recommend the net penetration level could be set with the low-medium penetration rate. In terms of synergies and conflicts, it is observed that

(1) the ATM, ADM and the Weather-related strategies are synergistic for clear day and rain-to snow day scenarios; (2) the ATM, ADM and the Weather-related strategies are synergistic for high demand snow day scenarios and (3) the ATM and the Weather-related strategy may not be effective when applied jointly for the low demand, snow day scenario considered. The analyses showed the most beneficial strategy or combination of strategies.

In the San Diego Testbed, Dynamic Lane Use, Dynamic HOV/Managed Lanes and Dynamic Speed Limits show neither a significant conflict nor a significant synergy. The increase of congestion at the entrances and exits of the HOV lanes due to the increase of demand triggered by Dynamic Lane Use, Dynamic HOV/Managed Lanes is sensed by Dynamic Speed Limits, which extends the congestion over a larger space and longer time in order to avoid abrupt speed changes. Dynamic Lane Use and Dynamic HOV/Managed Lanes alone would produce better traffic performance. Dynamic Speed Limits alone would produce an increase of safety, but with a more pronounced reduction of throughput. The combined effect of having an increase of safety with less reduction of throughput can be interpreted as a good compromise, which can be considered a synergy. Dynamic Merge Control and Dynamic HOV/Managed Lanes show a synergy: Dynamic HOV/Managed Lanes compensate the slightly negative effect in terms of traffic performance caused by Dynamic Merge Control, which facilitates the entrance from SR-78, at the expense of penalizing traffic coming from the northern boundary of the I-15 corridor in the southbound direction. In other words, the decision to activate Dynamic Merge Control or not should be dictated purely by the need to reduce queueing on the ramp coming from SR-78 rather than by overall traffic performance benefits, and if Dynamic Merge Control is activated, Dynamic HOV/Managed Lanes would compensate its slightly negative impact on throughput. Dynamic Merge Control, Dynamic HOV/Managed Lanes and Dynamic Routing show also a synergy: Dynamic HOV/Managed Lanes and Dynamic Routing compensate the slightly negative effect in terms of traffic performance caused by Dynamic Merge Control, which facilitates the entrance from SR-78, at the expense of penalizing traffic coming from the northern boundary of the I-15 corridor in the southbound direction. Again, the decision to activate Dynamic Merge Control or not should be dictated purely by the need to reduce queueing on the ramp coming from SR-78 rather than by overall traffic performance benefits, and if Dynamic Merge Control is activated, Dynamic HOV/Managed Lanes and Dynamic Routing would compensate its slightly negative impact on throughput.

Operational Conditions, Modes and Facility Types

In this category, research questions evaluating the benefits of implementing ATDM strategies under different operational conditions are assessed. Each of the strategy was implemented under different operational condition of varying demand, weather conditions, and incident severity. In general, as illustrated in Figure 3, it was seen that the highest benefits are sought when the demand levels and the incident severity are lower. Under high demand and high incident severity, Dallas testbed showed an increase in travel time, while the Phoenix testbed showed lower benefits for ATDM strategies.

The four operational conditions that were assessed for Dallas testbed were: 1) medium to high demand level with low severity incident; 2) high demand level with low severity incident; 3) high demand level with medium severity incident; and 4) medium demand level with high severity incident. In all these cases, a dry weather condition is assumed. The four operational conditions that were assessed for Phoenix tested were: 1) high demand with low incident severity; 2) high demand with high incident severity; 3) low demand with low incident severity; and 4) high demand with medium incident severity and wet weather. The three operational conditions that were assessed for the Pasadena testbed were: 1) High demand, low to medium incident frequency/severity, medium freeway travel times; 2) Medium to high demand, high incident frequency/severity, medium to low freeway travel times; 3) High demand, medium incident frequency/severity, high corridor travel times. The six operational conditions that were assessed for Chicago Testbed were: 1) High AM High PM Demand, No Incidents, 2) High AM, High PM Demand, No

