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

Summary Report for the Chicago Testbed

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16. Abstract

The primary objective of this project is to develop multiple simulation testbeds and transportation models to evaluate the impacts of Connected Vehicle Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) strategies. This report summarizes the evaluations conducted on the Chicago Testbed. The report summarizes the modeling aspects of the testbed, including the different operational conditions as well as the experimental results for the various weather and traffic conditions included in the analysis. The results identify synergistic ATDM and DMA strategies that work well together, and others that may work best when taken individually. Sensitivities of the strategies' impacts to various implementation aspects of the predictive strategies are investigated under different operational conditions.

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AMS 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. 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

Specifically, this report summarizes the testbed development and analysis activities that were performed as part of the Chicago Testbed. The strategies tested include Active Demand Management (ADM) and Active Traffic Management (ATM) strategies that are part of the ATDM strategy bundles, as well as weather-related strategies applicable to the Chicago testbed. The ATM strategies analyzed are Dynamic Shoulder Lanes, Dynamic Lane Use Control, Dynamic Speed Limits, and Adaptive Traffic Signal Control. The ADM Strategies consist of Predictive Traveler Information and Dynamic Routing. The Weather-related Strategies include Snow Emergency Parking Management, Traffic Signal Priority for Winter Maintenance Vehicles, Snowplow Routing, and Anti-Icing and Deicing Operations. Finally, the Speed Harmonization application, part of the INFLO Bundle for the DMA applications, was coded, implemented, and tested in the Chicago Testbed. In order to evaluate the effectiveness of these strategies that use connected vehicle information, various operational conditions are extracted and defined with a data-driven method that looked at the historical traffic flow data, weather data and incident data. The operational conditions in the Chicago Testbed were clustered into six types, each corresponding to a specific daily scenario with different levels of travel demand, patterns of weather events and occurrence of incidents.

The study addressed important research questions regarding the effectiveness of specific ATDM and DMA strategies under different operational conditions in a simulated testbed environment. The research questions fall under the following categories: (1) impact on application performance of different facility types under varied operational conditions, (2) synergies and conflicts among applications, (3) impact of prediction accuracy and communication latency, and (4) impact of connected vehicle data versus legacy systems data.

Chicago Testbed Overview

The Chicago Testbed network was extracted from the entire Chicago Metropolitan Area to enhance the estimation and prediction performance during the implementation procedure. The 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. Figure 1 depicts the original network for Chicago metropolitan area and the extracted Testbed network.

Figure 1: Map of the Extracted Network of Chicago [Source: NWU]

The extracted network for Chicago included 150 freeway links, 47 highways, 247 ramps (including 59 metered ramps) and over 4300 arterial links. The testbed also had almost 545 signalized intersections and simulated 24-hour demand at a 5-minute resolution, totaling over a million vehicles in each simulation period. The DTA simulation model was coded in DYNASMART, a mesoscopic simulation-based intelligent transportation network planning tool with both offline and online model options. Offline model (DYNASMART-P) includes dynamic network analysis and evaluation, and online model (DYNASMART-X) adds short-term and long-term prediction capabilities. In this study, DYNASMART-X is adopted as the TrEPS model for demand and state prediction.

Figure 2 illustrates the overall modeling framework. The framework adopts a rolling horizon approach, which integrates: (1) a traffic network estimation model that emulates the real-world traffic conditions; (2) a traffic network prediction model that predicts the traffic demand and network performance given prevailing traffic conditions; and (3) a decision support system that is responsible for evaluating the estimated and predicted traffic states and generating or adjusting traffic management operations.

Both simulation and evaluation are conducted with a moving horizon to predict and feedback the network performance. As illustrated in Figure 2, the network performance that covers a pre-defined horizon (e.g., 30 minutes) is continuously collected and transferred every roll period (e.g., 5 minutes). The offline simulation of real world does not stop and wait for the feedback from online prediction, and thus a latency may occur due to the calculation time and information transfer. At the interval that the offline model receives predictive information, the system evaluation and decision making modules are triggered to generate appropriate adjustment for the current traffic management strategies. The adjustments include updating route choices for ADM strategies, changing the service direction on reversible lanes or opening shoulder lanes for ATM strategies, and generating new snowplow route when weather-related strategies are triggered.

