

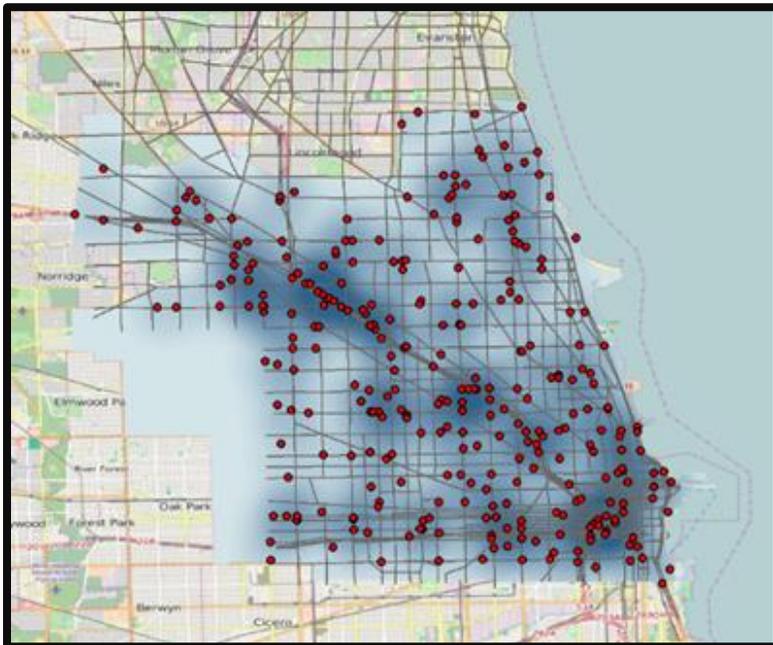
Analysis, Modeling, and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs

Evaluation Report for the Chicago Testbed

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Final Report — April 2017

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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. The results of this study project can be used by transportation agencies to identify and prioritize their investment options for implementing DMA and ATDM strategies that utilize connected vehicle technologies. This report documents the evaluations conducted on the Chicago Testbed, selected for this project because of the diversity of weather conditions encountered in the region. The report provides comprehensive documentation of the testbed development as well as the experimental results for the various weather and traffic conditions included in the analysis. These operational conditions were derived from historical data. Special attention is given to snow-related scenarios, for which unique strategies such as dynamic snowplow routing are considered. 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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Executive Summary

The report summarizes the evaluation procedures and results for the Road Weather Active Transportation and Demand Management (ATDM) strategies and Dynamic Mobility Applications (DMA) bundles tested in the Chicago testbed. The purpose of this project is to test those applications considering a proactive network management approach that adopts simulation-based prediction capabilities. The Chicago testbed was selected due to its variable weather environment, particularly snow events which are likely during the winter season.

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.

The Chicago Testbed was developed using the enhanced, weather-sensitive DYNASMART platform in conjunction with a micro-simulation tool ¹developed specifically for connected vehicle applications belonging to the DMA bundle. A summary table (Table E-1) shows the detailed benefits revealed in the Chicago AMS testbed with different strategies under varied operational conditions. An extensive set of experiments using the testbed under the various operational conditions resulted in the following observations regarding the above-mentioned research questions:

1. A highly connected environment as compared to the legacy system 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.

¹ Talebpoor, A., Mahmassani, H. S., & Bustamante, F. E. (2016). Modeling driver behavior in a connected environment: Integrated microscopic simulation of traffic and mobile wireless telecommunication systems. *Transportation Research Record: Journal of the Transportation Research Board*, (2560), 75-86. Please refer to section 6.1 for more details.

2. The effectiveness of information-related ADM strategies is influenced by the net penetration rate of the information. Low-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 ATDM (including ATM and ADM) and weather-related strategies are complementary 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 scenario. The ADM shows 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 high demand operational conditions. The ATM-ADM strategies show 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. The ADM strategy is effective for both freeway and arterial roads under clear day, but it shows more benefits on the freeway segments. The ATM strategy is more effective on freeway segments, improving average corridor speed and reliability under the rain to snow scenario. The weather-related strategy is most effective under snow scenario when demand is medium or high. In general, the strategy bundle which generates more benefits for one facility type usually works for another, as most strategies are implemented in the entire network.
5. Finally, the most effective applications and strategies vary under different operational conditions; it is desirable to revisit and refine these applications 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.

Table E-1 Summary of Benefits Under Different Operational Conditions with Different Strategies

Strategy	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 Operational Conditions (OC's) except OC4 (a snow-affected low demand scenario), 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.
Active Demand Management (ADM)	Clear Day	Improve corridor speed by 5.2% on freeway and by 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 by 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 by up to 20% on freeway Improve corridor speed by around 9% on arterial road, and reliability by up to 35% Improve network throughput by up to 2.85%

Strategy	Operational Condition	Benefit
	Snow with medium-low demand	Improve corridor speed by 2% on freeway
	Snow-Incident scenario	Improve corridor speed by 9% on freeway, and by 8.6% on arterial road
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 reliability by 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 by 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% Reduce travel time by 3%
	Snow with medium-low demand	Improve network throughput by about 0.36% Reduce travel time for 4.32%
	Snow-Incident scenario	Improve reliability by up to 18% on freeway and by 10% on arterial road
ADM+ ATM	Clear Day	Improve network throughput by up to 4.70% Short roll period, short prediction horizon and no latency settings result in better outcomes
	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% Long prediction horizons and roll periods result in better outcomes.
	Snow with medium-low demand	Improve network throughput by about 0.25%
	Snow-Incident scenario	Improve network throughput by up to 3.96%

Chapter 1. Introduction

The United States Department of Transportation (USDOT) initiated the Active Transportation and Demand Management (ATDM) and the Dynamic Mobility Applications (DMA) programs to achieve transformative mobility, safety, and environmental benefits through enhanced, performance-driven operational practices in surface transportation systems management. In order to explore a potential transformation in the transportation system's performance, both programs require an Analysis, Modeling, and Simulation (AMS) capability. 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, five testbeds were selected to form a diversified portfolio to achieve rigorous DMA bundle and ATDM strategy evaluation: San Mateo (US 101), Pasadena, ICM Dallas, Phoenix and Chicago Testbeds.

The primary purpose of this report is to document the evaluation conducted on the **Chicago** Testbed. This testbed was developed for the Chicago core area, which covers around 15 miles from north to south and 10 miles from east to west. A unique feature of the Chicago testbed along the spectrum of conditions exemplified by the five testbeds is the occurrence of severe winter weather, particularly snow events which are common for at least four months of the year. The Testbed area includes the Chicago downtown area, suburbs and cities north of Chicago connecting with major highway sections. These highway sections include the Kennedy Expressway (I90), the major road connecting downtown Chicago with O'Hare airport, the Edens Expressway (I94), the major north-south highway connecting downtown Chicago with many of the suburbs and cities north of Chicago, the Dwight D. Eisenhower Expressway (I290), the major east-west highway connecting downtown Chicago with the western suburbs, and Lakeshore Drive, the mostly freeway-standard expressway running parallel with and alongside the shoreline of Lake Michigan through Chicago.

This Testbed was used to test several ATDM strategies and DMA bundles considering a proactive network management approach that adopts simulation-based prediction capabilities. The objective is to evaluate the effectiveness of tested ATDM strategies and DMA bundles under several selected operational conditions. Three types of ATDM strategies and one DMA application were evaluated for this Testbed. The Active Traffic Management strategies analyzed include: Dynamic shoulder Lanes, Dynamic Lane Use Control, Dynamic Speed Limits (Basic), Adaptive Traffic Signal Control, Active Demand Management Strategies (consisting of Predictive Traveler Information and Dynamic Routing), as well as Weather-related Strategies (consisting of snow Emergency Parking Management, Traffic Signal Priority for Winter Maintenance Vehicles, Snowplow Routing, and Anti-Icing and Deicing Operations). The DMA application tested consists of the Speed Harmonization bundle. The Testbed is developed using the enhanced, weather-sensitive DYNASMART (DYnamic Network Assignment-Simulation Model for Advanced Road Telematics) platform, a discrete time mesoscopic simulation-assignment tool developed, extensively tested, and applied for intelligent transportation system applications.

1.1 Report Overview

This report includes an Executive Summary and twelve chapters as follows:

1. Chapter 1 – Introduction: Presents the report overview and objectives.
2. Chapter 2 – Testbed Details: Presents the regional characteristics of the Testbed (e.g., geographic characteristic) and the proposed modeling framework.
3. Chapter 3 – Operational Conditions and Calibration: Identifies the operational conditions used on the Testbed. This chapter also details the performance of the baseline scenarios under different operational conditions.
4. Chapter 4 – Applications and Strategies Modeled: Describes the ATDM strategies and DMA applications evaluated and proposes performance measurement for strategies evaluation.
5. Chapter 5 – Research Questions and Hypotheses: Lists the DMA and ATDM research questions answered by the Chicago Testbed and details respective hypotheses from the Analysis Plan.
6. Chapter 6 – DMA Application Modeling Details: Describes how DMA applications are modeled.
7. Chapter 7 – ATDM Strategy Modeling Details: Details how ATDM strategies are modeled.
8. Chapter 8 – Connected Vehicle Technology versus Legacy System: Describes the analysis approach and results for the research questions related to the Connected Vehicle Technology and Legacy System for DMA application
9. Chapter 9 – Synergies and Conflicts: Describes the analysis approach and results for the research questions related to the Synergies and Conflicts for ATDM strategies.
10. Chapter 10 – Prediction Accuracy and Latency: Presents the analysis approach and results for the research questions related to the Prediction Accuracy and Latency for ATDM strategies.
11. Chapter 11 – Operational Conditions and Facility Types with Most Benefit: Presents the analysis approach and results for the research questions related to the Operational Conditions and Facility Types with Most Benefit for ATDM strategies.
12. Chapter 12 – Conclusion: Summarizes the evaluation report.

Chapter 2. Testbed Details

This chapter describes the Chicago Testbed in detail, including the network and modeling framework.

2.1 Network Details

The Chicago Testbed network was extracted from the entire Chicago Metropolitan Area to enhance the estimation and prediction performance during the implementation procedure. The suggested 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. Figure 2-1 depicts the original network for Chicago metropolitan area and the extracted Testbed network, and Table 2-1 summarizes characteristics of the two networks.



Figure 2-1: Map of the Extracted Chicago Testbed Network [Source: NWU]

Table 2-1: Comparing Network Characteristics for Original and Extracted Networks of Chicago

Original Chicago Network	Chicago Testbed Network
<ul style="list-style-type: none"> ▪ 40,443 links <ul style="list-style-type: none"> 1,400 freeways 201 highways 2,120 ramps (96 of them are metered) 36,722 arterials ▪ 13,093 nodes <ul style="list-style-type: none"> 2155 signalized intersections 1,961 zones 1,944 internal 17 external ▪ Demand period <ul style="list-style-type: none"> 5 am -10 am 5-minute interval demand (~4,100,000 total demand) 	<ul style="list-style-type: none"> ▪ 4,805 links <ul style="list-style-type: none"> 150 freeways 47 highways 247 ramps (59 of them are metered) 4,361 arterials ▪ 1,578 nodes <ul style="list-style-type: none"> 545 signalized intersections 218 zones ▪ Demand period <ul style="list-style-type: none"> 24 hours 5-minute interval demand (~1,100,000 total demand)

2.2 Overall Modeling Framework

2.2.1 Modeling Tool

The Testbed is currently coded in DYNASMART, a (meso) simulation-based intelligent transportation network planning tool. It simulates and visualizes dynamic traffic assignment under certain circumstances. The model can be configured to run offline or online. The offline model (DYNASMART-P) includes dynamic network analysis and evaluation, while the online model (DYNASMART-X) adds short term and long term prediction capabilities.

DYNASMART models the evolution of traffic flows in a traffic network resulting from the travel decisions of individual drivers. The model is also capable of representing the travel decisions of drivers seeking to fulfill a chain of activities, at different locations in a network, over a given planning horizon. It is designed for use in urban areas of various sizes (large and small) and is scalable, in terms of the geometric size of the network, with minimal degradation in performance. DYNASMART can also model the fine details of transportation networks such as zones (any number of zones), intersections, links, origins and destinations. The user can specify any zonal configuration for the network, as long as it is consistent with the origin-destination demand matrix. Links may be modeled as freeways, highways, ramps, arterials, and high occupancy toll lanes, etc. Each link is represented by its length, number of lanes, existence of left-turn bays, maximum traffic speeds, etc. Two-way lane roads are modeled as two links (i.e., no overtaking is allowed by taking space in the opposing lane). Link junctions with different signalized and non-signalized control options are also modeled. Finally, DYNASMART-P can represent trip origins, destinations and even intermediate destinations for trip chaining.

Inheriting the core simulation components from DYNASMART-P, the primary distinction of the online operational tool (DYNASMART-X) is its capability of interacting with multiple sources of information and providing reliable estimates of network traffic conditions and predictions of network flow patterns. A comprehensive DYNASMART-X simulation is triggered by the following six algorithmic modules:

- Network State Estimation (RT-DYNA) module provides up-to-date estimates of the current state of the network. It has the full simulation functionality as DYNASMART-P, and its execution is synchronized to the real-world clock.
- Network State Prediction (P-DYNA) module provides future network traffic states for a pre-defined horizon, as an extension from the current network state estimated by RT-DYNA.
- OD Estimation (ODE) module uses a Kalman filtering approach to estimate the coefficients of a time-varying polynomial function that is used to describe the structural deviation of OD demand in addition to a historical regular pattern.
- OD Prediction (ODP) module uses the predicted OD coefficients provided by ODE to calculate the demand that is generated from each origin to each destination at each departure time interval. The predicted time dependent OD matrices are used for both current (RT-DYNA) and future (P-DYNA) stages.
- Short Term Consistency Checking (STCC) module uses the link densities and speeds of the simulator to evaluate the consistency of the flow propagation with the real-world observations and correct the simulated speeds.
- Long Term Consistency Checking (LTCC) module compares the simulated and observed link counts to calculate scaling factors that are used to adjust the demand level in both RT-DYNA and P-DYNA.

Note that STCC is executed much more frequently than LTCC. The purpose of these two levels of consistency checking is to minimize the deviation or discrepancy between what is estimated by the system and what is occurring in the real world, in an effort to control error propagation.

The algorithmic components described above form the main structure of the DYNASMART-X system. The interconnection between these components and the basic data flow model are illustrated in Figure 2-2. It also includes the interaction between DYNASMART-X system and external real world, as STCC, LTCC, and ODE form the data interface which receive measurements (count, speed, and occupancy) continuously from traffic detectors.

The graphical user interface (GUI) is another supporting component in DYNASMART-X, which aims to provide a convenient environment for executing the algorithms by allowing users to enter input data, and enables users to view and analyze simulation results "on the fly". Figure 2-3 presents a snapshot of DYNASMART-X system running for an example network of Chicago Testbed. The three windows in the user interface display the prevailing traffic conditions, a predicted traffic condition without implementing traffic management strategy, and a predicted traffic condition with management strategy.

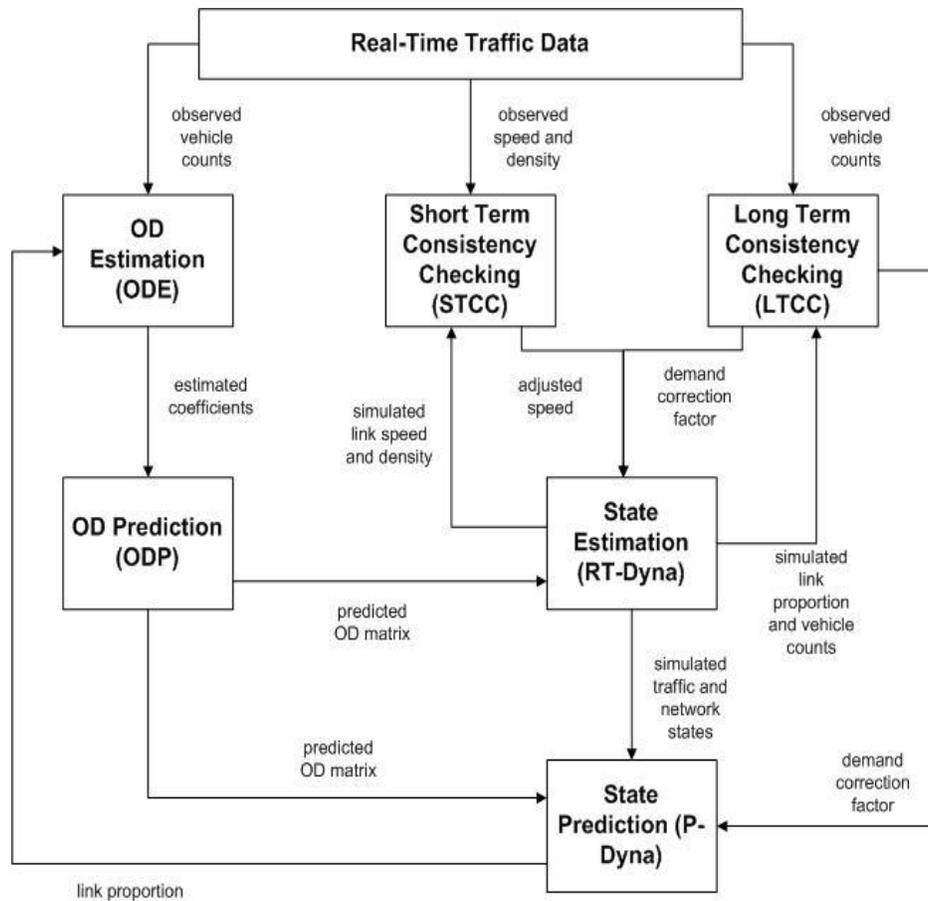


Figure 2-2: System Structure of DYNASMART-X and Data Flow [Source: NWU]

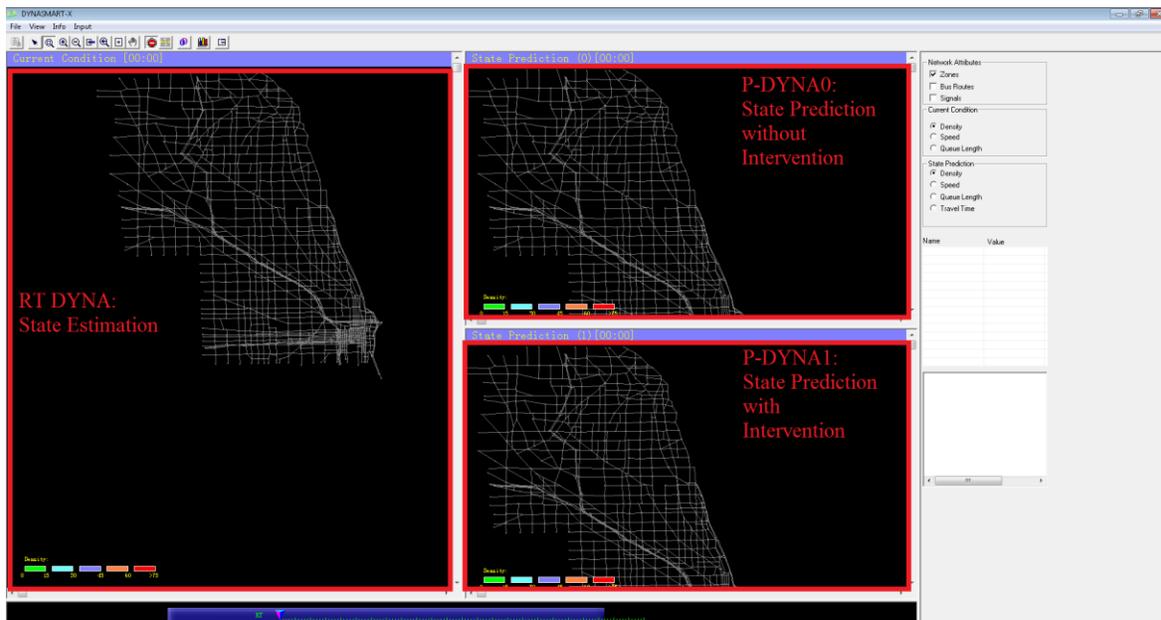


Figure 2-3: The Chicago Testbed Network as Displayed in DYNASMART-X GUI [Source: NWU]

2.2.2 Conceptual Framework

Figure 2-4 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.