Incidents, Moderate Rain AM, Moderate Rain to Snow, 3) Medium AM, High PM Demand, No Incidents, Moderate Snow, 4) Low AM Medium PM Demand, No Incidents, Moderate Snow, 5) Medium AM High PM Demand, No Incidents, Moderate to Heavy Snow, and 6) Medium AM to High PM Demand, AM Incidents, Moderate Snow. The four operational conditions that were assessed for San Diego Testbed were: 1) Southbound (AM) +Medium Demand + Medium Incident, 2) Southbound (AM) +Medium Demand + High Incident, 3) Northbound (PM) +Medium Demand + High Incident, and 4) Northbound (PM) +Medium Demand + Medium Incident

Given that all the Dallas operational conditions represented dry weather conditions, the effectiveness of the ATDM strategies in reducing the network congestion associated with adverse weather conditions is also examined using a hypothetical scenario. ATDM strategies that combine the dynamic routing strategy and the dynamic signal timing strategy are considered in the analysis. Based on the obtained simulation results, ATDM strategies helps in alleviating the network congestion due to the adverse weather. Travel time savings of 163,480 minutes and 84,913 minutes were recorded for two different scenarios of weather impacts on the traffic flow, namely, reduced free-flow speed and a combination of reduced free-flow speed and jam density. The performance of ATDM strategies is examined considering a hypothetical evacuation scenario for Dallas testbed. A demand scenario is created in which evacuees are traveling from their work places to a pre-defined set of safe destinations in the northern section of the corridor. Different combinations of ATDM strategies are implemented to evaluate their effectiveness in reducing the congestion associated with the evacuation scenario. These strategies include demand management, dynamic signal timing, traveler information provision, dynamic shoulder lane, and tidal flow operation. The results indicate that effective demand management and the dynamic shoulder lane could significantly reduce the congestion associated with the evacuation process.

The Pasadena testbed was analyzed using a total of three different operational condition. The prediction parameters that were identified as sensitive for each strategy for prediction were further assessed for operational conditions 2 and 3. For Adaptive Ramp Metering (ARM), prediction horizon and prediction latency were assessed as sensitive parameters. The increase in prediction horizon for ARM shows a higher rate of improvement for OC 3 which has the highest freeway congestion, followed by OC 1 which has the second highest freeway congestion, and finally OC 2 which has the lowest. Prediction horizon for ARM shows close correlation with the freeway congestion. For prediction latency, the results show consistently a network travel time savings degradation for all three operational conditions under longer prediction latency. The best strategies for freeway segment also prove to be the most effective ones for the arterial roads under most operational conditions. OC 4, a snow-affected low demand scenario, is the only exceptional case. It is because the arterial roads have fewer lanes than the freeway. As discussed in section 7.3, it was assumed the snowplow would block one lane during service. That leads to a 50% capacity loss during plowing operation for the arterial roads with two lanes. However, the freeway segments have more lanes, and it is more resilient to the negative impact of the plowing operation. Therefore, the Weather-related strategy may bring more negative impact on the arterial road than the freeway segment. For Dynamic Signal Control (DSC), the identified sensitive prediction parameter is prediction accuracy. The network travel time shows negative travel time savings for cases where the prediction accuracy falls to 50%. For Hard Shoulder Running (HSR) and Dynamic Junction Control (DJC) strategy, there were no prediction parameters that were identified as sensitive. Comparing the travel time savings for each operational condition, OC 3 which has the highest freeway congestion yields the highest travel time savings, followed by OC 1 which has the second highest freeway congestion, followed by OC 2. There is a strong correlation of travel time savings between freeway focused strategies with freeway level of congestion. For Dynamic Speed Limits and Queue Warning (QW) strategy, there is no prediction parameter because TRANSIMS is not used to evaluate this strategy. This strategy only differs with traveler compliance parameter. The trends show that with the increase in traveler compliance, the difference in both spatial and temporal speed difference on the freeway is reduced. The trends for the temporal speed difference for OC3 which has the highest freeway congestion shows very small reduction in temporal speed difference due to the oversaturated freeway. The reduction in spatial and temporal speed difference yields safety improvements by reducing abrupt changes in speeds by distributing them over a longer segment of the freeway. The dispersion of congestion also reduces the overall network travel time savings.