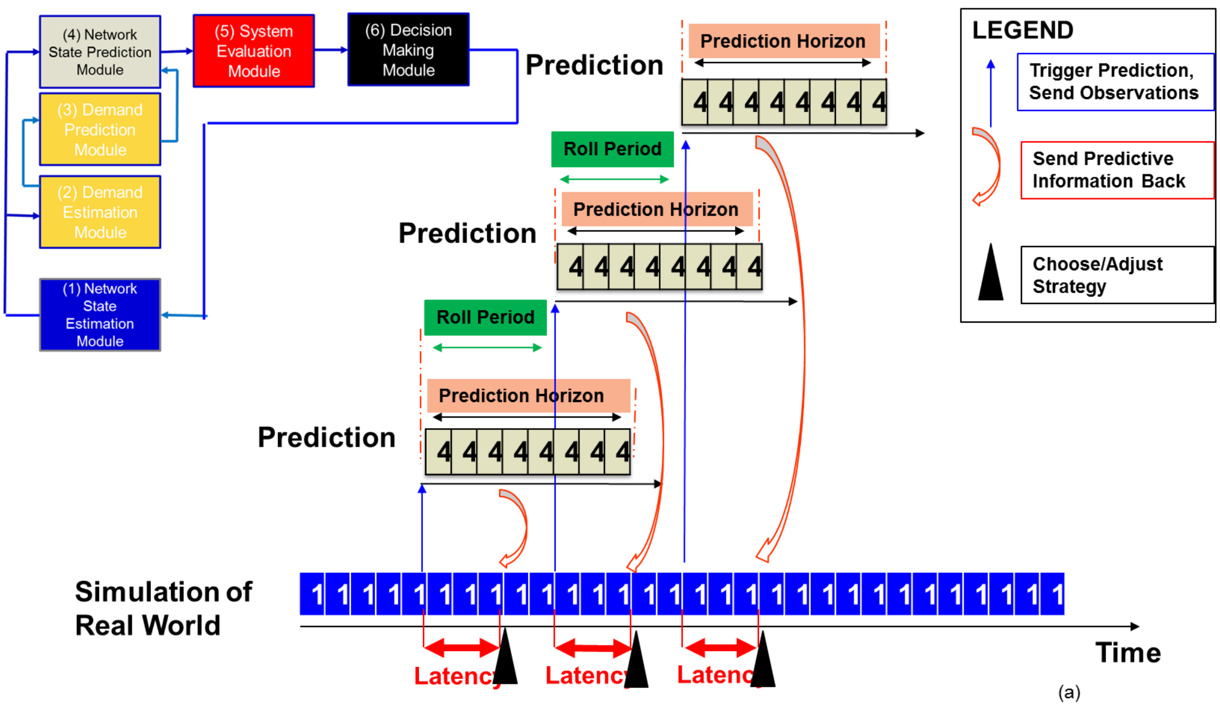

Figure 2. Framework for Modeling Traffic Network Management System [Source: NWU]

Full details on the evaluation approach and modeling methodology is provided in Mahmassani et al., *Analysis, Modeling, and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs — Analysis Plan for the Chicago Testbed*, FHWA-JPO-16-374, June 2016.

Summary of Operational Conditions

A cluster analysis was performed to determine the main operational conditions on the Chicago Testbed. Table 2 provides a description of the selected clusters representing operational scenarios for the Chicago Testbed. The table includes the base case under clear weather and other weather-affected traffic cases under rain and snow. Since incident data is not available with the needed spatial and temporal coverage for the cluster analysis, OC 6 was designated as a hypothetical weather-incident mixed scenario. The demand and weather pattern of OC 6 follows OC 3; based on that, the hypothetical weather-induced incidents are introduced.

Table 2. Operational Conditions Selected for the Chicago Testbed [Source: NWU]

Variables	*Number of Daily Records*	*Records (%)*	*Selected Date*	*Cluster Description*			
All	321	100%	-	AM Peak	PM Peak	Incident	Daily Weather
OC 1	67	21%	22-Apr-09	High Demand	High Demand	None	Clear / No Rain, No Snow
OC 2	5	2%	18-Feb-09	High Demand	High Demand	None	Moderate/Heavy Rain Changing to Moderate Snow
OC 3	3	1%	22-Dec-09	Medium Demand	High Demand	None	Moderate Snow
OC 4	4	1%	19-Dec-09	Low Demand	Medium	None	Moderate Snow
OC 5	1	1%	9-Jan-09	Medium Demand	High Demand	None	Moderate and Heavy Snow
OC 6 (hypothetical)	-	-	-	Medium Demand	High Demand	AM Peak	Moderate Snow

Figure 3 shows the temporal traffic demand patterns for the different operational conditions over the 24-hour period. Table 3 presents the details on baseline performance of the network under different operational conditions in terms of average travel time, average stop time and average trip distance. It also shows the generated vehicles according to the calibrated demand profiles. As mentioned earlier OC 3 and OC 6 share the demand profile with the same number of vehicle generated in the network within the 24-hour simulation horizon.