The network state estimation and prediction modules are developed based on the state-of-the-art TrEPS models (Ben-Akiva, Bierlaire, Koutsopoulos, & Mishalani, 2002; H. S. Mahmassani, 1998; H. S. Mahmassani & Zhou, 2005). It uses a simulation-based dynamic traffic assignment (DTA) approach for real-world traffic estimation and prediction, and is capable of capturing the network dynamics resulting from the network's demand-supply interaction. The DTA simulation model is coded in DYNASMART, a (meso) simulation-based intelligent transportation network planning tool. The model can be configured to run offline or online. 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.

As is shown in Figure 2-4, the closed-loop framework consists of six modules: a) network state estimation module, b) demand estimation module, c) demand prediction module, d) network state prediction module, e) system evaluation module, and f) decision making module. Modules a), e) and f) are conducted within the offline model, and Modules b), c) and d) are implemented in the online model. The offline model and online model are connected to transfer information. The link volume and speed from the offline model, which emulates the real-world traffic conditions, are treated as traffic flow observation and sent into the online model as the reference to adjust estimated and predicted traffic demand and state. The predictive traffic information from the network prediction module in the online model is sent back into the offline model for system evaluation and decision making.

Both simulation and evaluation are conducted with a moving horizon to predict and feedback the network performance. As illustrated in Figure 2-4 (a), 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. It is worth mentioning that the pre-defined horizon may be extended for the weather-related strategies when snow accumulation exceeds the threshold within one prediction stage (Figure 2-4 (b)). The long-time prediction (e.g., 3 hours) is required to calculate the snowplow routes given the assumption that the snowplow vehicle is expected to accomplish a round trip and return to the depot within 3 hours, but the ATDM strategies do not need long-time prediction to update the strategies. The longer prediction horizon takes longer calculation time and may lead to larger latency. Therefore, to save computational cost and reduce information transfer latency, the prediction horizon is extended if and only if the weather-related strategies are required.

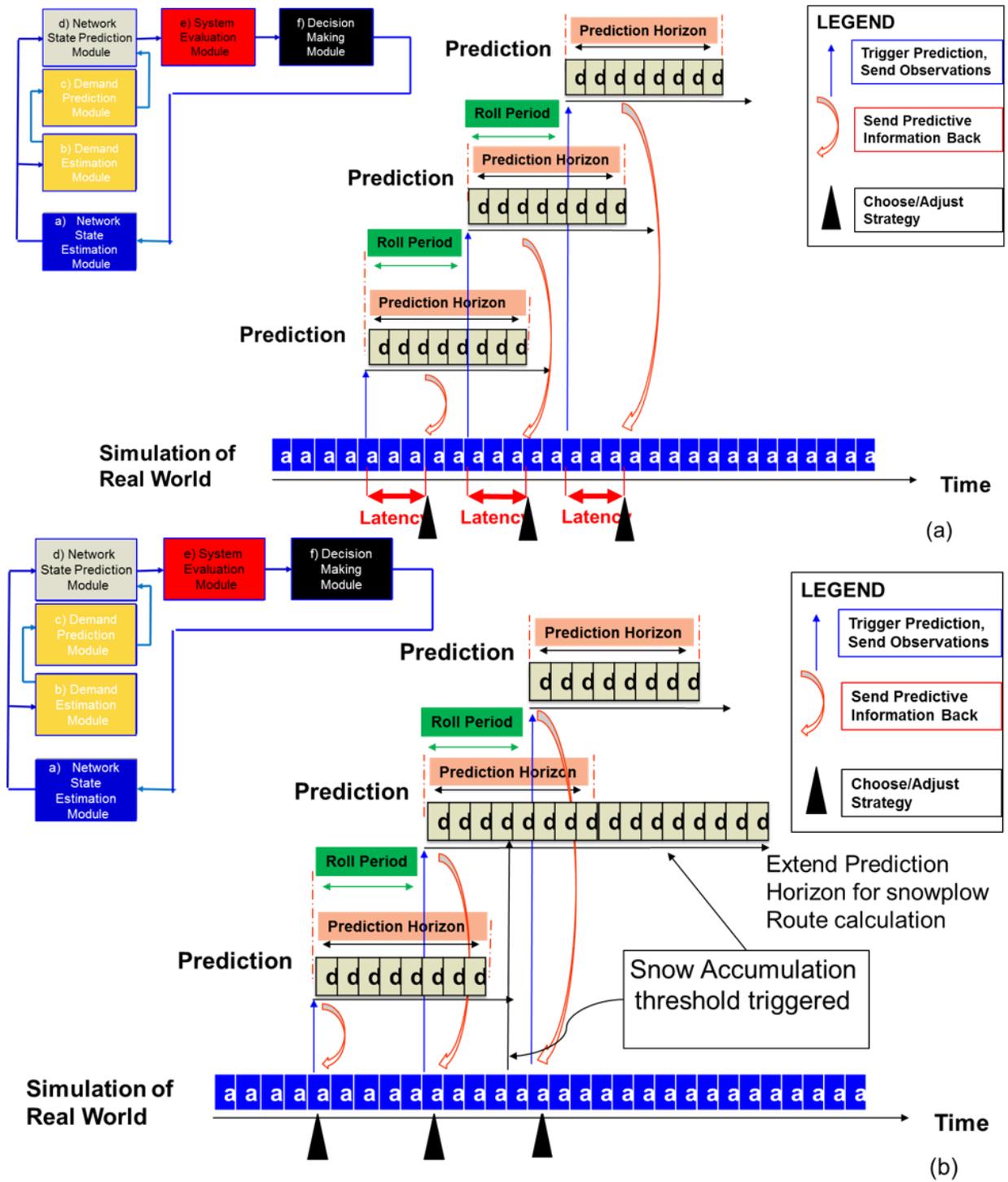


Figure 2-4: (a) Framework for Traffic Network Management System with Decision Making Capabilities; (b) Framework for Traffic Network Management System with Decision Making Capabilities for Weather-Responsive Strategies. [Source: NWU]

Chapter 3. Operational Conditions and Calibration

3.1 Operational Conditions

A cluster analysis was performed to determine the main operational conditions on the Chicago Testbed. The detailed approach and results of the cluster analysis are presented in the “Chicago Testbed Analysis Plan” document (FHWA-JPO-16-374). Based on the cluster analysis conducted for the Chicago Testbed, four main weather-related clusters are determined. Each cluster includes a specific weather condition and its corresponding traffic flow rate in terms of the attributes that describes operational conditions of the days in each cluster.

Table 3-1 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 3-1: The Selected Operational Scenarios for the Chicago Testbed

Variables	All	OC 1	OC 2	OC 3	OC 4	OC 5	OC 6 (hypothetical)
Number of Daily Records	321	67	5	3	4	1	-
Records (%)	100%	21%	2%	1%	1%	1%	-
Cluster Description	AM Peak	High Demand	High Demand	Medium Demand	Low Demand	Medium Demand	Medium Demand
	PM Peak	High Demand	High Demand	High Demand	Medium	High Demand	High Demand
	Incident	None	None	None	None	None	AM Peak
	Daily Weather	Clear / No Rain, No Snow	Moderate/ Heavy Rain Changing to Moderate Snow	Moderate Snow	Moderate Snow	Moderate and Heavy Snow	Moderate Snow

In order to calibrate the operational conditions, one specific daily scenario was selected from each cluster such that the temporal traffic flow profile for selected scenario is closest to the centroid of the cluster it belongs to. The selected daily scenarios for each cluster are as follows:

1. OC 1: April 22, 2009
2. OC 2: February 18, 2009
3. OC 3: December 22, 2009
4. OC 4: December 19, 2009
5. OC 5: January 09, 2009

The selected temporal profiles for weather conditions and traffic demand patterns are shown in Figure 3-1 and Figure 3-2 respectively. The rain/snow precipitation intensity and the visibility data are weather data obtained from the ASOS station at Chicago O'Hare airport.



Figure 3-1: Temporal Profiles of Selected Scenarios for Traffic Flow [Source: NWU]

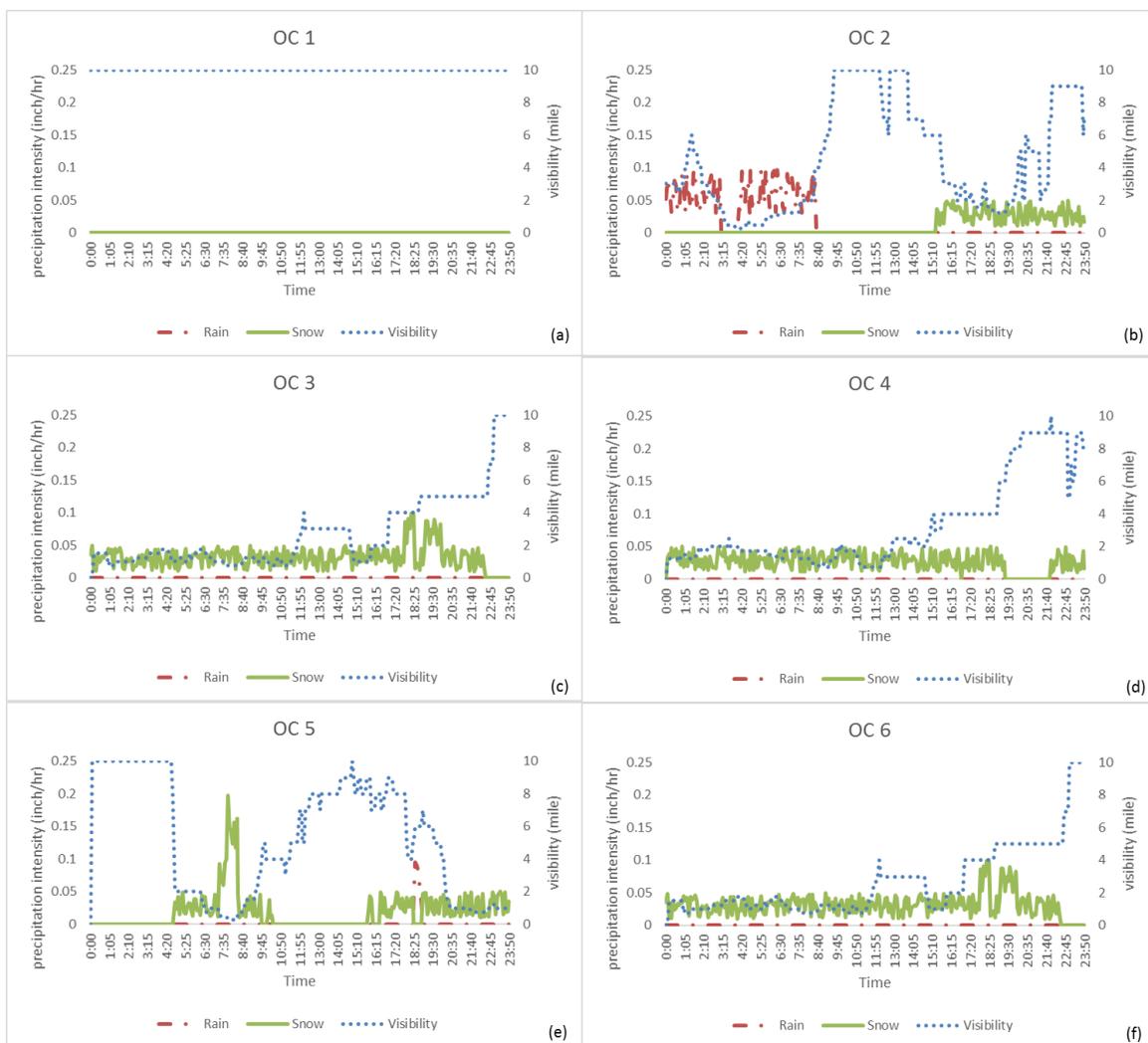


Figure 3-2: Temporal Profiles of Selected Scenarios for Weather Condition [Source: NWU]

The hypothetical incident events were determined according to historical car crash records. Figure 3-3 (a) displays the incident events which occurred in 2009, where the red dots show the exact locations and the heat map represents the kernel density estimation of incident events in Chicago. The kernel density formulation and estimation procedures adopted in this study are described in (Xie & Yan, 2008). Similarly,

the incident events caused by snow weather were extracted and plotted Figure 3-3

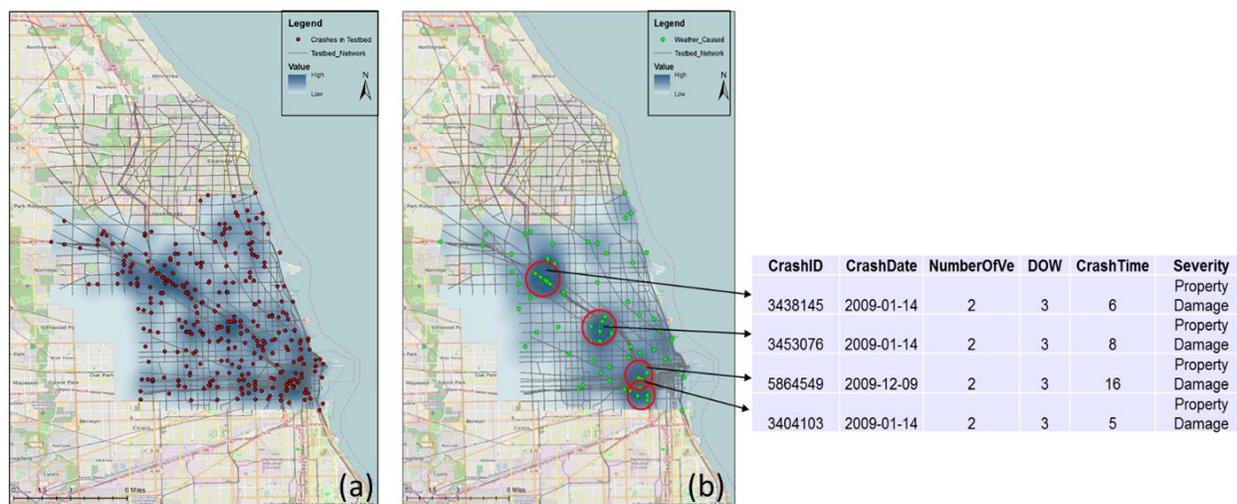


Figure 3-3 (b). It is observed that there are four dense areas of incidents, exhibited as red circles, which can be regarded as the accident-prone areas under snowy weather. Four hypothetical incident events were selected that are located around the center of these areas, two are on the interstate highway (5 AM and 6 AM) and the rest are on arterial roads (8 AM and 4 PM).

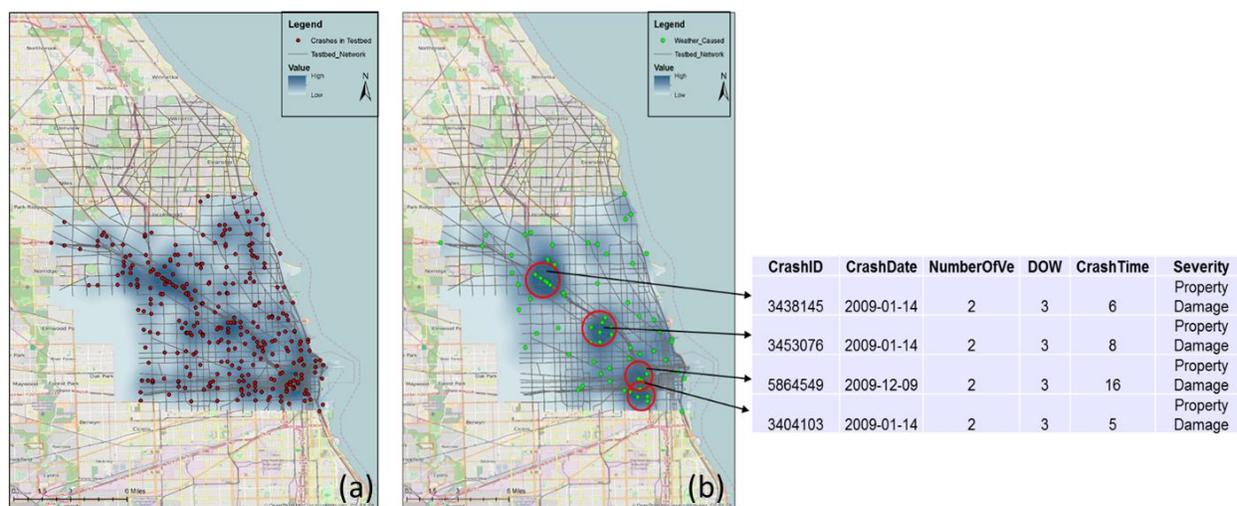


Figure 3-3: (a) Historical Incident Events in Chicago Network; (b) Historical Weather-Related Events in Chicago Network [Source: NWU]

3.2 Baseline Calibration

This section shows the network performance under baseline scenarios. The baseline scenarios were calibrated with loop detector data and weather observation data. The detailed calibration methodology and procedures were described in the calibration report.²

² Analysis, Modeling, and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs: Model Calibration Report for Chicago Testbed.