For the Chicago Testbed, it can be concluded that ADM provides the most benefits for operational conditions without snow effect, i.e. clear day and rain-to-snow day. The weather-related strategy generates the most benefits for snow-affected and high demand operational conditions. The ADM strategy yields the most improvement for the snow-affected and low demand operational conditions or the incident-mixed snow scenario. If the strategy is implemented for the entire horizon or within some specific period, like the afternoon peak hours with an incident, it provides the most benefit to the corridor. The dynamic snowplow routing plan may be less preferred than the static routing plan under low demand (off peak hours) operational conditions when the network is less congested. In order to serve the most important links first, the dynamic plan has more deadheading trips. These deadheading trips would reduce the link capacity and impose a negative impact to the traffic. Under the low demand, less congested scenarios, the benefit generated by the dynamic plan might be offset by the negative impact associated with the extra deadheading trips. One should pay close attention to the operational conditions when select which plan to deploy.

For the San Diego Testbed, Dynamic Lane Use and Dynamic HOV/Managed Lanes are effective only in congested situations. Additionally, the location of incidents and bottlenecks may reduce the effectiveness of this ATDM strategy, because if the congestion caused by them affects the access points to the HOV lanes, vehicles have difficulty in reaching the additional lane that allows bypassing the bottlenecks. Dynamic Speed Limits reduce the speed change between consecutive road segments, at the expense of reducing the overall speed along the corridor. With little congestion, the impact in terms of increase of delay is negligible, while as congestion increases the increase of delay increases, too, and is coupled with a slight decrease of throughput. Dynamic Merge Control facilitates the entrance from SR-78, at the expense of penalizing traffic coming from the northern boundary of the I-15 corridor in the southbound direction. When the I-15 traffic is lower than that entering from SR-78, this strategy has a positive overall impact on the corridor, because it reduces conflicts at the merge. Predictive Traveler Information with Dynamic Routing is more effective with higher demand and with more severe incidents. The benefit is evident if we focus on the I-15 corridor, while if we adopt a network-wide perspective, we can notice that in some operational condition the positive impact on the speed along the I-15 corridor is in fact counterbalanced by an overall slight increase of travel time because or rerouting along the arterials.

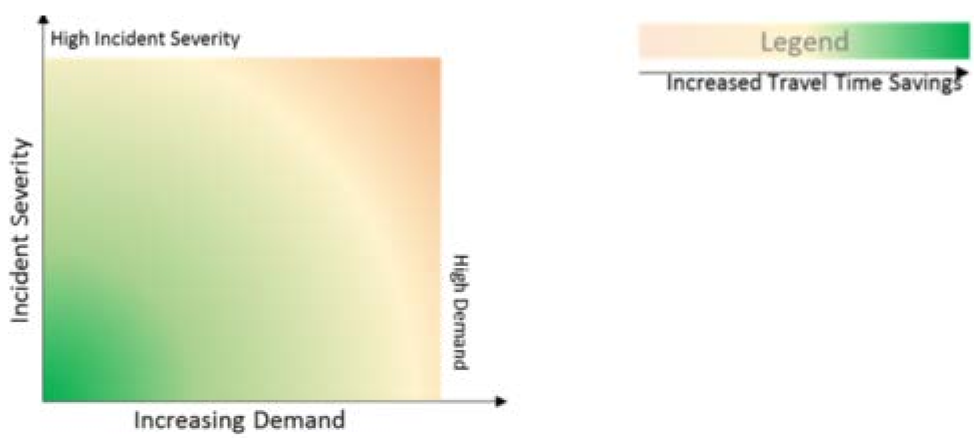


Figure 3. Generalized Impact of Demand Levels and Incident Severity on ATDM Implementation [Source: Booz Allen]

Prediction and Active Management

In this category, research questions evaluating the benefits of implementing ATDM strategies under different prediction attributes are summarized. Primarily two prediction parameters were assessed – prediction accuracy and prediction horizon. Prediction accuracy represents the degree to which the traffic state prediction is accurate, whereas, prediction horizon represents the time-horizon in future to which the traffic state prediction is made. As shown in Figure 4, increased prediction accuracy and shorted prediction horizon could improve the mobility benefits from ATDM implementation.