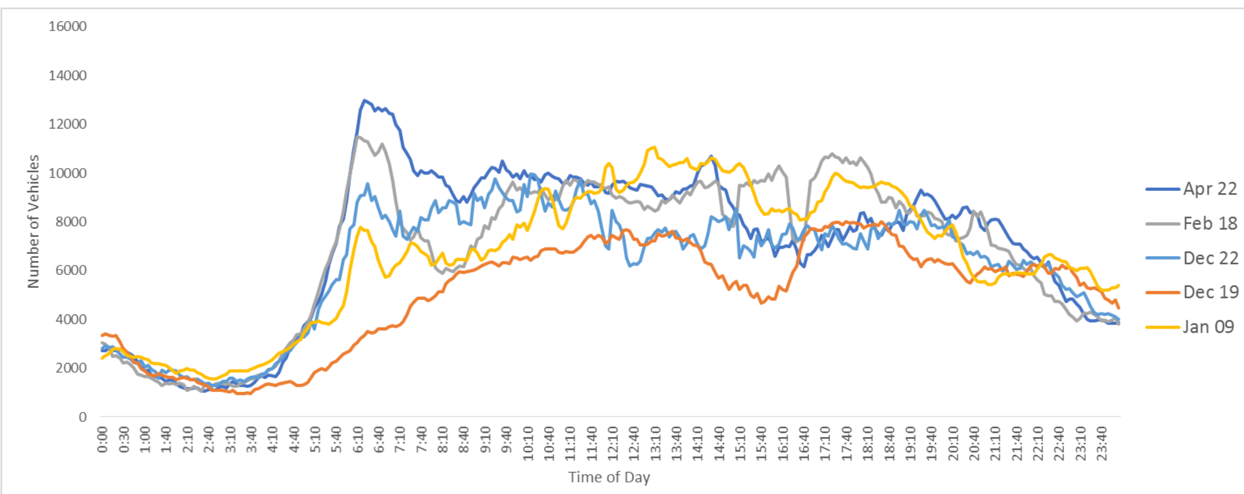

Figure 3. Temporal Profiles of Selected Scenarios for Traffic Flow [Source: NWU]

Table 3. Baseline Scenarios Under Different Operational Conditions [Source: NWU]

	OC 1	OC 2	OC 3	OC 4	OC 5	OC 6
Average Travel Time (min)	16.26	16.53	18.63	14.09	19.71	20.34
Average Stop Time (min)	4.67	5.86	5.90	3.35	6.33	6.44
Average Trip Distance (mile)	5.73	5.57	5.50	5.18	5.49	5.50
Generated Vehicles	1,191,575	1,065,901	986,978	902,225	1,076,431	986,978

Full details on the evaluation approach and modeling methodology is provided in Mahmassani et al., *Analysis, Modeling, and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs — Calibration Report for the Chicago Testbed*, FHWA-JPO-16-381, December 2016.

DMA Applications and ATDM Strategies Modeled

The Dynamic Mobility Application implemented and evaluated in this project is Speed Harmonization (SPD-HARM) within the INFLO Bundle.

The active transportation management concept is the capability of 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. Before implementing in real world, the ATDM strategies require logical design and evaluation in a virtual simulated environment. The Chicago Testbed focused on the following ATDM applications:

1. Active Traffic Management:
    a. Dynamic Shoulder Lanes
    b. Dynamic Lane Use Control
    c. Dynamic Speed Limits (Basic)
    d. Adaptive Traffic Signal Control
2. Active Demand Management:
    a. Predictive Traveler Information
    b. Dynamic Routing
3. Weather-Related Strategies:
    a. Snow Emergency Parking Management
    b. Traffic Signal Priority for Winter Maintenance Vehicles
    c. Snowplow Routing
    d. Anti-icing and Deicing Operations

A description of the application's assumptions and logic is provided for each of the strategy in Table 4.

Table 4. ATDM Strategy Modeling Logic [Source: NWU]

Strategy Bundle	*Strategy*	*Modeling Logic*	
		Description	*Logic*
Active Demand Management bundle	**Predictive Traveler Information**	DYNASMART-X implemented a simulation-based short-term traffic network state prediction module, which runs in a rolling horizon framework. The prediction module provides information on the time-dependent link travel times for a pre-defined future horizon (e.g., 30 minutes). These predicted travel times were used to develop different predictive traveler information strategies.	- Apply Predicted Information from the current interval for a pre-defined horizon - Generate Predicted Travel Times for all links from the current interval for the predicted horizon - Generate Predicted Turn Penalty for possible movements at each link from the current interval for the predicted horizon - Transfer the Predicted Information to the simulator and trigger Dynamic Routing.

Strategy Bundle	Strategy	Modeling Logic	
		Description	Logic
	Dynamic Routing	Travelers with access to predictive traveler information were given the ability to switch to new routes in DYNASMART. These drivers compare their current routes with the new routes. Drivers are assumed to switch to the new route if the difference in the travel time is greater than individual's pre-defined threshold. The route diversion could be occurring at any junction along their routes.	Assumptions: - The percentage of travelers with access to predictive individual information and are willing to change the route, namely the net penetration rate of Active Demand Management bundle, can be specified by user. Logic: - At each shortest path update interval, the shortest paths from the current node to the destinations of all vehicles are generated. - For travelers with access to information, if the travel time (cost) of the new shortest path is better than the time of the current path by a pre-defined threshold, the traveler is assumed to switch to the new path.