Table 3-2 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.

Table 3-2: Baseline Scenarios Under Different Operational Conditions

	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

Figure 3-4 displays the cumulative throughput and cumulative travel demand for each baseline scenario under different operational conditions, where the 24-hour demand and throughput obtained from the simulations are shown in blue and orange curves respectively. The gap between the curves indicates that the system did not satisfy the entire demand and serve all the generated vehicles until the moment.

For OC 1, there are three gaps within the 24-hour profiles that are highlighted within the purple circles. The first gap starts around 6:00, when the morning peak usually begins, and it ends around 15:00, from when the travel demand shows significant decrease in Figure 3-1. The second gap is short and not very significant. It corresponds to the travel demand starts to increase for the evening peak around 17:00. The third gap begins around 20:00 and it dues to the evening peak. For OC 2, it shows two gaps for the morning peak and one long gap for the evening peak. It can be observed from the time-dependent demand profile in Figure 3-1 that the first demand peak emerges during 5:40 to 7:20 and the demand drops until 8:30; after that, the demand increases again. Similar gaps can be found during the other scenarios and those gaps leave room for improvement on system performance when the ATDM or DMA strategies are to be implemented.



Figure 3-4: Cumulative Throughput and Travel Demand Under Different Operational Conditions [Source: NWU]

Chapter 4. Applications and Strategies Modeled

4.1 DMA Applications

The DMA application implemented and evaluated in this project is Speed Harmonization (SPD-HARM) within the INFLO Bundle. According to the features of DMA application, the speed harmonization application should be implemented in a connected vehicle (CV) environment.

In order to achieve this task, a 3-step procedure is proposed. First, the impact of CV environment is verified by checking the traffic flow-density diagram. Second, the impact of speed harmonization with no connected vehicles are tested individually. When speed harmonization is implemented at this elementary step, no connected vehicles are introduced in the network. Finally, connected vehicles was introduced in the network in conjunction with speed harmonization. Hence, the methodology and results for the DMA application are presented in the following sequential order:

- Impact of Connected Vehicle Environment only
- Impact of Speed Harmonization with no CV
- Impact of Speed Harmonization within a CV environment

Details for each step are provided in section 8.2.1.

4.2 ATDM Strategies

The Chicago Testbed focused only on the ATDM strategies summarized in Table 4-1. Chapter 7 presents the details of each strategy.

Table 4-1: ATDM Strategies Evaluated/Addressed by the Chicago Testbed

Type/Bundle	Strategy
Active Traffic Management Strategies	Dynamic Shoulder Lanes
	Dynamic Lane Use Control
	Dynamic Speed Limits (Basic)
	Adaptive Traffic Signal Control
Active Demand Management Strategies	Predictive Traveler Information
	Dynamic Routing
Weather-related Strategies	Snow Emergency Parking Management
	Traffic Signal Priority for Winter Maintenance Vehicles
	Snowplow Routing
	Anti-icing and Deicing Operations

4.3 Performance Measures

The performance measures quantify the achievement of DMA/ATDM program objectives in the following categories:

4.3.1 Overall Performance Measures

The overall performance measures refer to the basic measurement for the entire network, including average travel time, average stop time, average trip distance in the network and the total number generated vehicles for the entire 24-hour simulation horizon. These measures provide a general description of the aggregated performance across the entire network.

4.3.2 DMA-Specific

In order to measure the effectiveness of the DMA application, three types of measures were proposed. First is **flow-density relationship**, which captures the traffic flow model within the connected network under different market penetration rates. Second is **the time-dependent speed and standard deviation of speed** of those vehicles which are traveling on the freeway segment under the Speed Harmonization application. The objective of speed harmonization is to control the distribution of speed and to reduce the variance among the vehicles to maintain the stability of the freeway segment. The measurements for speed and reliability confirm the effectiveness of this application. The third measurement is **the time-dependent improvement of cumulative throughput** across the network for the testing scenario compared to the baseline scenario in terms of percentage and actual number.

The time-dependent improvement $i(t)$ can be calculated according to Eq (4-1)

$$i_{test}(t) = \left(\frac{\sum_t N_{test}(t)}{\sum_t N_{base}(t)} - 1 \right) \cdot 100\% \quad (4-1)$$

where $N_{test}(t)$ means the number of served vehicles at each interval in the targeted scenario, and $N_{base}(t)$ represents the number from the baseline scenario. It is worth mentioning that $i(t)$ is not guaranteed to be a positive value for every interval. If the test strategy yields to more cost at interval t_k , the $i(t_k)$ is negative.

To study the **travel time variability**, distance-weighted mean (μ) and standard deviation (σ) of the individual travel times are computed as follows:

$$m = \frac{\sum_{i=1}^n d_i t'_i}{\sum_{i=1}^n d_i} = \frac{\sum_{i=1}^n t_i}{\sum_{i=1}^n d_i} = \frac{1}{\bar{u}_s} \quad (4-2)$$

$$S = \sqrt{\frac{\sum_{i=1}^n d_i (t'_i - m)^2}{\sum_{i=1}^n d_i}} \quad (4-3)$$

Where

i :	Vehicle Index
n :	Number of Vehicles
d_i :	Travel Distance of Vehicle i
t_i' :	Travel Time Rate of Vehicle i (Min/Mile)
t_i :	Travel Time Rate of Vehicle i

4.3.3 ATDM-Specific

In order to address the research questions for ATDM strategies, three types of measures were adopted. First is **the time-dependent improvement of cumulative throughput** across the network defined in Eq (4-1) to check the effectiveness of the ATDM strategies under various scenarios. Second is to check **the time-dependent speed** across the entire 24-hour simulation horizon on different facility types (i.e., freeway segment and arterial corridor in the Chicago Testbed). The third type is to **check the time-dependent average unit travel time (travel time per mile) and travel time reliability** in the entire network to verify the efficiency of the proposed weather-related strategies, especially the dynamic snowplow routing strategy.

Chapter 5. Research Questions and Hypotheses

The Chicago Testbed analyses focused on the DMA and ATDM applications evaluation. This Chapter details the analysis hypotheses to address the research questions for the Chicago Testbed.

5.1 DMA Research Questions

The DMA application analyzed and evaluated using the Chicago testbed is discussed in Chapter 4. Table 5-1 presents the DMA research questions and associated hypotheses.

Table 5-1: DMA Research Questions and Corresponding Hypotheses

ID	DMA Research Question	Hypothesis
I Connected Vehicle Technology vs. Legacy Systems		
1	Q1. Will DMA applications yield higher cost-effective gains in system efficiency and individual mobility, while reducing negative environmental impacts and safety risks, with wirelessly-connected vehicles, infrastructure, and travelers' mobile devices than with legacy systems?	Not Addressed
	Q2. What is the marginal benefit if data from connected vehicle technology are augmented with data from legacy systems?	Compared to legacy systems, INFLO DMA application that make use of new forms of wirelessly-connected vehicle, infrastructure, and mobile device data will yield cost-effective gains in system efficiency and individual mobility, while reducing negative environmental impacts and safety risks.
	Q3. What is the marginal benefit if data from legacy systems are augmented with data from connected vehicle technology?	
VIII Prediction and Active Management Investment		
2	Can new applications that yield transformative benefits be deployed without a commensurate investment in prediction and active management (reduced control latency)? How cost-effective are DMA bundles when coupled with prediction and active management?	DMA application (Speed Harmonization) can be deployed and will be most cost-effective only when coupled with prediction and active management.

5.2 ATDM Research Questions

The ATDM strategies analyzed and evaluated using the Chicago testbed are discussed in Chapter 4. Table 5-2 presents the ATDM research questions and the corresponding hypotheses.

In the analysis plan, the hypothesis was proposed for each research question category instead of individual research questions. However, some research questions are not addressed in the Chicago testbed

Q8: since varied traffic modes (such as transit or bus) are not simulated and compared in the Chicago testbed, this question is not addressed.

Q12, 13,15: these two questions deal with geographic coverage. However, in the Chicago testbed, the coverage of ATDM strategies are almost fixed as reality (e.g. reversible lane for Kennedy expressway, ADM, Weather-related strategies for the entire network, and speed-harm and shoulder lane control on some highway segments), it is not applicable to test coverage.

Q16: The Connected Vehicle related tests were only conducted for DMA research questions. Cross bundle tests were not performed.

Q17 and 18: the long-term behaviors cannot be tested with daily patterns. They can be tested with monthly or seasonal patterns and behaviors

Table 5-2: ATDM Research Questions and Corresponding Hypotheses

ID	Research Question Category	ATDM Research Question Category	Hypothesis
1	Synergies and Conflicts	<p>Q1. Are ATDM strategies more beneficial when implemented in isolation or in combination (e.g., combinations of ATM, ADM, or APM strategies)?</p> <hr/> <p>Q2. What ATDM strategy or combinations of strategies yield the most benefits for weather related operational conditions?</p> <hr/> <p>Q3. What ATDM strategies or combinations of strategies conflict with each other?</p>	<p>Some ATDM strategies could create synergy when deployed together, while other strategies could be conflicting with each other; resulting in a reduction in the overall benefits.</p> <p>Under different weather scenarios, the extent of synergy or conflict among strategies may vary.</p>
2	Prediction Accuracy	<p>Q4. Which ATDM strategy or combination of strategies will benefit the most through increased prediction accuracy?</p> <hr/> <p>Q5. Are all forms of prediction equally valuable - i.e., which attributes of prediction quality are critical (e.g., length of prediction horizon, prediction accuracy, prediction speed, and geographic area covered by prediction) for each ATDM strategy?</p>	<p>The value of prediction will be higher under inclement weather conditions.</p> <p>The value of prediction will vary depending on the operational conditions experienced in the system.</p>

ID	Research Question Category	ATDM Research Question Category	Hypothesis
3	Active Management or Latency	Q7. Which ATDM strategy or combinations of strategies will most benefit through reduced latency?	The most beneficial combination of strategies through reduced latency may vary under different weather related operational conditions.
4	Operational Conditions, Modes, Facility Types with Most Benefit	Q8. Which ATDM strategy or combinations of strategies will be most beneficial for certain modes and under what operational conditions?	Not addressed
		Q9. Which ATDM strategy or combinations of strategies will be most beneficial for certain facility types (freeway, transit, and arterial) and under which kind of weather related operational conditions?	Most benefits will be achieved in the high congestion and inclement weather scenarios. Some weather-responsive ATDM strategies are focused on arterial streets more than freeway.
		Q10. Which ATDM strategy or combinations of strategies will have the most benefits for individual facilities versus system-wide deployment versus region-wide deployment and under which kind of weather related operational conditions?	The benefits of ATDM strategy or combination of strategies will vary from regions, facility types and systems.
5	Prediction, Latency, and Coverage Tradeoffs	Q11. What is the tradeoff between improved prediction accuracy and reduced latency with existing communications for maximum benefits?	Increased communication level with less prediction accuracy could lead to similar results as less communication level with higher prediction accuracy.
		Q12. What is the tradeoff between prediction accuracy and geographic coverage of ATDM deployment for maximum benefits?	Not addressed
		Q13. What is the tradeoff between reduced latency (with existing communications) and geographic coverage for maximum benefits?	Not addressed

ID	Research Question Category	ATDM Research Question Category	Hypothesis
		Q14. What will be the impact of increased prediction accuracy, more active management, and improved robust behavioral predictions on mobility, safety, and environmental benefits?	<p>Increased prediction accuracy, more active management (reduced latency), and improved robust behavioral predictions result in significant mobility, safety, and environmental benefits.</p> <p>Key attributes of prediction quality (e.g., prediction horizon, prediction accuracy, speed of prediction, and geographic prediction coverage) vary critically depending on ATDM strategies considered and weather related operational conditions encountered.</p>
		Q15. What is the tradeoff between coverage costs and benefits?	Not addressed
6	Connected Vehicle Technology and Prediction	Q16. Are there forms of prediction that can only be effective when coupled with new forms of data, such as connected vehicle data?	Not addressed
7	Short-Term and Long-Term Behaviors	Q17. Which ATDM strategy or combinations of strategies will have the most impact in influencing short-term behaviors versus long term behaviors and under which kind of weather related operational conditions?	Not addressed
		Q18. Which ATDM strategy or combinations of strategies will yield most benefits through changes in short-term behaviors versus long- term behaviors and under which kind of weather related operational conditions?	Not addressed.

Chapter 6. DMA Application Modeling Details

6.1 INFLO Bundle

6.1.1 Speed Harmonization

Advances in wireless communication technology and increasing processing power can create an interconnected network of moving vehicles and stationary facilities. With this network, vehicles are able to communicate with other moving vehicles (V2V communication) and with traffic management system (V2I communication). The flow of information in these networks not only improves the safety but also increases the efficiency of operating vehicles. From planners' perspectives these networks allow them to monitor the traffic conditions online and, if required, implement any strategy to control the flow condition quickly.

This study utilizes a microscopic simulation framework of Talebpour et al. (Talebpour, Mahmassani, & Bustamante, 2016)³ to establish the speed-density relationships at different market penetration rates (MPRs) of connected vehicles. Calibrated speed-density relationships are then used as input to the mesoscopic simulation tools to simulate the network-wide effects of connected vehicles. Speed harmonization is then implemented in the network with connected vehicles in the traffic stream. Following section provides details on the modeling approach adopted for speed harmonization. Section 8.2 provides further information on integration of microscopic and mesoscopic models.

6.1.1.1 Modeling Approach

Speed harmonization (or variable speed limit control) is an active traffic management strategy that adjusts and coordinates the maximum appropriate speed limit on the basis of the prevailing traffic condition, road surface condition, and weather condition information. Such strategies are used to deal with congestion, incidents, or special events, maximizing the traffic throughput by delaying breakdown formation and minimizing incident-related hazards. (Active Traffic Management (ATM) Feasibility Study, 2007)

When a freeway segment is operating at near capacity, shock waves may appear and propagate because of frequent lane changing—merging maneuvers or sudden deceleration. The shock wave propagation may eventually result in traffic flow breakdown, with a corresponding increase in travel delay, decrease in throughput, and more important, potentially unsafe driving situations. Speed harmonization aims at avoiding shock wave formation, dampening its propagation, and minimizing incident-related hazards by controlling vehicular speeds and creating a more uniform traffic flow. A successful and efficient implementation of speed harmonization depends highly on the sensor coverage of intelligent transportation systems, the selection of efficient enforcement strategies (to increase driver compliance with the posted speed limit), the implementation of appropriate and effective control strategies for speed limit selection, and the selection of the road segments for implementing the corresponding logic (Waller, Ng, Ferguson, Nezamuddin, & Sun, 2009).

³ Talebpour, A., Mahmassani, H. S., & Bustamante, F. E. (2016). Modeling driver behavior in a connected environment: Integrated microscopic simulation of traffic and mobile wireless telecommunication systems. *Transportation Research Record: Journal of the Transportation Research Board*, (2560), 75-86.

Speed harmonization testing used the Southeast bound traffic on I-94 segment in Chicago. Figure 6-1 shows the decision tree for the speed limit selection, which is based on the decision tree introduced by Allaby et al. (Allaby, Hellenga, & Bullock, 2007). The decision is based on the prevailing traffic conditions (i.e., speed, flow, and density) at the shock wave detection point. If a shock wave is predicted at a location, the upstream speed limit is updated. Once a speed is updated on a sub-segment, it cannot be changed for 2 minutes in order to prevent rapid fluctuations in the speed limit.

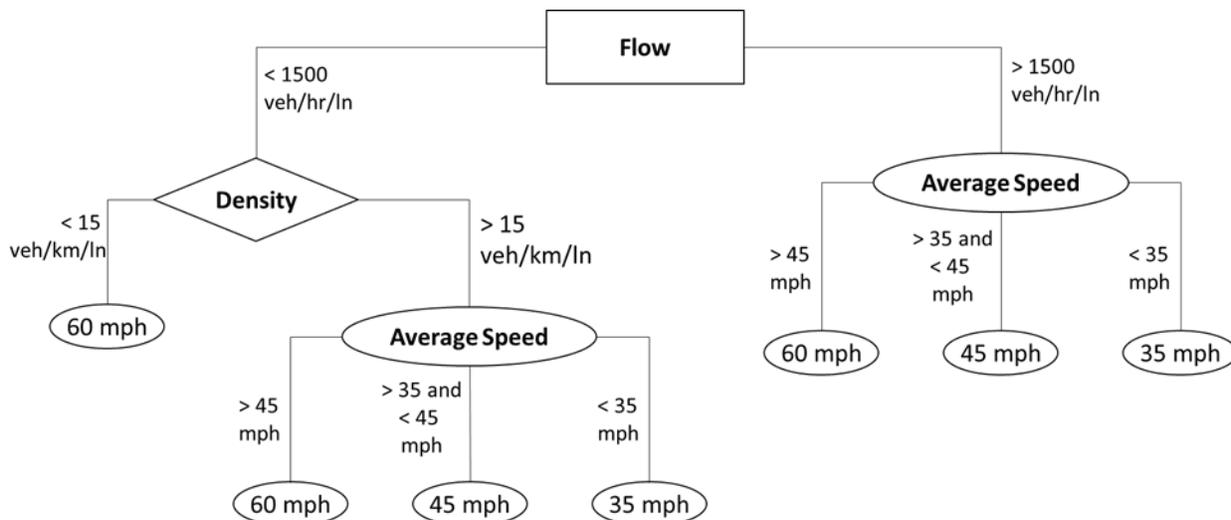


Figure 6-1: Speed Harmonization Decision Tree (veh = vehicle) [Source: NWU]

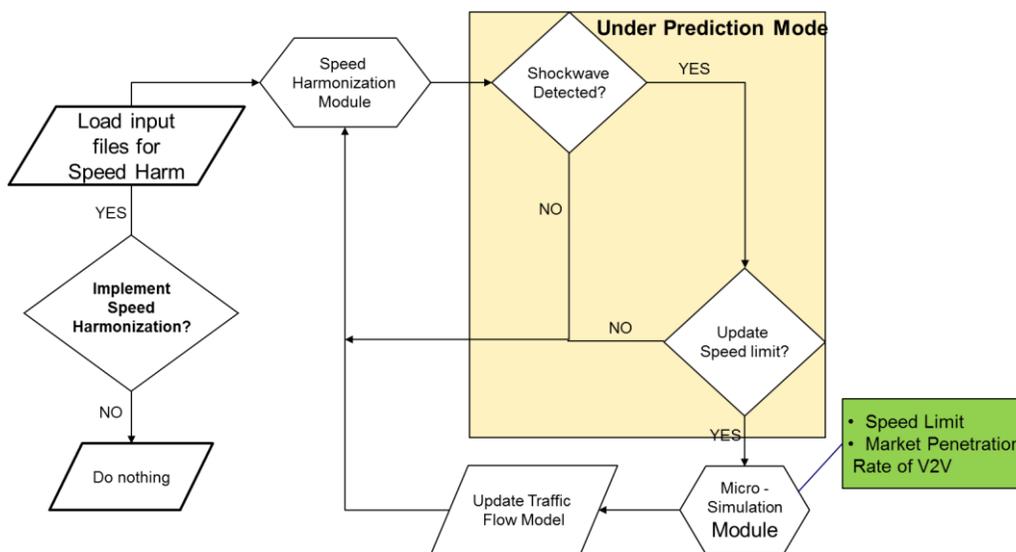


Figure 6-2: Flowchart of Speed Harmonization [Source: NWU]

Figure 6-2 presents the framework adopted for this study to implement speed harmonization. As shown in the figure speed harmonization is not coded in the meso-simulation tool, namely DYNASMART for the Chicago Testbed, but instead is implemented through the involvement of a micro-simulation tool, through which we can control the speed limit for the vehicles and the market penetration rates in the connected environment. Link based data was collected at an interval of 5 minutes. The shockwave detection is part of the prediction module, referred to as modelling framework (i.e., a part in the DYNASMART-X). Shockwaves are predicted every 2 minutes and if predicted, speed limits are implemented 1 minute before the actual occurrence with prediction horizon of 30 minutes. The intervals between upstream and

downstream locations were determined by conducting a sensitivity analysis. Speed limits were changed at 2 to 5 mile upstream intervals, in steps of 1 mile. From the flow-density diagrams it was observed that the extremes (i.e., highest flow; highest densities were affected with the upstream intervals). Interval that allows highest flow at low density was picked up as the optimal one (Figure 6-3). Legends in the Figure 6-3 refer to the upstream distance in miles where the speed limit was changed. For clear days, rain-snowy and snowy day the optimal upstream location was found to be 2, 2 and 3 miles respectively. It can be observed that the optimal interval has shifted further away for the snowy day which could be because of the increased stopping distance increases due to reduction in the traction.