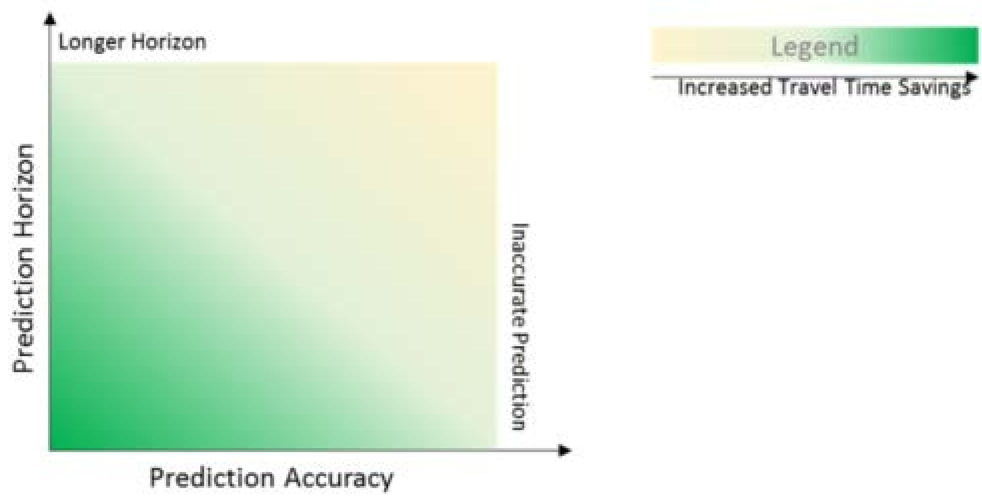


Figure 4. Generalized Impact of Prediction Horizon and Accuracy on Travel Time Savings due to ATDM Implementation

Prediction Accuracy

For the Dallas Testbed, a superior network performance is obtained when perfect demand prediction is assumed. The network performance gradually worsens with the increase in the level of demand prediction error. For example, savings of 7,806 and 12,341 minutes are recorded for the scenarios with 5% demand prediction error in the underestimation and overestimation cases, respectively. As the error increases to 10%, the savings are reduced to 2,252 and 3,298 minutes, respectively. For the Phoenix Testbed, it is found that the performance of adaptive ramp metering is very sensitive to the prediction accuracy. After certain system errors are superimposed to the prediction accuracy, the adaptive ramp metering will be under or overestimated in different scenarios. For the Pasadena testbed, prediction accuracy has the most significant effect on arterial focused strategies when selecting the appropriate plans. The operational results for scenarios where the prediction accuracy falls to 50% demonstrates noticeable operational deteriorations for DSC and DRG strategies. DSC strategy even shows negative operational benefits when the prediction accuracy falls to 50%. The freeway focused strategies, ARM and HSR + DJC, shows small operational changes between 100%, 90%, and 50% prediction accuracy.