Active Traffic Management Strategies	**Dynamic Shoulder Lane**	DYNASMART represents highway links at link level with a set of characteristics, including lane number, traffic flow model and capacity. To model the dynamic lane shoulder strategy, each shoulder lane is modeled in the network separately with the normal lanes.
		This shoulder lane was configured to serve the traffic as long as the strategy is active (e.g., peak period, etc.). There is flag to tell whether the shoulder lane is active or not in order to keep the original network characteristics.
			if (time to start lane strategy){
			for (freeway shoulder links){
			- Update VMS at each ramp to tell shoulder is open
			- Keep the other characteristics the same
			- Turn the flag on
			}
			}
			if (time to terminate lane strategy){
			for (freeway shoulder links){
			- Update VMS at each ramp to tell shoulder is close
			- Keep the other characteristics the same
			- Turn the flag off
			}
			}

	Dynamic Reversible Lane	DYNASMART represents highway links at link level with a set of characteristics, including lane number and capacity. To model the Dynamic Reversible Lane, the VMS is adopted to indicate the service direction of the reversible lane. The reversible lanes are modeled as two sets of connected (and continuous) links in the network and only one is open to serve the network. This reversible express lane was configured to serve the	At each simulation interval
			If (any onramp to reversible lane is open) {
			- calculate the clearance time
			- if (current time +clearance time >= schedule time to switch direction){
			Close onramps
			Flush vehicles to exit
			}
			}
			Else {

Strategy Bundle	Strategy	Modeling Logic	
		Description	Logic

		traffic as long as the strategy is active (according to the Kennedy Expressway Schedule).
		The time to switch the direction is predicted in the DYNASMART-X. To ensure the safety of switch service direction, a clearance time and "flush" vehicle mechanism was adopted to clear and close the current links. If there are no vehicles on the current link, the VMS would tell the drivers that the service direction is switched.
			If (time to open reversible lane){
			If (any vehicles on the opposite directions){
			Flush vehicles to exit
			}
			Else {
			Open Onramps
			}
			}
			}

	Dynamic Speed Limits	DYNASMART represents highway links at link level with a set of characteristics, including posted speed limit for and posted speed limit adjustment margin. To model the dynamic speed limit, the speed limit adjustment margin of selected links could be changed. This dynamic speed limit would be configured to serve the traffic as long as the strategy is active (e.g., peak period, heavy snow, etc.). There is flag for selected links to tell whether the strategy is active or not in order to keep the original link characteristics.	if (dynamic speed limits strategy starts){
			for (selected freeway links){
			- Change the speed limit margin according to the speed limit reduction or increase
			- Keep the other characteristics the same
			- Turn the flag on
			}
			}
			if (shoulder lane strategy terminates){
			for (selected freeway links){
			- Change the speed limit margin back to original value according to the speed limit reduction or increase
			- Keep the other characteristics the same
			- Turn the flag off
			}
			}

	Adaptive Traffic Signal Control	DYNASMART is capable of simulating both pre-timed signal plan and the actuated signal plan. Different signal timing plans can be specified for any signalized intersection within different time periods during the simulation horizon. A signal control scheme is described in terms of its activation start and end times for all intersections considered in this scheme. Any given signal can have different plans in terms of max and min green times, offsets during the simulation horizon. These schemes are implemented in the simulation based on their activation times. Offsets can be specified for pre-	Assumption: Each control scheme is defined by its start and end times. All junctions in this scheme are defined in terms of their new timing plans.
			if (Control Scheme is activated){
			for (Junctions in this scheme){
			for (all signal phases at this junction){
			GreenInterval = newGreen
			RedInterval = newRed
			Offset = newOffset
			}
			}
			}

Strategy Bundle	Strategy	Modeling Logic	
		Description	Logic
		timed as well as the dual ring control plans. The offsets can vary over different time periods to accommodate the traffic flow better.	

Weather-related Strategies	**Snow Emergency Parking Management**	The emergency parking ban on arterial roads is enforced to create enough space for snowplow operation. The emergency parking ban goes into effect on certain arterial roads when at least 2 inches of snow falls on the street. The links that are subjected to parking ban are determined by the city of Chicago. Within the modeling framework, if the parking ban is violated on any specific link, it cannot be accessed and plowed by the snowplow.	Assumption: If snow emergency parking ban is not enforced on a link, then it cannot be accessed by the snowplow.
			for (t in simulation time interval){
			snowdepth=snowdepth+snowrate(t)
			if (max snow depth> 2 inches){
			Triger parking ban
			For (all arterial roads with parking ban){
			If (the parking ban is not enforced on a link){
			Remove the link from the network available to the snowplow
			}
			}
			}
			}