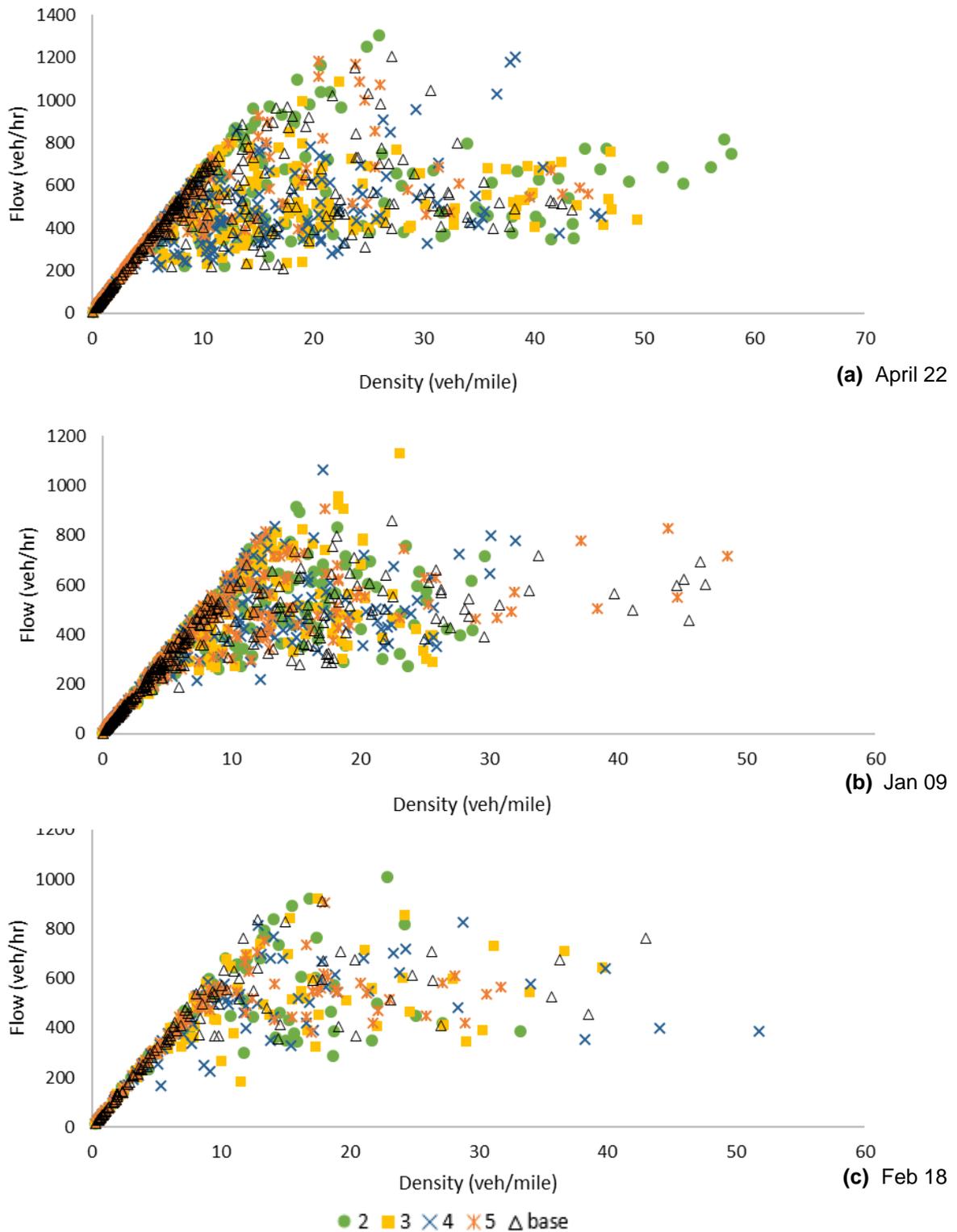


Figure 6-3: Speed Harmonization: Optimal Upstream Location Selection [Source: NWU]

Chapter 7. ATDM Strategy Modeling Details

Active transportation demand management strategies improve the ability of an agency to enhance trip reliability, safety, and throughput of the surface transportation system by dynamically managing and controlling travel and traffic demand, and available capacities, 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 ATDM bundles evaluated are discussed below.

7.1 Active Traffic Management Strategies

Active Traffic Management (ATM) strategies include four individual ATDM strategies, namely, dynamic shoulder lanes, dynamic reversible lanes, dynamic speed limits and adaptive traffic signal control. The first three strategies were implemented on the freeway sections and the last one was designed and applied to the main arterial roads. The rationale behind predictive ATM strategies is that the operation time and detailed strategy settings are determined by evaluation results from the network prediction in a moving horizon framework.

7.1.1 Dynamic Shoulder Lanes

The dynamic shoulder lanes allow vehicles to drive on the shoulder lanes during the specific time of day. The period to open shoulder lanes is the peak hour on the weekdays (i.e., 5-9 AM for the inbound direction and 3-7 PM for the outbound direction for weekdays), when general traffic is moving at less than 35 mph. This operational setting is based on the I-55 Bus-on-Shoulder Demonstration program suggested by the Illinois Department of Transportation. More details can be found at the website for this program (<http://www.idot.illinois.gov/transportation-system/Network-Overview/transit-system/i-55-bus-on-shoulder>). In order to move the most people through congestion and promote public transportation, the shoulder option was an added feature that can be used when available.

Note that the shoulder was closed in during maintenance. For this study, winter maintenance was evaluated. Thus, the primary lanes of the highway, ramps and interchanges are the first priority for snow removal. As a result, the shoulder may not be available for several days during and immediately after a winter storm. Shoulders are plowed and cleared of snow as soon as conditions allowed after a snowstorm. The shoulder lanes are not available during the medium and heavy snow conditions.

7.1.1.1 Modeling Approach

As shown in Figure 7-1, there are several freeway segments in the Chicago testbed: I-94 to the northern suburban areas, I-90 to the northwestern suburban areas, I-290 to the western suburban areas, and I-90 and I-94 merges and connects to the downtown area. In addition, the Lake Shore Drive connects the downtown area and the northern part of the Chicago city. Among these segments, Lake Shore Drive does not have the shoulder lanes, and I-90/94 is parallel to the Kennedy Expressway, which is the reversible lane in the Chicago testbed. As such, the candidates for the dynamic shoulder lane strategy are I-90, I-94 and I-290 segments. As with I-290, 95% of the segments are wider than 8 inches, 77% of the segments are with shoulder lanes wider than 10 inches, and over 62% are wider than 12 inches. The details of the

shoulder widths are listed in Table 7-1 ("Roadway Existing Conditions," 2013). The shoulder lanes are paved and with rumble strips at the edge.

Along northbound and southbound I-90/94, the existing shoulder widths vary between four and five feet. In order to build the I-90 "Golden Corridor" (Val, 2016) and "Smart Corridor" (Rossi, 2015), the I-90 project allows express buses on the shoulder. The Illinois Tollway has included beefed-up shoulders as part of its reconstruction and widening of I-90 from the Kennedy in Chicago to Barrington Road in Hoffman Estates. The Tollway hopes to try out "connected technology" on the 10 bus routes that will be operating on the shoulder of the new I-90 (Figure 7-2). Therefore, the dynamic shoulder lane strategy was implemented on I-290 and I-90.

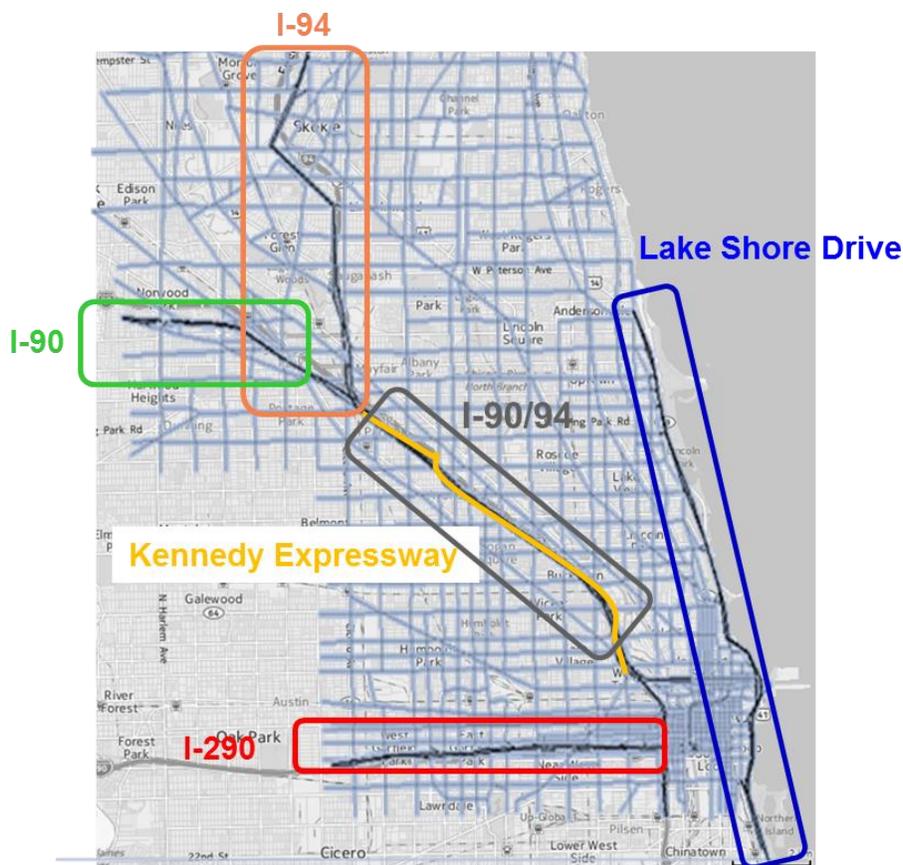


Figure 7-1: Freeway Segments in the Chicago Testbed [Source: NWU]

Table 7-1: Existing Mainline Shoulder Widths

Shoulder Width	Westbound				Eastbound				Overall	
	Left		Right		Left		Right			
2' to < 4'	1,620	8%	0	0%	0	0%	0	0%	1,620	2%
4' to < 6'	463	2%	0	0%	293	1%	0	0%	756	1%
6' to < 8'	792	4%	0	0%	891	4%	0	0%	1,683	2%
8' to < 10'	11,425	53%	584	3%	911	4%	773	5%	13,693	18%
10' to < 12'	7,076	33%	232	1%	3,036	14%	1,068	7%	11,412	15%
12' to < 14'	0	0%	9,570	55%	15,713	72%	13,823	86%	39,106	51%
14'	0	0%	7,044	40%	1,077	5%	445	3%	8,566	11%
Total	21,376		17,430		21,921		16,109		76,836	

Overall right shoulder lengths are less than left shoulder lengths due to ramps entrances and exits.



Figure 7-2: The New I-90 of the Chicago Metropolitan Area [Source: NWU]

Figure 7-3 shows the procedure to implement this strategy. The implementation is involved within both estimation and prediction module according to the schedule of dynamic shoulder lane to open shoulder lanes is the peak hour on the weekdays. The schedule is predefined same as I-55 Bus-on-Shoulder program, which allows vehicles traveling on shoulder lane during 5-9 AM for the inbound direction and 3-7 PM for the outbound direction for weekdays. If the module is triggered to implement this strategy, the module is checking the current status of shoulder lane and compared it with the predefined schedule so that Variable Message Sign (VMS) informs whether shoulder lane is available or not.

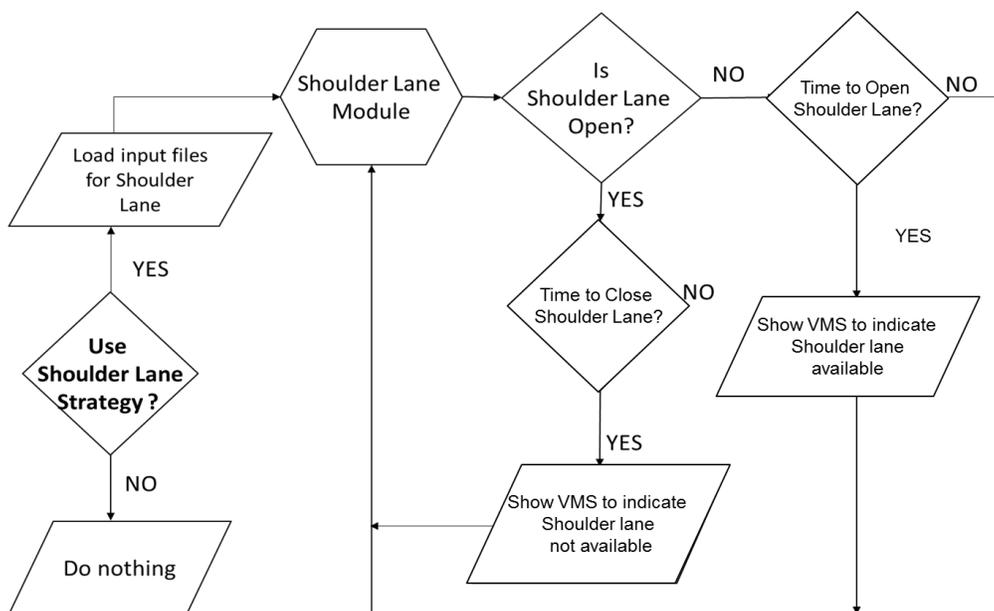


Figure 7-3: Flowchart of Dynamic Shoulder Lane [Source: NWU]

7.1.2 Dynamic Lane Use Control

The dynamic lane use control is applied to the dynamic reversible lane in the Chicago testbed. To match actual conditions on the Chicago testbed, the reversible lane is proposed for the Kennedy Expressway, which is operated based on both a schedule (shown in Table 7-2) as well as real-time schedule posted on the website <http://www.kennedyexpresslanes.com/>. However, the direction for service changes in response to special events, weather conditions, and incidents on the highway

The reversible lanes affect a large portion of the downtown expressway network, not just the Kennedy Expressway itself. The reversible lanes almost always open in the direction of higher volume of vehicles although the corresponding travel time may be lower due to the extra lanes going in the direction of that higher volume.

Table 7-2: Kennedy Reversible Schedule

Day of Week	From	To	Target Start
Monday - Thursday	Inbound	Outbound	12:30 PM
Friday	Inbound	Outbound	1:30 PM
Monday - Friday	Outbound	Inbound	11:00 PM
Saturday	Inbound	Outbound	2:00 PM
	Outbound	Inbound	5:00 PM
	Inbound	Outbound	8:30 PM
Sunday	Outbound	Inbound	12:01 AM
	Inbound	Outbound	2:00 PM
	Outbound	Inbound	11:00 PM

Note that the Friday afternoon schedule may be altered to accommodate heavy inbound travel times in reality. In those instances, the flip from outbound to inbound may occur as early as 6:00 PM based on congestion, impacts to other facilities, incidents and special events. However, in this study, the default schedule is followed as the Friday scenario is calibrated with medium level demand (OC 5) and no incident or special event occurs.

Modeling Approach

Figure 7-4 shows the procedure to implement this strategy. To guarantee the availability when reversing the direction for service, vehicles are “flushed” to take a detour from the expressway segment. The clearance time is 10% more than the expected travel time for the segment. Note that this strategy is implemented when the TrEPS model predicts the traffic condition for the prediction horizon as well as the system is simulating the real world. In other words, the implementation is involved within both estimation and prediction module.

If reversible lane strategy is implemented, the reversible lane module is triggered with specific input files. Within any simulation (including estimation and prediction) interval, the module is checking where any onramp to reversible lane is already open first. If not, the module checks if it is time to open reversible lane according to the schedule. As the reversible lane should be always open for one direction, the answer should be YES to this question. Before open any direction service, the system should always check if there is any vehicle on the other direction. If not, it is safe to open; otherwise, the vehicles should be flushed first to the exit (i.e., the nearest off-ramp of reversible lane). On the other hand, if there is any direction already open for service, the module calculates the clearance time and predicts time to close onramps and stop provide more service. Besides, if the clearance time is estimated to be longer than scheduled time, the module decides to flush vehicles so that the other direction can be open on time.