Prediction Horizon

The network performance generally improves as the length of the prediction horizon increases. In other words, positive correlation is observed between increasing the length of prediction horizon, and total travel time/ savings in the network. For example, Dallas testbed was evaluated using different prediction horizons. Using 15-minute prediction horizon resulted in less travel time savings compared to that obtained for the scenario in which 60-minute prediction horizon is considered. For the 15-minute prediction horizon, a saving of 9,114 minutes is recorded. This saving increased to 21,586 minutes when the prediction horizon increased to 60 minutes. For the Phoenix Testbed, freeway travel time was assessed with Adaptive Ramp Metering under different configurations. A longer prediction horizon resulted in a slight reduction in the average travel times and the impact of communication latency on the traffic mobility was also marginal (less than 1%). For the Pasadena testbed, longer prediction horizon yields better operational performance for all strategies. The impacts of prediction horizon is most noticeable for freeway focused strategies, ARM and HSR + DJC, when the prediction horizon is increased from 30-minutes to 60-minutes. Prediction horizon is more noticeable for arterial focused strategies when prediction horizon is increased from 15-minutes to 30-minutes. For the Chicago Testbed, clear weather scenarios prefer prediction accuracy with a shorter prediction horizon and roll period for the peak hours when travel demand is high, while the snow-affected scenarios prefer a longer prediction horizon, and are sensitive to accuracy and latency. More frequent updates with shorter roll periods of the predictive strategies may lead to instabilities in system performance. As with the hypothetical scenario, i.e. the combined incident-snow scenario reaches a trade-off state between accuracy and prediction horizon, and is not particularly sensitive to latency due to incident-related delay.

Prediction Latency and Coverage Trade-Offs

In this category, the effectiveness of ATDM under different prediction latencies and geographic coverage were assessed. Prediction latency represents the delay in running the prediction algorithm and implementing the appropriate response plan, and the coverage represents the geographic area that is within the prediction scope. The Dallas, Phoenix, Pasadena and Chicago testbeds were used to assess these.

For the Dallas Testbed, promptly responding to the incident (zero latency) helped in alleviating the congestion, and achieving considerable saving in total network travel time. On the other hand, as the latency increases, the system does not respond to the congestion for longer period. By the time the plan is generated, its effectiveness in alleviating the congestion reduces. For example, a saving of 15,125 minutes is recorded for the scenario with zero latency. As the latency extends to 20-minutes, an increase in the travel time, compared to the baseline scenario, is observed implying that the scheme is no longer effective because of the change in the network conditions. For limited area coverage, the recommended ATDM strategies fail to significantly achieve significant travel time savings. On the other hand, as the coverage expands, more information on the congestion pattern in the area is obtained and also more traffic control devices could be included (traffic signals and DMSs) to developing the generated ATDM recommendations. Thus, more significant improvement in the network performance can be achieved. Based on the obtained simulation results, extending the covered area provides more total network travel time saving. For example, travel time saving of 9,930 minutes is obtained for the spatial coverage of two miles. The saving is increased to 16,460 minutes as the coverage is extended to four miles.

Similar analysis with Phoenix Testbed with variable prediction latencies showed that as latencies go up, effectiveness of ATDM Strategies go down. Specifically, two traffic conditions were evaluated and the latencies were set as 5 minutes and 10 minutes for adaptive ramp metering strategies. The evaluation results show up 4% reduction of freeway travel times along the segment if the prediction latency was reduced from 10 min to 5 min.

The Pasadena testbed has demonstrated that prediction latency has a significant effect on arterial strategies compared to freeway strategies. Though ARM is typically considered a freeway focused strategy, it is also the transition from aterial collector roads to and from the freeway. The ARM does show degradation with increase in prediction latency from 5-minutes to 10-minutes. This degradation is likely due to vehicles metered at a rate that was recommended for a traffic state 10-minutes before. HSR + DJC strategy shows negligeble changes between 5-minute to 10-minute prediction latency.

As far as the Chicago Testbed was concerned, the sensitivity of system performance to the specific operational settings implemented depends on the particular operational conditions experienced on a given day. In other words, the best settings are one operational condition are not necessarily best under all operational conditions. Different from OC1, OC3 prefers longer prediction horizon and roll period, and is only sensitive to latency for the evening peak hours. Though the predictive information is updated more frequently with a short roll period, it may still lead to an unstable system as vehicles may change routes very often. OC6 reaches a trade-off state between short roll period and long prediction horizon., and it is not sensitive to latency due to incident-related delay. By and large, the use of the predictive approach ensures that the deployed strategies result in improved overall network performance. The improvements resulting from application of a particular strategy, or bundle of strategies, depend on selecting appropriate operational settings. The operational settings include net penetration rate and prediction/latency features, and the combination of strategies.

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

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

[FHWA-JPO-16-386]

U.S. Department of Transportation