	Traffic Signal Preemption for Winter Maintenance Vehicles	It is assumed that the link travel speed and capacity depend on the depth of the snow accumulated on the pavement surface. Once a link is plowed, the snow depth on that link becomes 0 and the speed and capacity restores to the original states. The routing plan of the snowplows are determined by solving an optimization model with an objective function that maximizes the difference between the access benefit and the operation cost. The problem is solved with a cluster first, routing the second method. During the snowplow operation, a link's capacity and density will be affected. It was assumed that a lane is blocked by the maintenance vehicle during plowing and cannot be accessed by other vehicles.	Assumption: The link capacity and speed depends on the snow depth accumulated on the road surface
			For (t in simulation time interval){
			For (all links in network){
			Update LinkSnowDepth
			Update link capacity and link velocity
			If (plow finish serving the link at t){
			Linkservedtime=t
			LinkSnowDepth=0
			Restore the link capacity
			}
			If (snowplow is traversing on a link at time t){
			Update link capacity
			}
			}
			}

	Snowplow Routing	The plowing and deicing/anti-icing operation are conducted in conjunction. Snowplows spread the chemicals to the road surface while servicing the road. Chemicals are spread to the road surface to slow the snow accumulation rate. The	Initial Linkservedtime=infinite
			For (t in simulation time interval){
			For (all links in network){
			If (plow finish serving the link at t){
			Linkservedtime=t
			}

Strategy Bundle	Strategy	Modeling Logic	
		Description	Logic

		performance of chemical is subject to various factors such as air temperature, humidity, wind, solar radiation, rate and type of precipitation, pavement type as well as traffic condition. It is hard, if not impossible, to calculate the actual performance of chemicals on the fields without conducting field tests. For this research, it is assumed that the chemicals can keep the road free of ice for one hour.	If (Linkservedtime <= t <= Linkservedtime+60 mins){
			Snowdepth remains the same
			}
			Else{
			Snowdepth=snowdepth+snowrate(t)
			}
			}
			}

	Anti-icing and Deicing Operations	The emergency parking ban on arterial roads is enforced to create enough space for snowplow operation. The emergency parking ban goes into effect on certain arterial roads when at least 2 inches of snow falls on the street. The links that are subjected to parking ban are determined by the city of Chicago. Within the modeling framework, if the parking ban is violated on any specific link, then it cannot be accessed and plowed by the snowplow.	Assumption: snow will not accumulate on the road surface if the anti-icing operation was conducted less than an hour ago
			for (t in simulation time interval){
			for (link i in the network){
			if (anti-icing treament was conducted less than 1 hour ago){
			snowdepth=snowdepth
			}else{
			snowdepth=snowdepth+snowrate(t)
			}
			update capacity reduction ratio of link i at time t
			update speed reduction ratio of link i at time t
			if (link i is plowed and is treated with anti-icing chemical at time t){
			link anti-icing flag=1 //anti-icing effect
			snowdepth=0
			update capacity reduction ratio of link i at time t
			update speed reduction ratio of link i at time t
			}
			}
			}

Strategy Bundle	Strategy	Modeling Logic	
		Description	Logic

DMA	**Speed Harmonization**	The current Speed Harmonization model in DYNASMART updates the link speed limit based on the current weather condition (different snow/rain intensities).
		This system was updated to include traffic data. The updated model checks for shockwave occurrence every six seconds. Once a shockwave is identified, the model updates the speed limit, based on the shockwave characteristics, to resolve the shockwave. Note that the speed harmonization logic (e.g. SPECIALIST or any other logic) is external to DYNASMART.
			For (selected freeway links)
			{
			If (shockwave is identified based on the decision tree)
			{
			Update the speed limit upstream of the shockwave based on the speed harmonization logic.
			}
			}

Full details on the evaluation approach and modeling methodology is provided in Mahmassani et al., *Analysis, Modeling, and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs — Evaluation Report for the Chicago Testbed*, FHWA-JPO-16-387, March 2017.

Summary of Findings and Conclusions

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

Connected Vehicle Technology Versus Legacy Systems

This analysis was primarily aimed at answering the impact of data from CV technology on the DMA applications versus the impact of data from legacy systems. To capture this impact, three scenarios were considered: (1) impact of connected environment under low, medium and high demands and under 10%, 50% and 90% market penetrations, (2) impact of speed harmonization without connectivity on the different operational conditions, and (3) impact of speed harmonization in a connected environment for different operational conditions and under different market penetrations. In this study, flow characteristics in a connected environment were identified based on a microscopic simulation tool. The calibrated speed-density relations were utilized in a mesoscopic simulation tool to study the network-wide effects of connected vehicles. A summary of the impacts is provided in Table 5.

Table 5. Impact of Connected Vehicles and Speed Harmonization on Throughput [Source: NWU]

Scenario	*Operational Condition*	*Benefit*
Only Connected Vehicle (CV)	---------	The network achieves increase in the throughput and gets more reliable with the increase in the MPR of connected vehicles
Speed Harmonization without CV	All scenarios	In all OC's except OC4, system achieves up to 1.5% increase in throughput during morning, mid-day and evening times. Impact is marginal in OC4 because the demand level is low which means that there are not many vehicles to address
Speed Harmonization with CV	All scenarios	Speed harmonization in a connected environment provides a slight improvement in the throughput. Travel speed increases and gets more reliable as the variation in speed was reduced.