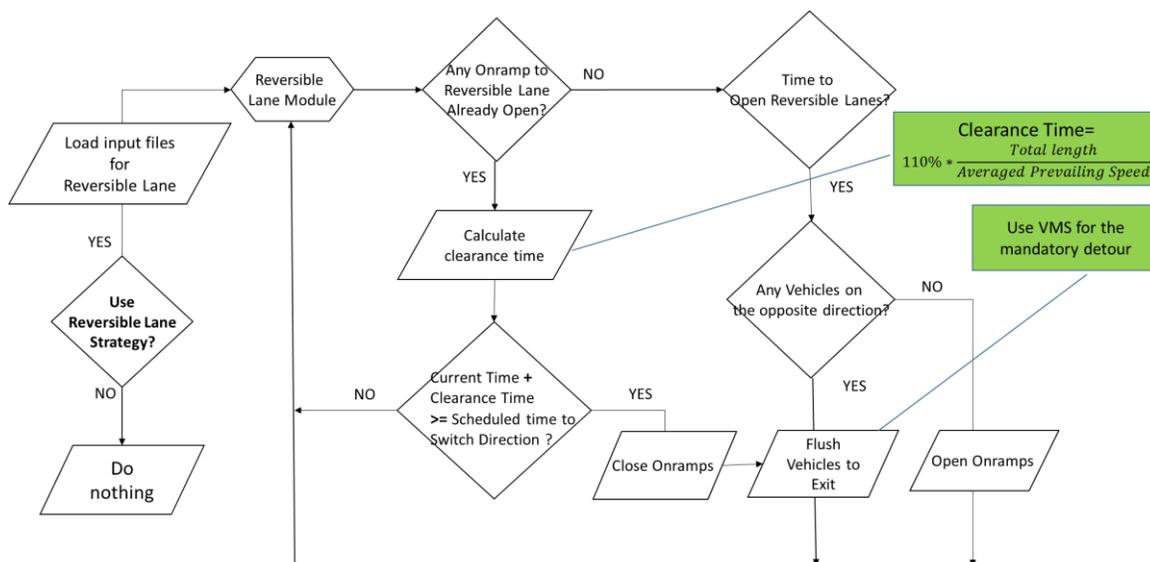


Figure 7-4: Flowchart of Dynamic Lane Use Control [Source: NWU]

7.1.3 Dynamic Speed Limit

Dynamic speed limit is a process of updating the speed limits in response to the predictive and prevailing traffic conditions. It can take into account the weather condition and other local geometries and road conditions. For the Chicago Testbed, the dynamic speed limit is generated according to the decision tree and implementation flowchart designed for speed harmonization, which were presented in section 6.1.1.

7.1.4 Adaptive Traffic Signal Control

The adaptive traffic signal control refers to (vehicle) actuated signal control operation which favors major direction vehicle progression. It takes into consideration the real-time and predictive traffic demand in order to adjust corresponding phase's green time. The adaptive traffic signal control requires a minimum (G-min) and a maximum (G-max) green time set up for each of the signalized intersections.

DYNASMART continues to extend the green (beyond G-min) up to G-max, as long as vehicles are detected at the stop bar. To allow for preferential treatment of vehicles traversing in the major direction, G-min for major approaches and G-max for minor approaches were set to correspond to green times obtained from pre-timed signal timing plan (and weather-responsive signal timing plan, if applicable).

7.1.4.1 Modeling Approach

Each corridor consists of a number of fully actuated signalized intersections. Specific features of the three corridors are described below.

Case 1: W Peterson Avenue. It is a 4-mile corridor with 8 signalized intersections connecting I-94 Freeway and Lakeshore Drive Highway. The intersection spacing ranges between 0.17 and 1 mile with an average spacing of 0.56 miles

Case 2: W Chicago Avenue. It is a 4-mile corridor with 11 signalized intersections connecting I-90 Freeway to the city. The intersection spacing ranges between 0.13 and 0.62 miles with an average spacing of 0.35 miles

Case 3: McCormick Boulevard. It is a 4-mile corridor with 9 signalized intersections. This corridor is located in the city and is relatively away from the freeways and highways. The intersection spacing ranges between 0.24 and 0.52 miles with an average spacing of 0.45 miles

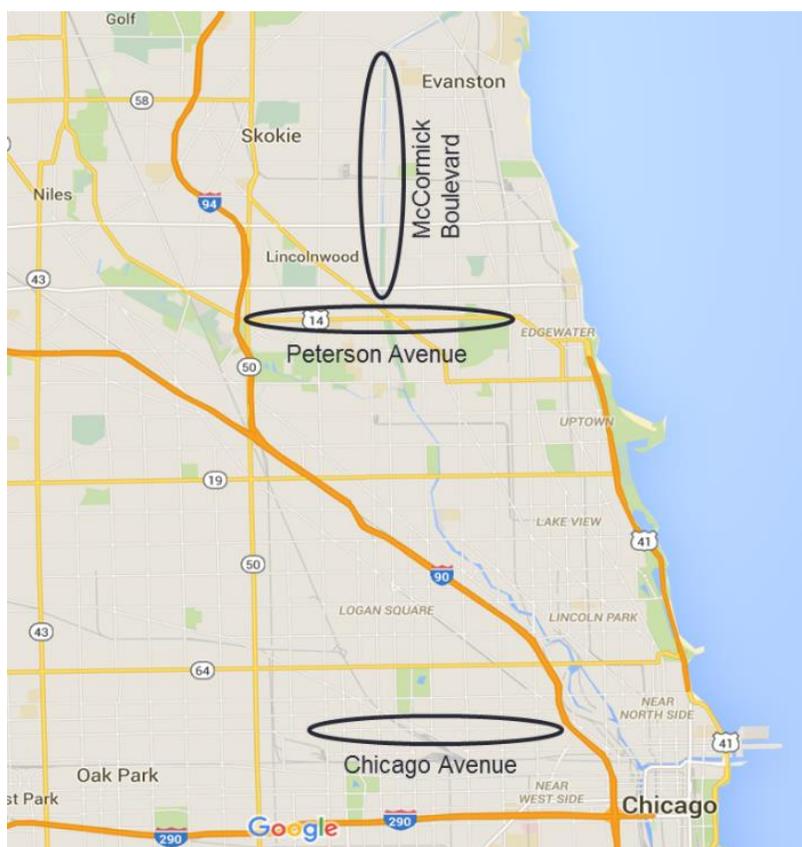


Figure 7-5: Corridors with Adaptive Traffic Signal Control [Source: Google Maps & NWU]

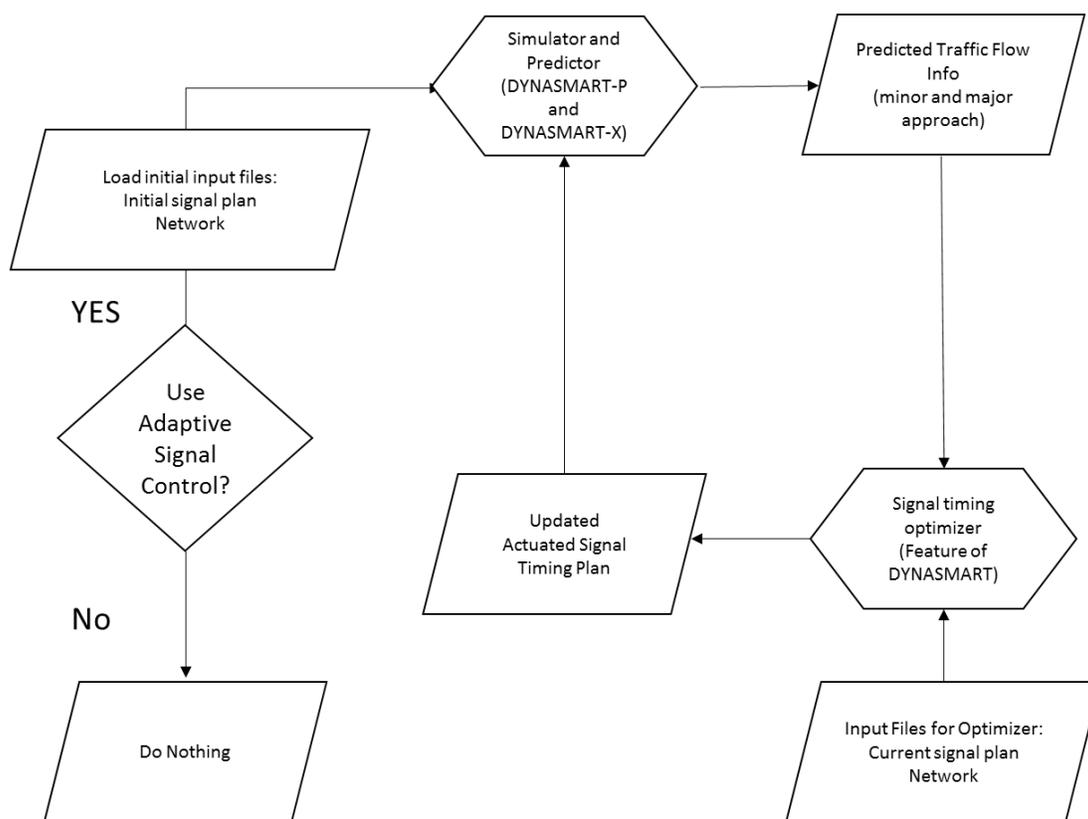


Figure 7-6: Flowchart of Adaptive Signal Control [Source: NWU]

Figure 7-6 introduces the implementation procedure of the adaptive signal control strategy. To implement the strategy under any operational condition, the simulator and predictor loads initial input files to generate and update traffic flow information for the signal timing optimizer. Meanwhile, the optimizer requires the current signal plan and network features to generate an updated actuated signal plan for the simulator and predictor. The procedures are conducted in a loop to simulate the traffic conditions and optimize the signal plan.

7.2 Active Demand Management Strategies

Active Demand Management Strategies (ADM) bundle include two individual ATDM strategies, which are predictive traveler information and dynamic routing. The ADM strategies are implemented as a bundle. The travel time (cost) to calculate time-dependent shortest path for dynamic routing is obtained from predictive traveler information within a pre-defined prediction horizon, which also belongs to prediction features to be evaluated and tested in this study.

7.2.1 Predictive Traveler Information

The prediction traveler information is calculated by TrEPS which predicts the traffic state, including traffic flow, travel time, speed, and other parameters for a predefined prediction horizon and helps choose and adjust the traffic management strategy and operations.

7.2.1.1 Modeling Approach

To implement this strategy, we emphasized the connection between the prediction results and the real-world simulation. To do so, we adopted the DYNASMART-X as the predictor and DYNASMART-P as the emulator, which is capable of reproducing traffic conditions given either traffic origin-destination matrix or individual trip data. To implement and evaluate the strategies, the DYNASMART-P and DYNASMART-X are running simultaneously, but DYNASMART-P, regarded as the real world, loads demand from individual trip data, where we provide vehicle departure information and the original paths; DYNASMART-X loads from OD matrix to simulate the real-world in DYNASMART-P. At the beginning of each prediction stage, DYNASMART-P is sending the link volume and speed to DYNASMART-X as the real-world observations to adjust the estimation status in DYNASMART-X, and after prediction finishes, DYNASMART-X will send the travel time and turn penalty back to DYNASMART-P as the predictive traveler information. Note that vehicles that have access to the predictive traveler information are able to update their routes to the new shortest path calculated by the dynamic routing strategy.

7.2.2 Dynamic Routing

The dynamic routing strategy calculates the shortest path for the vehicle from its current node to its destination. The shortest path can achieve both user equilibrium and system optimum. In this study, we adopted the user equilibrium and the Variable Message Sign (VMS) as the main constraint to generate the shortest path. Although all links in the network have been coded in the testbed model but some links may not be available during certain period of time (with VMS), and the shortest path calculation should avoid those links dynamically.

7.2.2.1 Modeling Approach

Once the predictive travel cost is available from online model, the shortest path (SP) calculation becomes dynamic with involvement of time-dependent travel time. In a static simulation environment where predictive travel cost is not available, the SP is calculated with prevailing travel time and assigned for individual vehicles. If a vehicle is able to receive en-route information, the route of this vehicle is updated when the travel cost of the new calculated SP is less than the pre-specified path and the cost savings exceed the threshold (e.g. 1 minute or 5 minutes for the entire trip). Once the predictive travel cost is available from online model, the shortest path calculation becomes dynamic with involvement of time-dependent travel time. The difference between static SP and dynamic SP lies in that the travel time $t(l)$ for link l keeps the same during the static SP calculation when the vehicle is moving, but in the dynamic SP calculation, the travel time $t(l, \tau)$ for link l keeps updating according to the arrival time τ at link l . As such, the dynamic SP with predictive travel information provides a better emulation than the static SP assignment.

The predictive information strategy and dynamic routing strategy are implemented in a bundle according to the design framework shown in Figure 7-7. Note that the predictive information will be sent back to the simulation of the real world from the predictor, but it is not guaranteed that every driver in the transport system can have access to the information. If some drivers have access to the predictive information, they can decide whether to update their route choice according to their individual route choice rule.

If ADM strategy bundle is implemented, the ADM module is triggered with specific input files. Every prediction roll period, the ADM module refers to the traffic prediction, gets predictive link travel time, and calculates the new SP. But the new SP are only provided for the drivers who have access to predictive traveler information. For these part of drivers, they can check whether the saving time is larger enough and decide whether to update their path; other drivers can only follow the old SP.

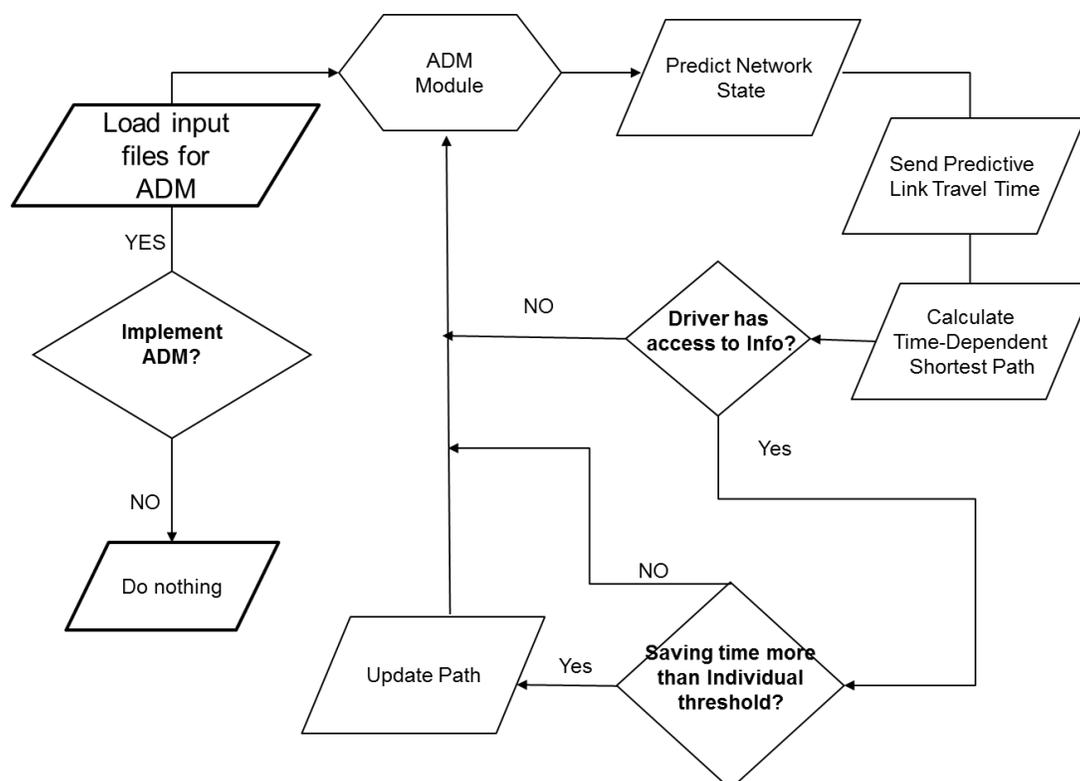


Figure 7-7: Flowchart of Active Demand Management Strategies [Source: NWU]

7.3 Weather-Related Strategies

Weather related strategies includes snow emergency parking management, traffic signal priority for winter maintenance vehicles, and snowplow routing. To simulate the weather related strategies a Winter Maintenance Module (WMM) was incorporated with a mesoscopic simulation tool. The logic of WMM is shown in Figure 7-8. Throughout the simulation horizon, the WMM continuously reads the predicted weather information for the next 3 hours and predicts the road surface condition and snow depth without anti-icing operation. When the road surface condition deteriorates to a predefined threshold, the WMM generates a maintenance plan and simulates it.

First, the emergency parking ban on arterial roads is enforced to ensure enough space for snowplow operation. Then the snowplow routing is generated based on road surface condition and predictive traffic volume and link speed for the next 3 hours. The objective function of snowplow routing is formulated to serve maximum traffic volume, where the links to be plowed are categorized with service hierarchy according to maintenance rule. After the snowplow routes are generated, signals at critical intersections are reset to give the priority to maintenance vehicles. 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. All other things being equal, the snowplow operation would reduce a link's capacity and increase the density. The anti-icing/deicing operation is done in conjunction with the plowing operation by spreading chemicals to the surface of road. The chemicals can lower the freezing-point of water, melt the remaining ice and snow on the road surface and prevent the formation of bonded snow and ice in the future.

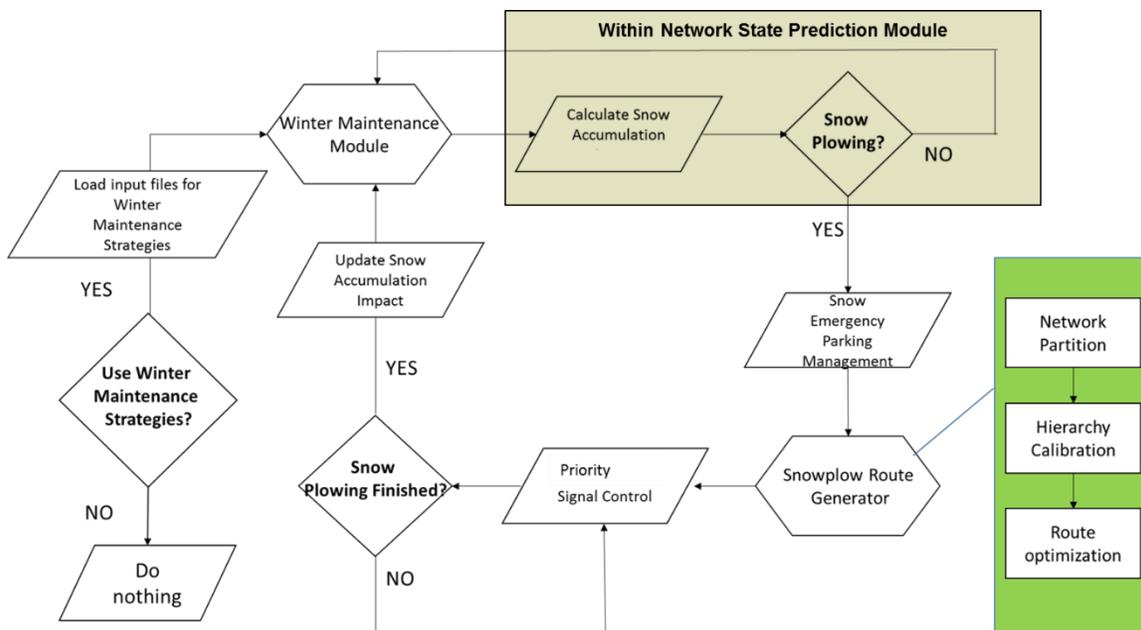


Figure 7-8: Implementation Procedures of Weather-Responsive Strategy [Source: NWU]

7.3.1 Modeling Approach

First, the emergency parking ban on arterial roads is enforced to create enough space for snowplow operation. The emergency parking ban goes into effect on the arterial roads that are marked as blue in Figure 7-9 when at least 2 inches of snow falls on the street. The vehicles park on the arterial when the ban is enforced will be ticketed or towed. Within the modeling framework, if the parking ban is violated on any specific link, then it will not be accessed and plowed by the snowplow.