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

Synergies and Conflicts Between Applications and 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. Additionally, the impact of different market penetration rates was assessed for individual and combination of strategies. In order to assess the synergies and conflicts, experimental scenarios provided in Table 6 were simulated and the results were evaluated.

Table 6. Experimental Scenarios for Assessing Synergies and Conflicts [Source: NWU]

Experiment Factor	Tests	Strategy	Net Penetration Level	Roll	Horizon	Latency
Percentage of vehicles that have the access to predictive information for ADM	OC1 (Clear Day)	Doing nothing	0 %	-	-	-
		ADM	30 %	5	30	0
		ADM	50 %	5	30	0
Combination of strategies	OC1 (Clear Day); OC2 (Rain to Snow)	Do nothing	0 %	-	-	-
		ADM	30%	5	30	0
		ATM	0%	5	30	0
		ADM +ATM	30%	5	30	0
	OC3, 4 (Moderate Snow); OC5 (Heavy Snow); OC6 (Moderate Snow + Incident)	Do nothing	0 %	-	-	-
		ADM	30%	5	30	0
		ATM	30%	5	30	0
		WR	30%	5	30	0
		ADM + WS	30%	5	30	0
		ADM +ATM + WS	30%	5	30	0

From the simulation 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. In terms of synergies and conflicts, a summary of the results for implementing strategies in isolation and combination is provided in Table 7. 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 strategies 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.

Table 7. Impact of Strategies in Isolation and Combination Under Different Operational Conditions [Source: NWU]

Strategy	*Operational Condition*	*Benefit*
Active Demand Management (ADM)	Clear Day	Improve network throughput by up to 1.57%
	Rain to Snow Scenario	Improve network throughput by up to 2.58%
	Snow with medium-high demand	Improve network throughput by up to 2.85%
Active Traffic Management (ATM)	Clear Day	Improve network throughput by up to 1.75%
	Rain to Snow Scenario	Improve network throughput by up to 1.43%
	Snow with medium-high demand	Improve network throughput by up to 1.98%
Weather Related Strategies (WS)	Snow with medium-high demand	Improve network throughput by up to 2.86%
	Snow with medium-low demand	Improve network throughput by about 0.36%
ADM+ ATM	Clear Day	Improve network throughput by up to 4.70%
	Rain to Snow Scenario	Improve network throughput by up to 4.78%
ADM+ WS	Snow with medium-high demand	Improve network throughput by up to 4.16%
	Snow with medium-low demand	Improve network throughput by about 0.63%
	Snow-Incident scenario	Improve network throughput by up to 4.04%
ADM+ WS+ ATM	Snow with medium-high demand	Improve network throughput by up to 6.63%
	Snow with medium-low demand	Improve network throughput by about 0.25%
	Snow-Incident scenario	Improve network throughput by up to 3.96%

Prediction and Active Management

As far as the prediction characteristics are concerned, the three parameters that were assessed were prediction horizon, prediction accuracy and prediction latency. Prediction horizon is defined as the time into future to which a prediction is made. Prediction accuracy is defined in terms of the roll period which defines the data update frequency of the prediction system with the simulation. Lastly, prediction latency is defined as the communication latency with which strategies are implemented in the DYNASMART-X.

Table 8 shows the experimental scenarios that were used to assess the different prediction characteristics.

Table 8. Experimental Scenarios for Assessing Prediction Characteristics [Source: NWU]

Experiment Factor	Tests	Strategy	Net Penetration Level	Roll	Horizon	Latency
Roll Period (Prediction Accuracy)	OC1 (Clear Day)	Do nothing	0 %	-	-	-
		ADM + ATM	30%	5	30	0
		ADM + ATM	30%	15	30	0
Prediction Horizon (Prediction Accuracy)	OC1 (Clear Day)	Do nothing	0 %	-	-	-
		ADM + ATM	30%	5	15	0
		ADM + ATM	30%	5	30	0
Latency	OC1 (Clear Day)	Do nothing	0 %	-	-	-
		ADM + ATM	30%	5	15	0
		ADM + ATM	30%	5	15	3
		ADM + ATM	30%	5	15	5
Tradeoff between Prediction Roll Period, Horizon, and Latency	OC3 (Moderate Snow)	ATM+ADM+WS	30%	5 15	15 30	0 5
	OC6 (Snow + Incident)	ATM+ADM+WS	30%	5 15	30 60	0 5

Figure 4 demonstrates the percentage improvement in throughput due to (a) roll periods of 5 minutes and 15 minutes on OC1 with respect to the baseline, (b) prediction horizons of 15 minutes and 30 minutes on

OC1 with respect to the baseline, (c) prediction latency of 0, 3 and 5 minutes on OC1 with respect to the baseline, (d) prediction parameters on OC3, and (e) prediction parameters on OC6. From the simulation results, it can be concluded that the best-performing settings for predictive strategies vary under different operational conditions. To implement the strategies in the real world, it is desirable to revisit and refine these values through field deployment experience. 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.

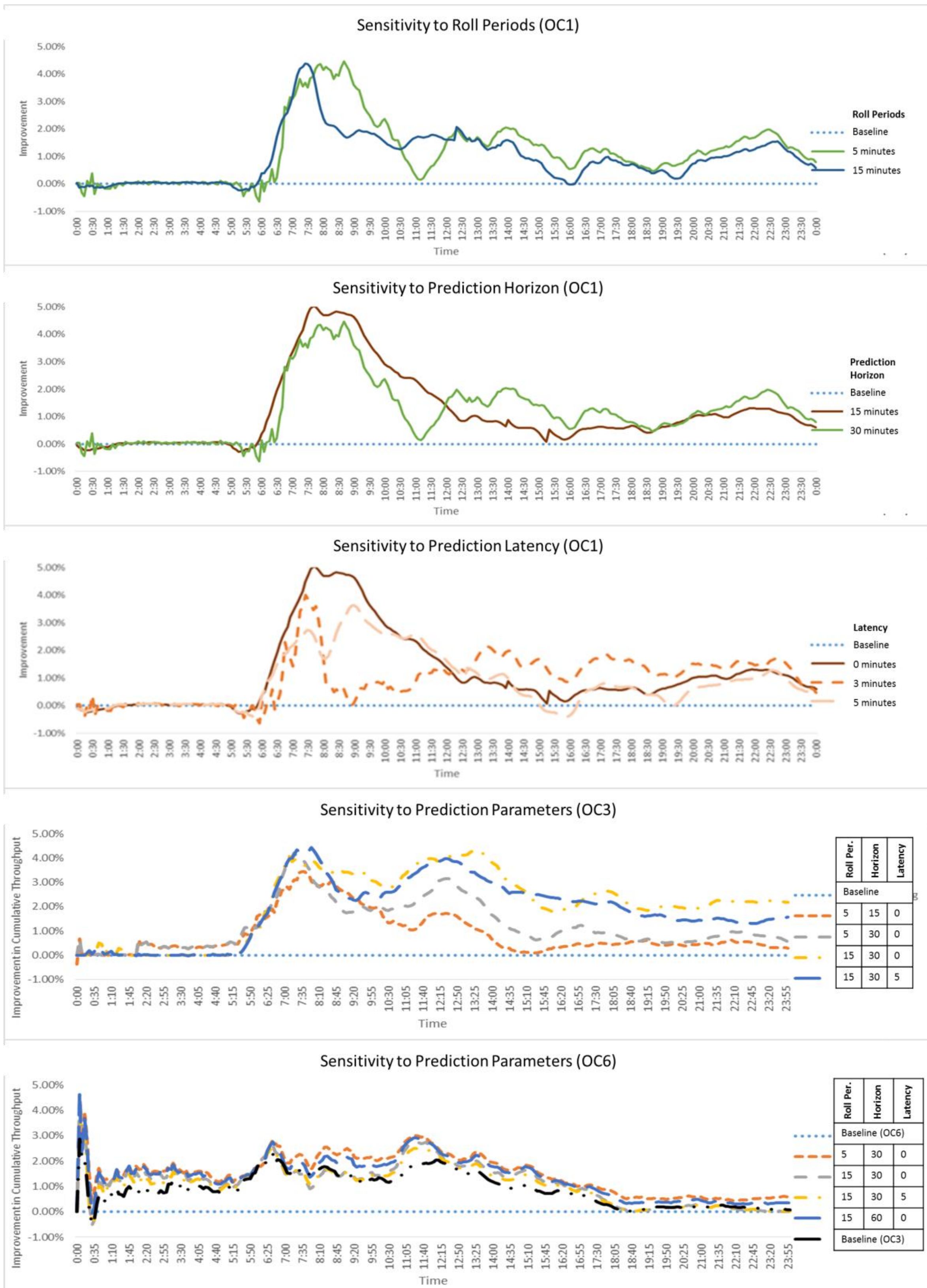

Figure 4. System Throughput Improvement Under Different Prediction Parameters [Source: NWU]

Operational Conditions and Facilities with Most Benefits

As far as the research questions related to operational conditions and facility types are concerned, the analyses found the best ATDM strategies for each operational condition and vice-versa. Additionally, the benefits were delineated between freeways and arterials to identify strategies that impact each facility types individually. To answer these questions, individual strategies were assessed for different operational conditions and the results were categorized into arterial and freeway-based results. A summary of the performance of strategies under different operational conditions is shown in Table 9.

From the simulation results, 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 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. For snowplow routing, 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.

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.