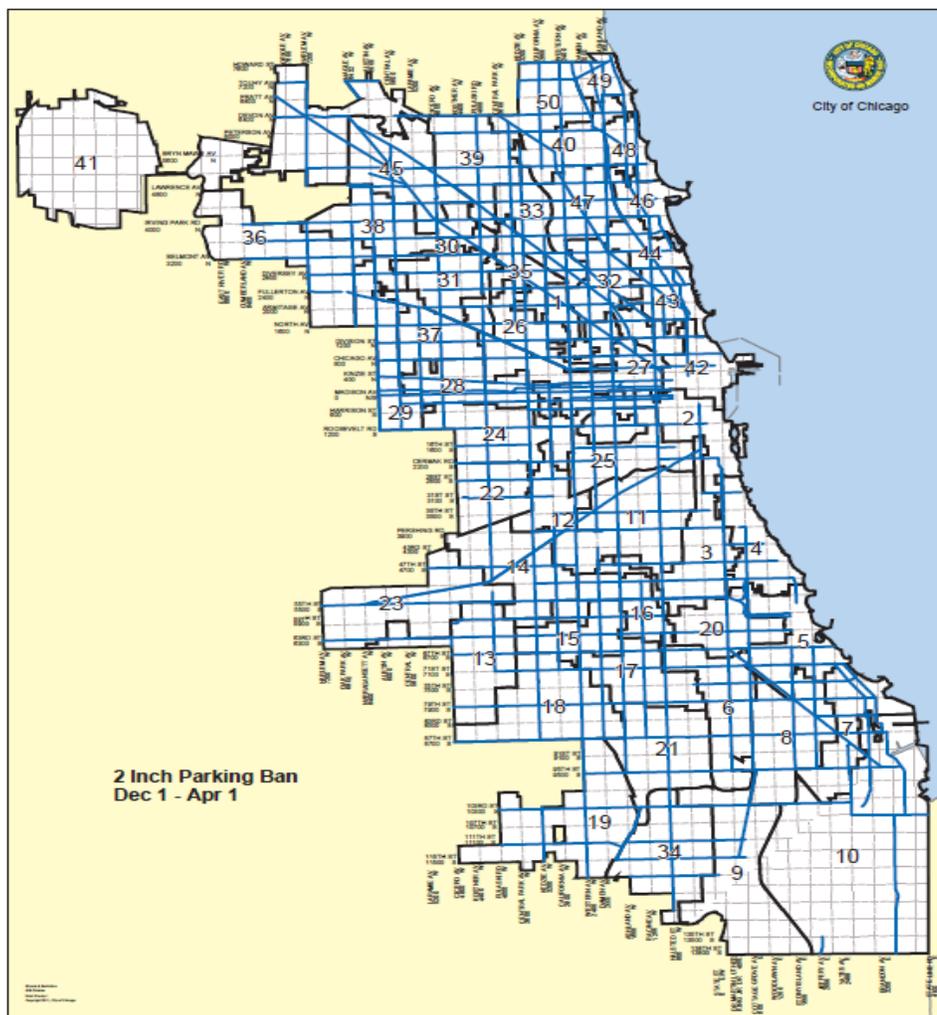


Figure 7-9: Two Inch Parking Ban Map [Source: NWU]

Then the snowplow routes are generated based on road surface condition and real-time traffic volume and link speed. We define the problem on a connected and directed graph $G=(V, A)$, where $V=\{0, \dots, n\}$ is the vertex set and $A=\{(i, j) : i, j \in V \text{ and } i \neq j\}$ is the arc set. The network is served by a homogeneous snowplow fleet $R= \{1, 2, \dots, M\}$. Vertex 0 is the depot where M snowplow vehicles are based. An additional vertex v_a represents an artificial depot, used as the start and end point of all routes. For every arc $(i, j) \in A$, let n_{ij} be the number of lanes, l_{ij} be the arc length and p_{ij} be the priority weight of arc ij . We incorporate the service hierarchy in the objective function by defining the priority weight p_{ij} which is calibrated both by the link volume and the type of arc. Highway, freeway, bus routes and hospital routes have the highest priority. VOT is defined as the average value of time of all travelers within the network. Each arc has an associated required service time t_{ij} and an associated traverse time t'_{ij} . $st(t)$ is the liquid water equivalent (LWE) snow intensity at time t . The LWE of snow is defined as the depth of water if one melts the snow to be measured. Depending on the snow density, the actual snow depth ranges from 4 to 10 times the LWE depth. For more information about liquid water equivalent measurement, please see (U. S. D. o. T. F. A. Administration, 2015). d_{ij}^t is the LWE of snow accumulated on the surface of arc (i, j) at time t . The relationship among snow depth, link speed reduction and capacity reduction is complicated. Due to the limitation of literature, we made the simplified assumptions showed in Table 7-3. d_{ij}^t is defined as following:

$$d_{ij}^t = \begin{cases} \int_0^t st_t dt & \text{if } t < t_{ijm}^k \\ \int_{t_{ijm}^k}^t st_t dt & \text{if } t > t_{ijm}^k \end{cases} \quad (7-1)$$

To simulate the real time traffic condition on an arc $(i,j) \in A$ at time t , let $v_{ij}(t)$ denote expected average speed without any snowplow operation and $q_{ij}(t)$ represent the predicted traffic volume. $v'_{ij}(t, t_{ijm}^k)$ is the predicted speed on an arc (i,j) at time t if the arc is scheduled to be plowed at t_{ijm}^k . $v'_{ij}(t, t_{ijm}^k)$ is different from the $v_{ij}(t)$ because the snow accumulation reduces speed or/and capacity. All snowplow operation starts at t_0 when the snow accumulation surpasses a threshold and must be completed within the required service time window before t_e .

Table 7-3: Snow Accumulation vs. Speed Reduction and Capacity Reduction

d_{ij}^t (inches LWE)	Speed Reduction	Capacity Reduction
(0, 0.2]	11%	None
(0.2, 0.4]	16%	None
(0.4, 0.8]	20%	50%
(0.8, ∞)	Lane closure	Lane closure

We define three decision related variables similar to (22):

- x_{ijm}^k : binary variable equals to 1 if and only if arc (i,j) is served by snowplow m and appears in the k th position of its route
- y_{ijm}^k : binary variable equals to 1 if and only if arc (i,j) is traversed by vehicle m and appears in the k th position of its route while deadheading
- t_{ijm}^k : is the start time of service or traversal of arc (i,j) by vehicle m and this arc appears in the k th position of the route.

The problem can be formulated mathematically as follows:

$$\text{minimize } \sum_{(i,j) \in A} D(t_{ijm}^k, q_{ij}) * VOT * p_{ij} - \sum_{(i,j) \in A} y_{ijm}^k * t'_{ij} * \text{TraverseCost} \quad (7-2)$$

$$D(t_{ijm}^k, q_{ij}) = \int_{t_0}^{t_e} \left(\frac{l_{ij}}{v_{ij}^t} - \frac{l_{ij}}{v'_{ij}(t, t_{ijm}^k)} \right) * q_{ij}(t) dt \quad (7-3)$$

Constraints:

$$t_{ijm}^k + t_{ij} x_{ijm}^k + t'_{ij} y_{ijm}^k = \sum_{(h,j) \in A} t_{jhm}^{k+1} (x_{jhm}^{k+1} + y_{jhm}^{k+1}) \quad (7-4)$$

$$\sum_{m \in R, k \in K} (x_{a0m}^k + y_{a0m}^k) = M \quad (7-5)$$

$$\sum_{m \in R, k \in K} (x_{oam}^k + y_{oam}^k) = M \quad (7-6)$$

$$\sum_{(i,j) \in A} (x_{ijm}^k + y_{ijm}^k) = \sum_{(j,h) \in A} (x_{jhm}^{k+1} + y_{jhm}^{k+1}) \quad (7-7)$$

$$\sum_{k,r} x_{ijm}^k = n_{ij} \quad (7-8)$$

$$\sum_{(i,j) \in A} (x_{ijm}^k + y_{ijm}^k) \leq 1 \quad (7-9)$$

$$x_{ijm}^k \in \{0,1\} \quad (7-10)$$

$$y_{ijm}^k \in \{0,1\} \quad (7-11)$$

$$t_{ijm}^k > 0 \quad (7-12)$$

The objective function consists of two parts: the benefit of plowing and the operational cost of maintenance. The benefit is calculated as the difference between the total predictive travel times with and without plowing multiplied by the value of time. Although the operation cost consists of service cost and deadheading cost, we only include the deadheading cost in the objective function because the service cost is constant that won't change under different scenarios (Corberán & Prins, 2010). Constraints (7-4) guarantees time consistency of service and traversal times. Constraints (7-5) and (7-6) ensure all paths start and end at the depot. Constraint (7-7) enforces flow conservation. Constraint (7-8) states that all lanes of arc ij must be served. Constraint (7-9) requires that each position of a route can only be assigned one arc.

After the snowplow routes are generated, signals at critical intersections are reset to enable priority for snowplows. The snowplow operation on a link would reduce the link capacity and increase the density. It was assumed that a lane is blocked by the maintenance vehicle during plowing and cannot be accessed by other vehicles and cannot be accessed by other vehicles. Given a link i , let n_i denote the number of lanes; l_i represent the link length; C_i be the link capacity, and q_i be density. When a snowplow is plowing the link, the reduced capacity is estimated as $C'_i = C_i(1 - \frac{1}{n_i})$ and the lane density is calculated as $q_i = \frac{\text{number of vehicles}}{n_i l_i - l_i}$

The plowing and deicing/anti-icing operation are conducted in conjunction. Snowplows spread the chemicals to the road surface while servicing the road. The chemicals melt the reset of the snow and ice on the pavement and prevent further formation of ice and snow bond. The 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.

Chapter 8. Connected Vehicle Technology versus Legacy Systems

8.1 Research Questions

This chapter helps us to study the impact of connected vehicles in comparison to the regular vehicles. Accordingly, the following research questions are addressed:

- What is the marginal benefit if data from connected vehicle technology is augmented with data from legacy systems?
- What is the marginal benefit if data from legacy systems is augmented with data from connected vehicle technology?

The benefits analyzed are for the entire network based on the flow-density diagram, as well as network- and corridor- wide system performance. In this section the term “connectivity” means in the presence of connected vehicles.

8.2 Analysis Approach

To capture the effects of connectivity at network level, it is critical to model the collective effects of the interactions between connected and regular vehicles on traffic flow. Accordingly, this study utilizes the microscopic simulation framework of Talebpour et al. (Talebpour et al., 2016) to identify the speed-density relationships at different market penetration rates (MPRs) of connected vehicles. This tool utilizes different mathematical models for regular and connected vehicles and is capable of capturing the collective effects of the interactions between them on traffic flow dynamics. In particular, gap acceptance and lane changing models were incorporated to capture the effects closely. The calibrated speed-density relationships are then used as input to the mesoscopic simulation tools to simulate the network-wide effects of connectivity. From the calibrated speed-density relationships, it is evident that the flow conditions improve with the advent of connectivity in the network.

The acceleration behavior of regular vehicles is modeled based on the state-of-the-art car-following model of Talebpour et al. (Talebpour, Mahmassani, & Hamdar, 2011). This model is based on Kahneman and Tversky’s prospect theory (Kahneman & Tversky, 1979) which recognizes that drivers have different perceptions encountering congested versus uncongested regimes. Accordingly, they introduced two value functions, one for modeling driver behavior in congested regimes and one for modeling driver behavior in uncongested regimes. The acceleration behavior of connected vehicles is modeled based on the Intelligent Driver Model (IDM) (Kesting, Treiber, & Helbing, 2010). IDM specifies a following vehicle’s acceleration as a continuous function of the vehicle’s current speed, the ratio of the current spacing to the desired spacing, and the difference between the leading and the following vehicles’ velocities. Perceptive parameters such as desired acceleration, desired gap size, and comfortable deceleration are considered in this model (Kesting et al., 2010; Treiber, Hennecke, & Helbing, 2000).

This study utilized the speed-density relationship to translate traffic flow dynamics in a connected environment from the microscale scale framework mentioned above to the mesoscale tool. Accordingly, a 5.5-miles highway segment on I-290 in Chicago is simulated with the above microscopic simulation tool at different MPRs of connected vehicles and different speed limits. Figure 8-2 shows the geometric

characteristics of this highway segment. The resulting speed-density curves are identified based on the microscopic simulation results. Figure 8-1 shows the schematic of the calibration approach based on the microscopic simulation results. Speed-density curves are identified based on multiple simulation runs (with different initial random number seeds) until convergence is achieved. Once the model is calibrated, it formed the basis of the implementation of speed harmonization in the mesoscopic simulations. Note that the parameters of this model are calibrate against Next Generation Simulation (NGSIM) data (Federal Highway Administration, 2006).

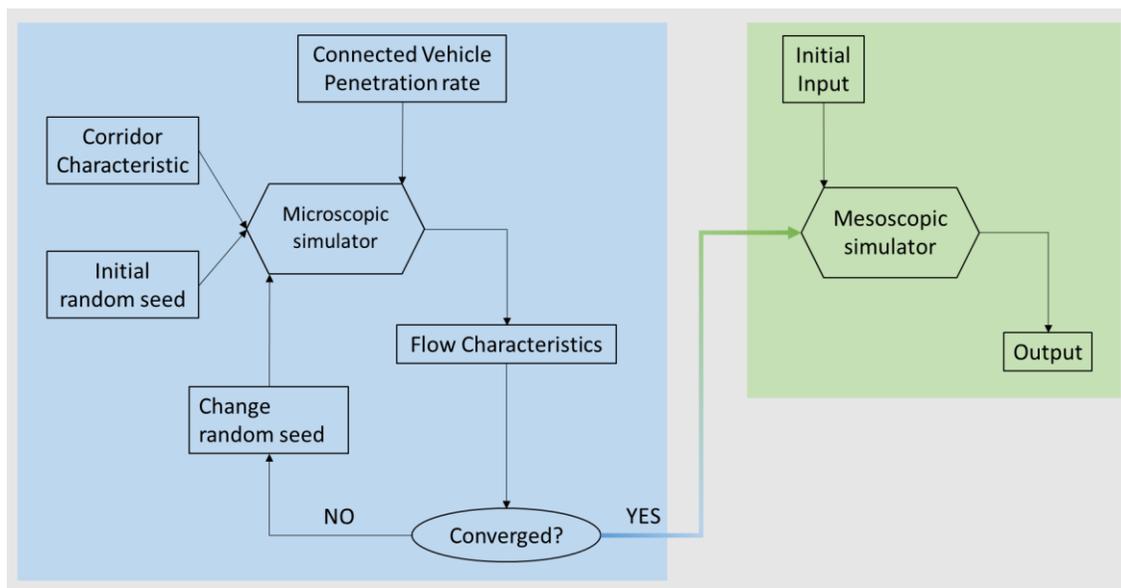


Figure 8-1: Schematic of the Calibration and Simulation Frameworks [Source: NWU]

Four different MPRs of connected vehicles are selected (i.e., 0%, 10%, 50%, and 90%) along with four different speed limit values (i.e., 15, 35, 45, and 55 mph). Connected vehicles were simulated with 100% compliance with recommended speeds. Figure 8-3 shows the calibrated speed density curves. At lower speed limits, higher MPRs delay the breakdown and speed drops are observed at higher densities. At higher speed limits, however, the breakdown happens at similar densities over all MPRs. Moreover, regardless of the speed limit, as the MPR of connected vehicles increases, higher speeds can be achieved at the same density value. This is particularly significant in the congested regime of the speed-density curves.



Figure 8-2: Geometric Characteristics of the Selected Segment in Chicago, IL [Source: NWU]

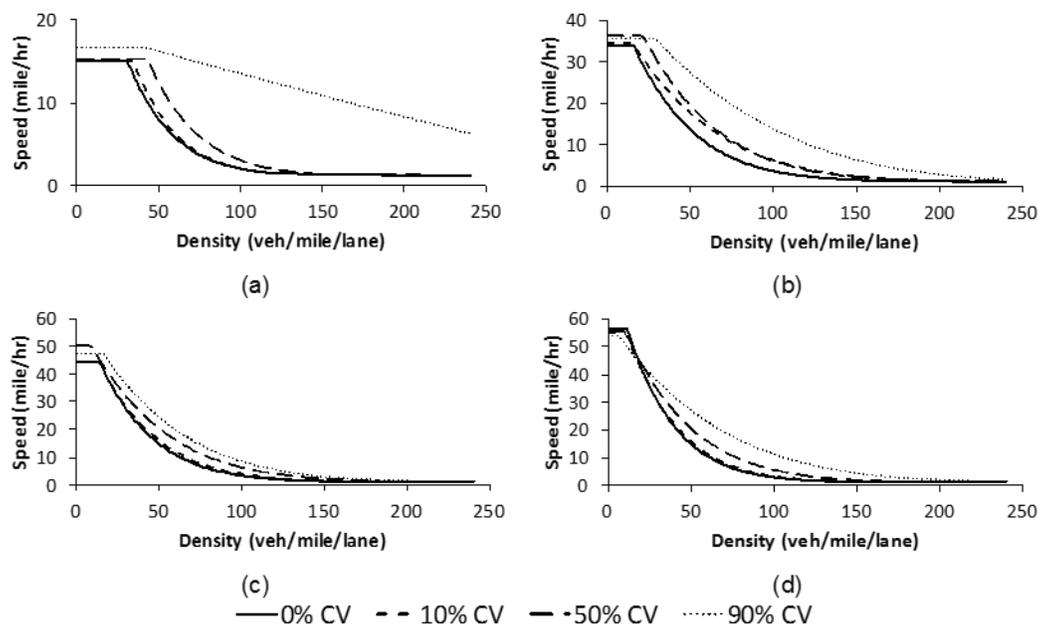


Figure 8-3: Speed-Density Curves at Different Market Penetration Rates of Connected Vehicles for Different Speed Limits: (a) 15 mph; (b) 35 mph; (c) 45 mph; and (d) 55 mph [Source: NWU]

8.2.1 Scenarios

8.2.1.1 Step 1: Impact of Connected Environment

Three demand levels (i.e., low, medium and high) were simulated at four different MPRs of connected vehicles (i.e., 0, 10, 50 and 90%) on the freeways, where the rest of the vehicles are regular vehicles with no connectivity. The normal demand level was calibrated in accordance with a historical static O-D matrix and time-dependent traffic counts on observational links. The demand level refers to the demand pattern extracted from the same distribution of normal level but with different fraction of vehicles. Low demand level has 40%, medium demand level has 70% and high demand level has 90% of the normal level vehicles. The entire planning horizon or simulation period was divided into 5-min interval series. For each 5-min interval, the space mean speed, network density, network flow rate, distance-weighted travel time rate, and distance-weighted standard deviation of travel time rate were computed.

8.2.1.2 Step 2: Impact of Speed Harmonization with No Connectivity

Figure 8-4 shows the scenarios tested for the step 2 to check the impact of speed harmonization with no connectivity in the meso-simulation tool. The speed harmonization messages are sent to all the vehicles only through DMS signs and that there are no V2V and V2I communications. At this stage, there are no connected vehicles in the network. Six scenarios were tested and each one of them represents the speed harmonization test for an operational condition mentioned in section 3.1.

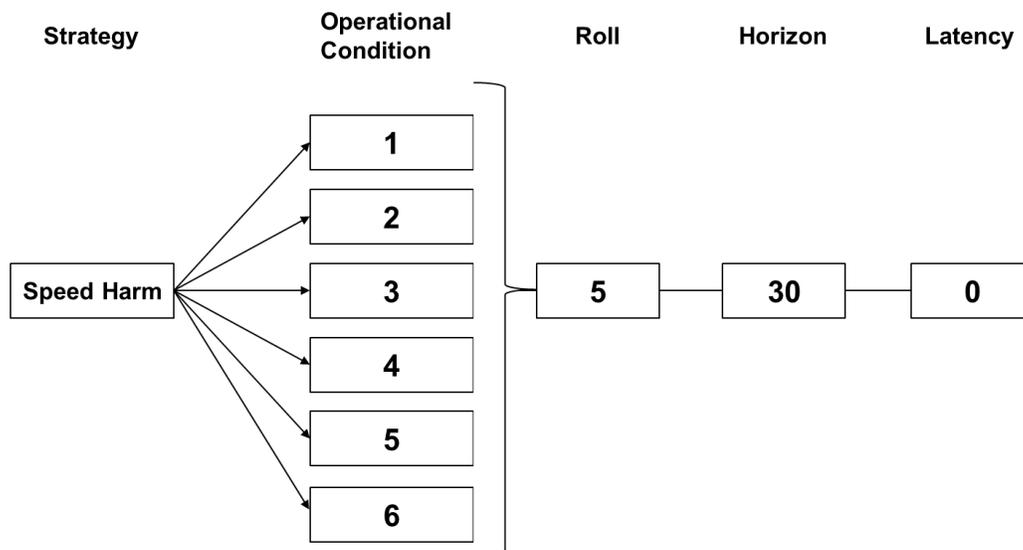
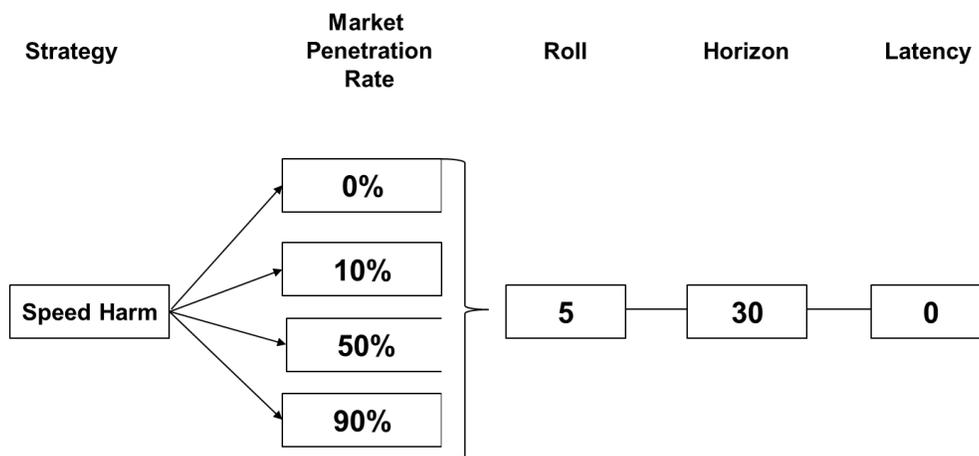


Figure 8-4: Tests Configuration for Speed Harmonization Effect [Source: NWU]

8.2.1.3 Step 3: Impact of Speed Harmonization within a Connected Environment

Figure 8-5 shows the scenarios tested for the step 3 to check the impact of speed harmonization within a connected environment with the meso-simulation tool in conjunction with the micro-simulation tool. 24 scenarios were tested and each represents the speed harmonization test for an operational condition with a specific market penetration rate.



Tests for OC 1 ~ 6

Figure 8-5: Tests Configuration for Speed Harmonization Under a Connected Environment [Source: NWU]

8.2.2 Results

8.2.2.1 Impact of a Connected Environment

Figure 8-6 shows the fundamental diagrams for different MPRs of connected vehicles on the Chicago highway network at the low demand level. In this figure, an increase in connectivity results in a decrease in density and/or increase in flow. Increase in connected vehicles enables vehicles to move at a higher

flow rate which avoids the high density levels on the network. The breakdown density and flow were increased, which resulted in a higher throughput in the highway network. Additionally, increase in connected vehicles can reduce the maximum density experienced on the network. Until 50% MPR, the flow rate increases with the increase in the connected vehicles and the maximum density experienced by the network remains the same. At 90 percent MPR, in addition to the increased flow rate, maximum density reduces as well. It indicates that connected vehicles can potentially increase the freeway/highway network capacity and throughput at low demand levels.

Figure 8-7 shows the fundamental diagrams for different MPRs of connected vehicles at the medium demand level. As compared to Figure 8-6, the impact of connected vehicles increases with MPR. The flow rate increases with an increase in MPRs of connected vehicles at the same density level. Moreover, at 50% and higher MPRs, higher flow rates are achieved at the same density, which can result in a faster recovery after breakdown. Note that at high MPRs, a clear hysteresis loop is observed at both low and medium demand levels (see Figure 8-6 and Figure 8-7). Figure 8-8 shows the fundamental diagrams for different MPR levels in Chicago’s freeway/highway network at the high demand level. In this case, not all vehicles reach their destinations due to gridlock, making corridors highly dense. In fact, the high demand level simulation reveals the effects of connected vehicles on network-wide traffic flow dynamics under the extreme condition. In this case, significant breakdown and scatter in the NFDs are observed at all MPRs. In the extreme condition, low MPRs of connected vehicles do not result in an improvement in flow and/or density and the flow-density relationship remains almost unaffected. At 50% MPR, the network starts to experience an increase in the flow rate for the same density level, as compared to 0% and 50% MPR. At 90% MPR, highway network performs at its best as the highest flow rate is achieved. At high demand level, highways show a small hysteresis loop and finally breaks down to never recover again, but still higher throughput is achieved as compared to other lower MPRs. Therefore, connected vehicles can potentially enable the network to enhance its throughput rate, even in extreme conditions.

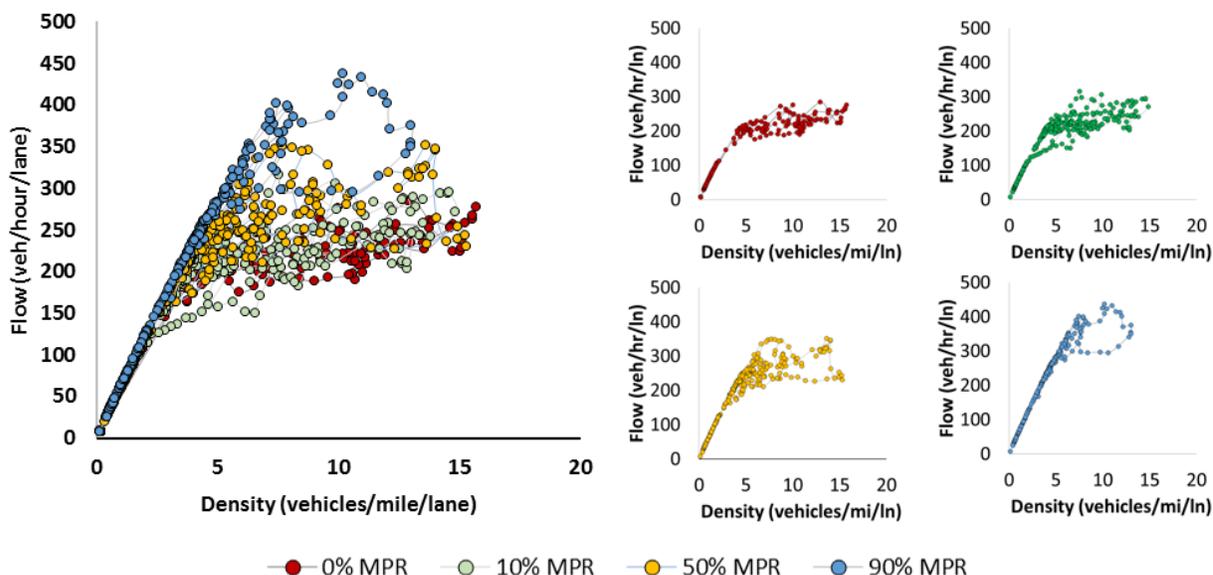


Figure 8-6: Fundamental Diagram for Chicago Highway Network at Different Market Penetration Rates of Connected Vehicles Under Low Demand [Source: NWU]

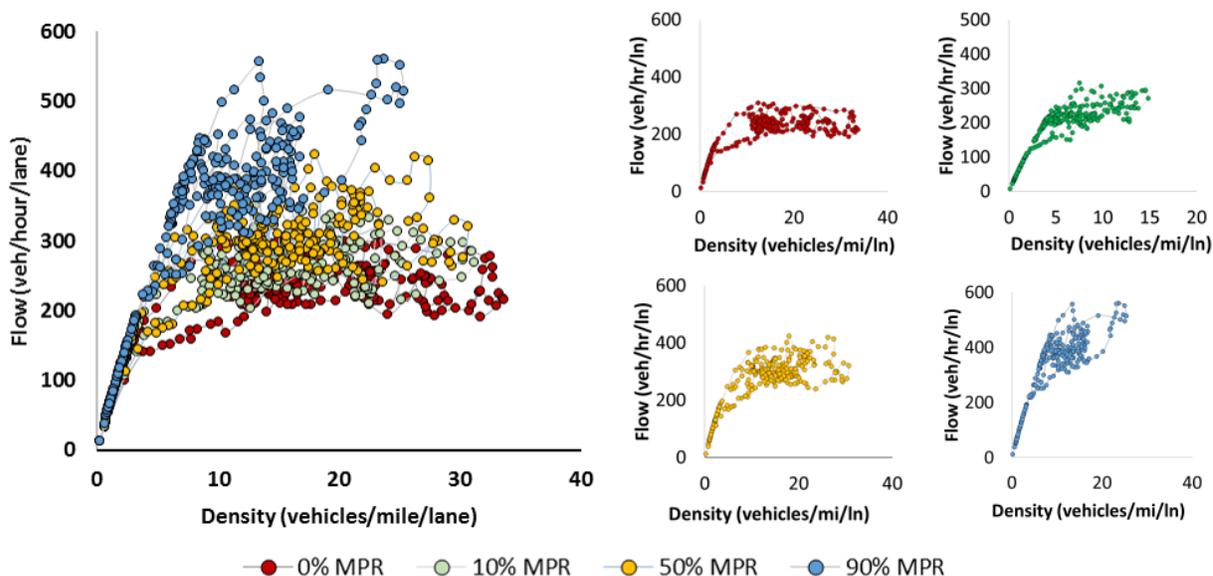


Figure 8-7: Fundamental Diagram for Chicago Highway Network at Different Market Penetration Rates of Connected Vehicles Under Medium Demand [Source: NWU]

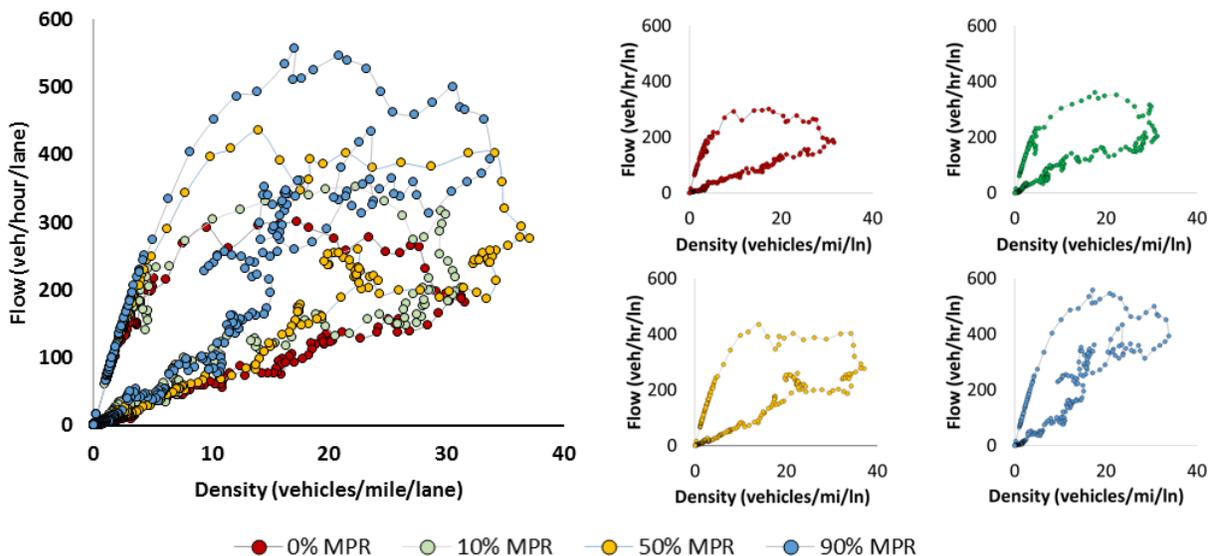


Figure 8-8: Fundamental Diagram for Chicago Highway Network at Different Market Penetration Rates of Connected Vehicles Under High Demand [Source: NWU]

At the low demand level (Figure 8-9), as MPR increases, the network experiences a reduction in maximum density and an increase in flow rate at the same density level. Connected vehicles are improving the throughput while controlling the density of the vehicles. At the medium demand level (Figure 8-10), closed loop hysteresis is observed at all MPRs. The width of the hysteresis loop reduces with an increase in the MPRs of connected vehicles. This implies that increase in the MPRs of connected vehicles facilitates the recovery. At the high demand level (Figure 8-11), grid-lock is observed, making corridors highly dense. The network follows the similar flow-density relationship as Figure 8-6 and Figure

8-8 but with little improvement with increase in the MPRs of connected vehicles. It is the extent of the relationship that gets affected. With an increase in the MPR, the maximum density decreases. Moreover, connected vehicles can potentially enhance throughput in the full network.

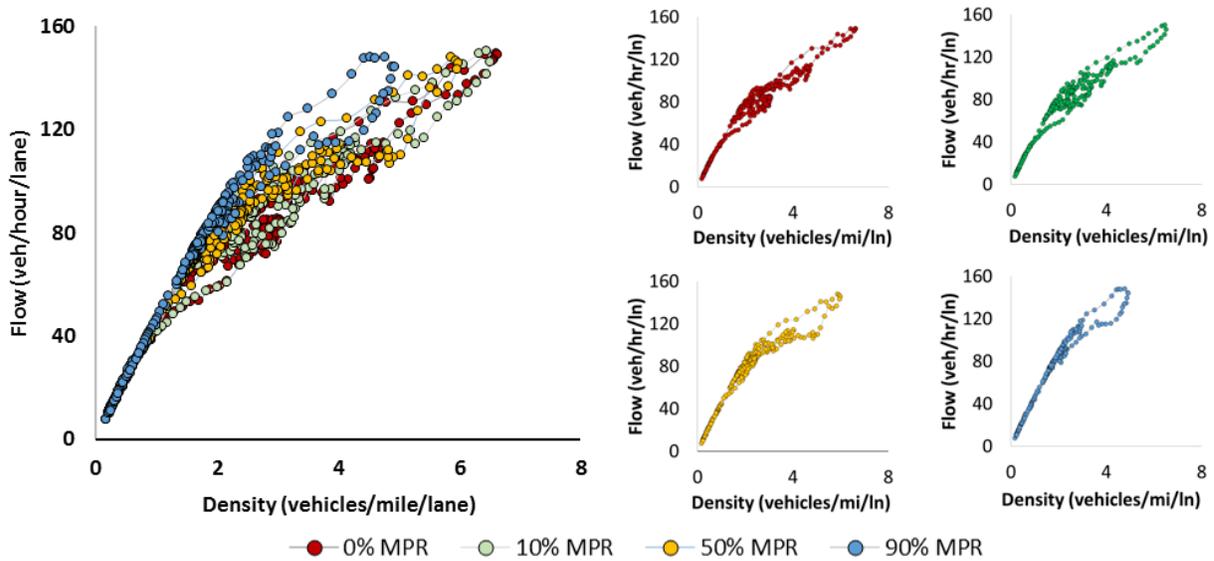


Figure 8-9: Fundamental Diagram for Chicago Whole Network at Different Market Penetration Rates of Connected Vehicles Under Low Demand [Source: NWU]