Table 9. Summary of Benefits under Different Operational Conditions with Different Strategies [Source: NWU]

Strategy	*Operational Condition*	*Benefit*
Active Demand Management (ADM)	Clear Day	Improve corridor speed by 5.2% on freeway and around 3.9% on arterial road Improve network throughput by up to 1.57%
	Rain to Snow Scenario	Improve corridor speed by 4.5% on freeway and around 2.9% on arterial road Improve network throughput by up to 2.58%
	Snow with medium-high demand	Improve corridor speed by 8% and reliability up to 20% on freeway Improve corridor speed by around 9% on arterial road and reliability up to 35% Improve network throughput by up to 2.85%
	Snow with medium-low demand	Improve corridor speed by 2% on freeway
	Snow-Incident scenario	Improve corridor speed by 9% on freeway, 8.6% on arterial road

Strategy	*Operational Condition*	*Benefit*
Active Traffic Management (ATM)	Clear Day	Improve corridor speed on arterial roads and freeway during peak hours; Improve reliability on arterial road by around 8% Improve network throughput by up to 1.75%
	Rain to Snow Scenario	Improve corridor speed by 6.4% and improve reliability up to 30% on freeway; Improve reliability by up to 14% on arterial road Improve network throughput by up to 1.43%
	Snow with medium-high demand	Improve corridor speed by 8% and reliability up to 11% on freeway Improve corridor speed by around 9% on arterial road Improve network throughput by up to 1.98%
	Snow with medium-low demand	Improve reliability by 3.2% on freeway Improve reliability by 5.4% on arterial road
	Snow-Incident scenario	Improve reliability by up to 30% on freeway
Weather Related Strategies (WS)	Snow with medium-high demand	Improve corridor speed by 6% and reliability by 2.6% on freeway Improve corridor speed by 8.5% on arterial road Improve network throughput by up to 2.86% Save travel time by 3%
	Snow with medium-low demand	Improve network throughput by about 0.36% Save travel time by 4.32%
	Snow-Incident scenario	Improve reliability by up to 18% on freeway and 10% on arterial road

Conclusions

The Chicago AMS Testbed was developed and analyzed using the enhanced, weather-sensitive DYNASMART platform in conjunction with a special-purpose micro-simulation tool for the DMA bundle in a connected vehicle environment. In order to evaluate the effectiveness of the ATDM strategies and DMA bundles, various operational conditions were defined through a data-driven method that used the historical traffic flow data, weather data and incident data. The operational conditions in the Chicago Testbed were clustered into six types, each representing a specific daily scenario and pertaining to different levels of travel demand and weather events. The six operational conditions for the Chicago Testbed consists of five historical scenarios calibrated according to the daily representative traffic and weather conditions, and one hypothetical scenario which is a snow-incident mixed scenario that was proposed based on the historical weather-induced car-crash data.

Three ATDM bundles consisting of ADM, ATM and weather-related strategies were identified and designed for the specific weather-affected scenarios. In addition, the DMA bundle INFLO, which consists of Speed Harmonization, was also implemented on the testbed. In order to address the research questions and evaluate the effectiveness of the proposed ATDM strategies and DMA bundles under various operational conditions, a set of experiments were designed and conducted with multiple experimental factors. The factors include the net penetration effect of the ADM strategy, the synergies and conflicts among the strategies, the sensitivity of system performance to the prediction quality (i.e. prediction accuracy, prediction horizon) and the communication latency, and choice of strategies given different levels of measurement (i.e. the system-wide or individual facility performance).

A total of 110 scenarios reflecting the above operational conditions, ATDM/DMA strategies, and strategy implementation features, were evaluated using 440 simulation runs to generate the results. The following observations were made regarding the research questions:

1. A highly connected environment improves the ability of a congested network to avoid or delay the onset of flow breakdown, and to accelerate the rate of recovery from flow breakdown once it occurs, thereby helping to avoid gridlock. The impacts of connected vehicles become more prominent as demand increases. Connected vehicles can improve the system's performance by increasing throughput and enhancing travel time reliability at all demand levels.
2. The effectiveness of information-related ADM strategies is influenced by the net penetration rate of the information. Low to medium penetration rates are most effective at improving system performance with limited coordination, while high penetration rates require coordination in vehicle routing to achieve benefits.
3. The ATM, ADM and weather-related strategies are synergistic for clear day and rain-to snow day scenarios, as well as for snow day scenarios with high demand. However, the ATM and weather-related strategies may not be effective when applied jointly for the low demand, snow day scenarios. The ADM strategy provides the most benefits for operational conditions without snow effect, i.e. clear day and rain-to-snow day. The weather-related strategies result in the most benefits for snow-affected and high demand operational conditions. The ATM-ADM strategies generate the most benefit without the snow effect. The real-time snowplow routing plan may not be warranted relative to well-planned static routes for low demand (off peak hours) operational conditions. In general, the most effective combination of strategies depends on the operational conditions (demand, weather), the facility type, and the time of day.
4. Finally, best-performing settings for predictive strategies vary under different operational conditions; it is desirable to revisit and refine these values through field deployment experience. The snow-affected scenarios operate best under 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.

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