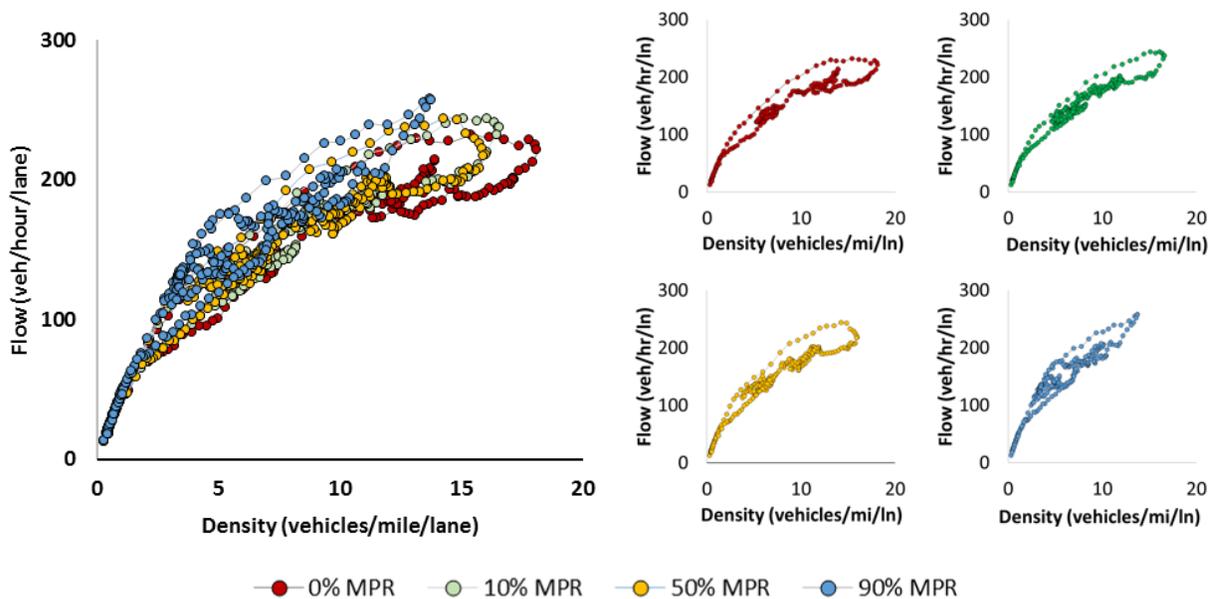


Figure 8-10: Fundamental Diagram for Chicago Whole Network at Different Market Penetration Rates of Connected Vehicles Under Medium Demand [Source: NWU]

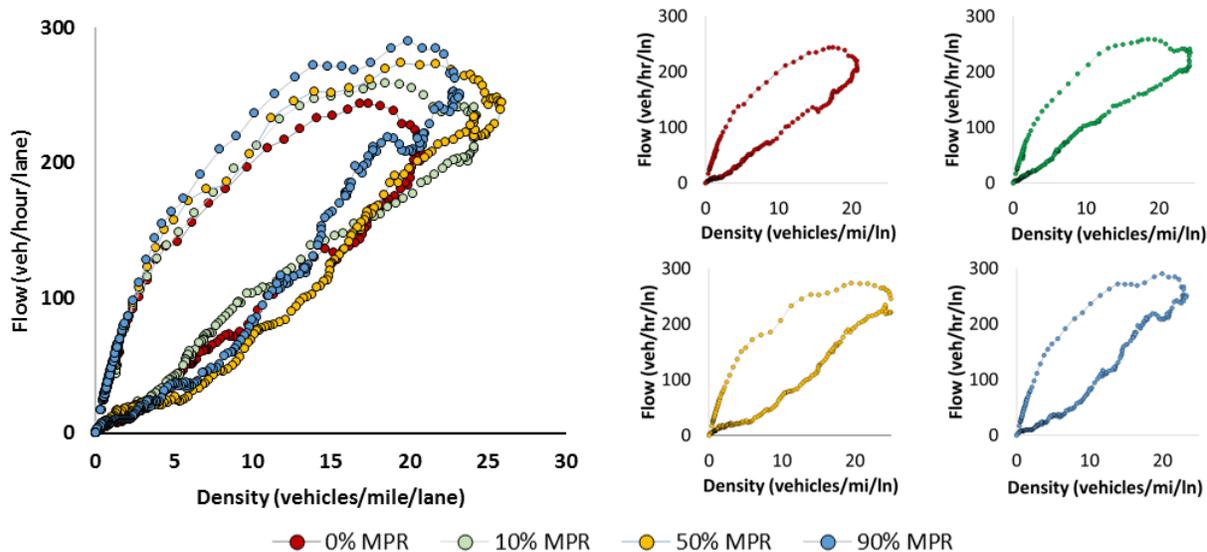


Figure 8-11: Fundamental Diagram for Chicago Whole Network at Different Market Penetration Rates of Connected Vehicles Under High Demand [Source: NWU]

Table 8-1 through Table 8-3 give a summary of the impact of connected vehicles on the flow of vehicles. It can be observed that with Increase in MPR, the flow rate increases at all demand levels for highway network and at high demand level for the whole network. Impact is not prominent for low and medium demand level for whole network.

Table 8-1: Statistical Summary of the Impact of Connected Vehicles at Low Demand Level

MPR	Flow on Whole Network (vphpl)			Flow on Highway Network (vphpl)		
	Min.	Avg.	Max.	Min.	Avg.	Max.
0 CV	8	71	149	0	74	302
10 CV	8	71	150	1	93	361
50 CV	8	71	148	0	113	435
90 CV	8	71	148	1	162	558

Table 8-2: Statistical Summary of the Impact of Connected Vehicles at Medium Demand Level

MPR	Flow on Whole Network (vphpl)			Flow on Highway Network (vphpl)		
	Min.	Avg.	Max.	Min.	Avg.	Max.
0 CV	13	130	232	12	204	309
10 CV	13	129	244	13	224	351
50 CV	13	129	244	13	255	424
90 CV	13	128	258	13	320	561

Table 8-3: Statistical Summary of the Impact of Connected Vehicles at High Demand Level

MPR	Flow on Whole Network (vphpl)			Flow on Highway Network (vphpl)		
	Min.	Avg.	Max.	Min.	Avg.	Max.
0 CV	0	60	244	0	74	302
10 CV	1	74	259	1	93	361
50 CV	0	86	274	0	113	435
90 CV	0	96	290	1	162	558

The results presented in Figure 8 12 show the effects of connected vehicles on travel time reliability at low, medium, and high demand levels in Chicago. For all MPRs, weighted mean and standard deviation of travel time follow one linear trend with different extents. This finding indicates that the linear relationship that Mahmassani et al. (H. Mahmassani, Hou, & Saberi, 2013) found between the mean and standard deviation of travel time at the network-level is still applicable to the connected driving environment. At the low demand level (Figure 8 12(a)), with an increase in MPR, the extent of the distribution gets smaller, which implies that the travel time variability decreases. Additionally, there is a slight reduction in the standard deviation for the same travel time with an increase in MPR. This implies that travel time reliability increases as MPR of connected vehicles increases. At the medium demand level (Figure 8 12(b)), the impact of connected vehicles is more perceptible than at the low demand level. Similar to the low demand case, with an increase in MPR, the extent of the distribution gets smaller, but the reduction is more significant than in the low demand case. At the high demand level (Figure 8 12(c)), the weighted mean and standard deviation of travel time, follow the same linear pattern with different extents. With an increase in the MPR of connected vehicles, the maximum mean and standard deviation of travel time decreases and the standard deviation decreases for the same mean travel time. At all demand levels, the network is performing better and getting more reliable with the increase in the MPR of connected vehicles, while following the same linear travel time variability relation

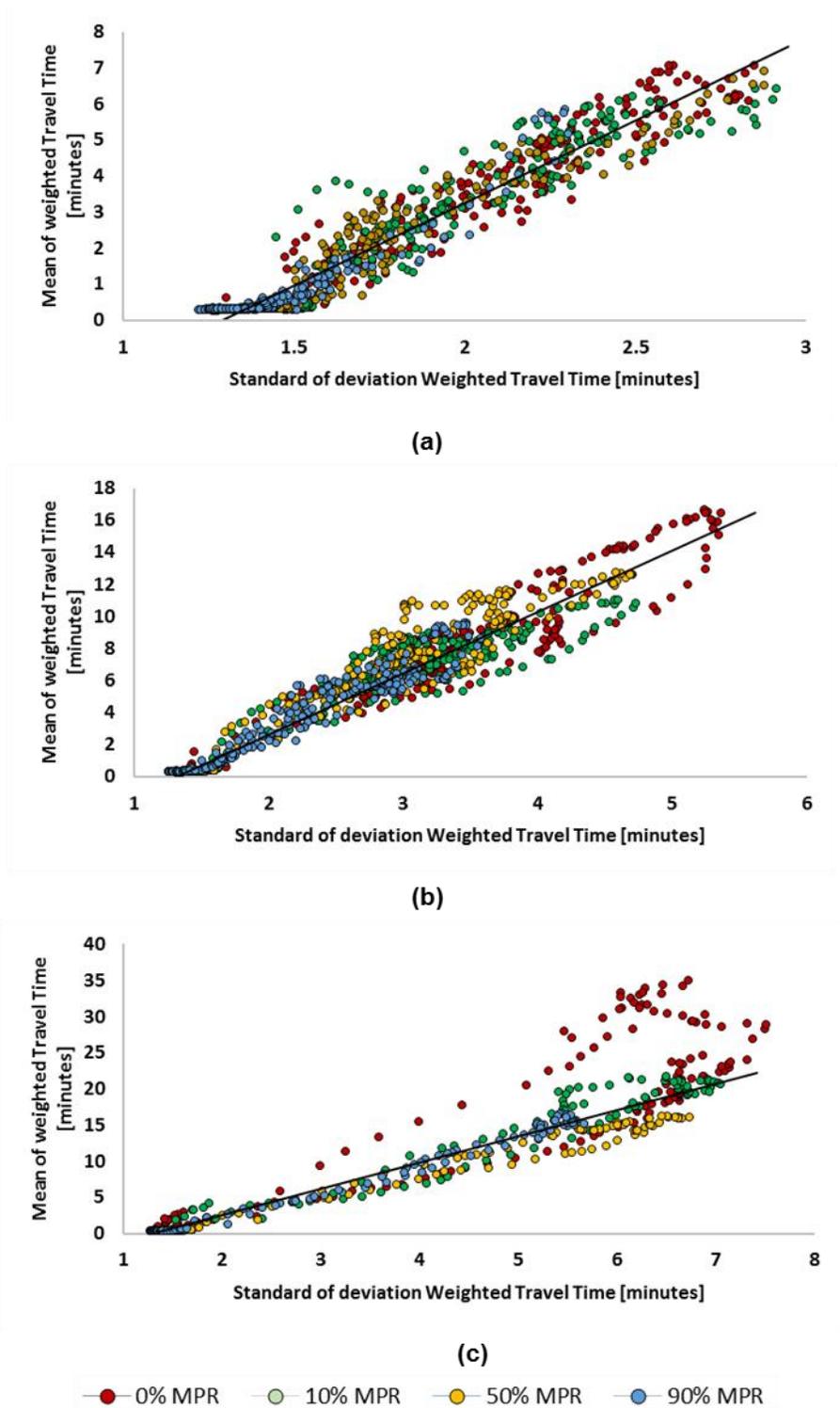


Figure 8-12: Travel Time Variability Measures for Chicago with (a) Low Demand; (b) Medium Demand; and (c) High Demand [Source: NWU]

The results presented in Figure 8-12 show the effects of connectivity among vehicles on travel time reliability at low, medium, and high demand levels in Chicago. For all MPRs of connected vehicles, weighted mean and standard deviation of travel time follow one linear trend with different extents. This

finding indicates that the linear relationship that Mahmassani et al. (H. Mahmassani, Hou, & Saberi, 2013) found between the mean and standard deviation of travel time at the network-level is still applicable to the connected driving environment. At the low demand level (Figure 8-12 (a)), with an increase in MPR of connected vehicles, the extent of the distribution gets smaller, which implies that the travel time variability decreases. Additionally, there is a slight reduction in the standard deviation for the same travel time with an increase in MPR. This implies that travel time reliability increases as MPR of connected vehicles increases. At the medium demand level (Figure 8-12 (b)), the impact of connectivity among the vehicles is more perceptible than at the low demand level. Similar to the low demand case, with an increase in MPR, the extent of the distribution gets smaller, but the reduction is more significant than in the low demand case. At the high demand level (Figure 8-12 (c)), the weighted mean and standard deviation of travel time, follow the same linear pattern with different extents. With an increase in the MPR of connected vehicles, the maximum mean and standard deviation of travel time decreases and the standard deviation decreases for the same mean travel time. At all demand levels, the network is performing better and getting more reliable with the increase in the MPR of connected vehicles, while following the same linear travel time variability relation.

8.2.2.2 Impact of Speed Harmonization with No Connectivity

Figure 8-13 through Figure 8-15 present the impact of speed harmonization with no connected vehicles in 6 OCs. Results shown are compared to the do nothing case where no strategy is applied. It is evident that with speed harmonization, in all OC's except OC4, system achieves increased throughput in 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.

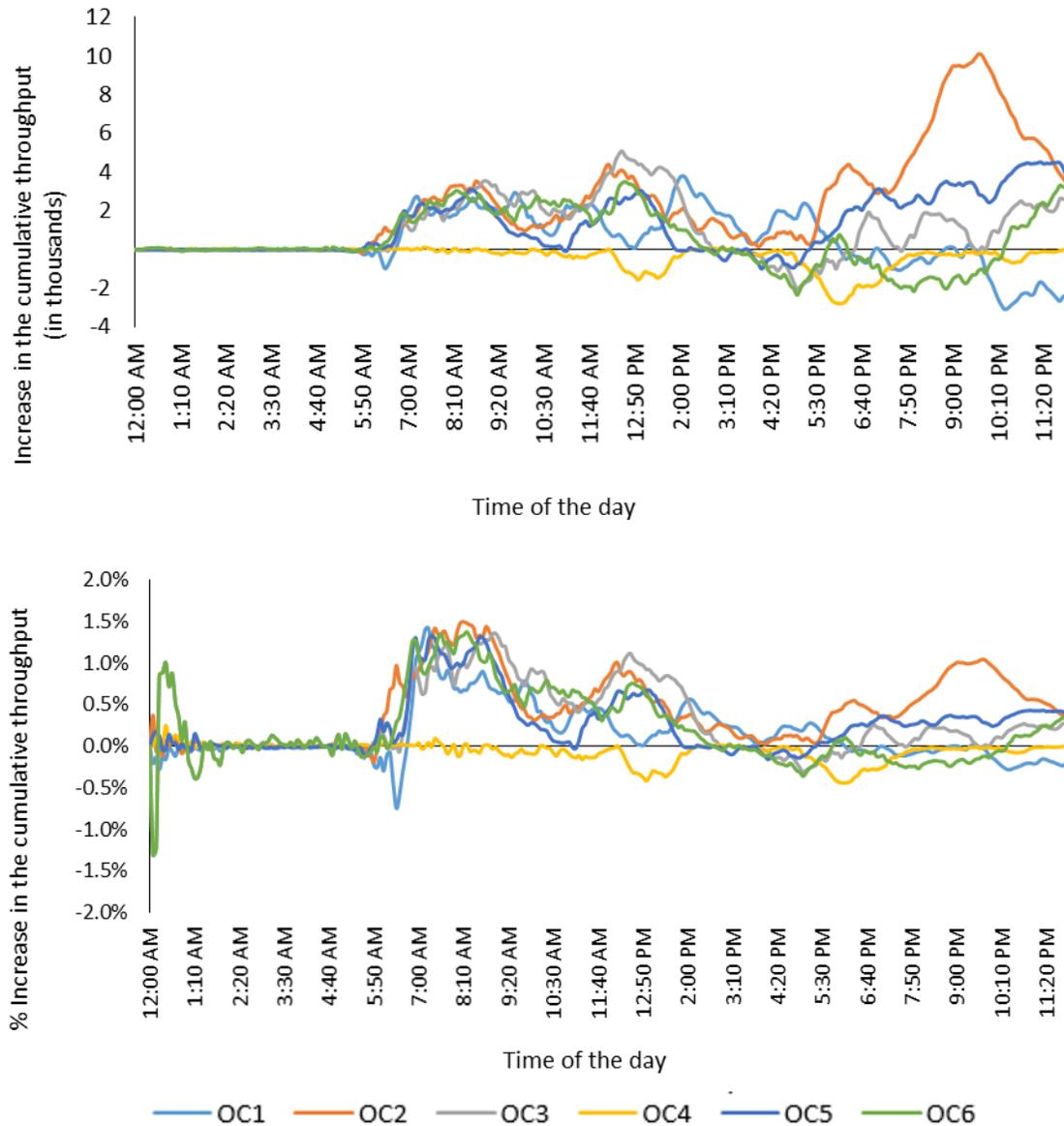


Figure 8-13: Impact of Speed Harmonization [Source: NWU]

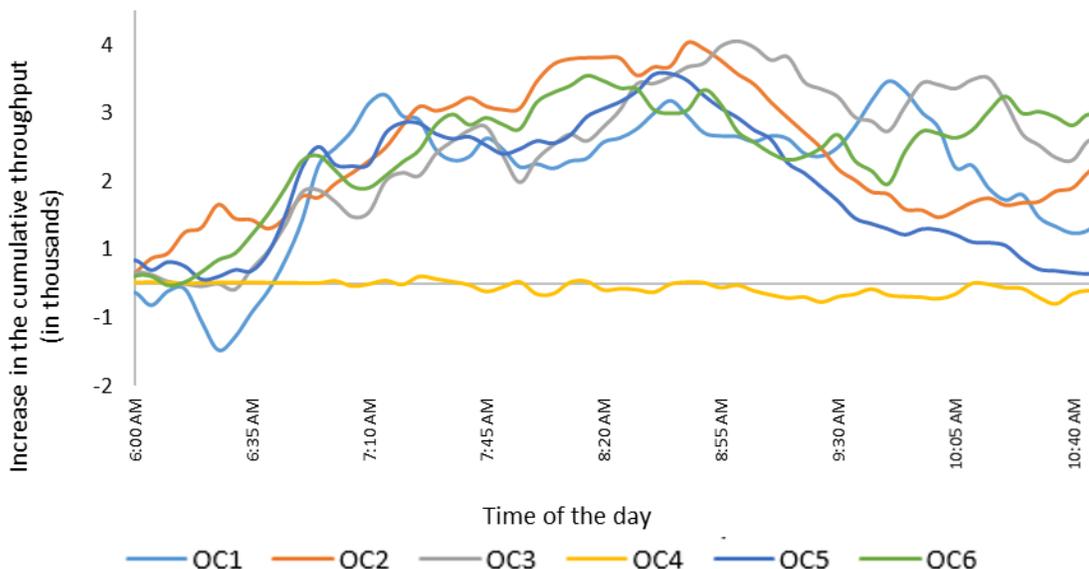


Figure 8-14: Impact of Speed Harmonization During Morning [Source: NWU]

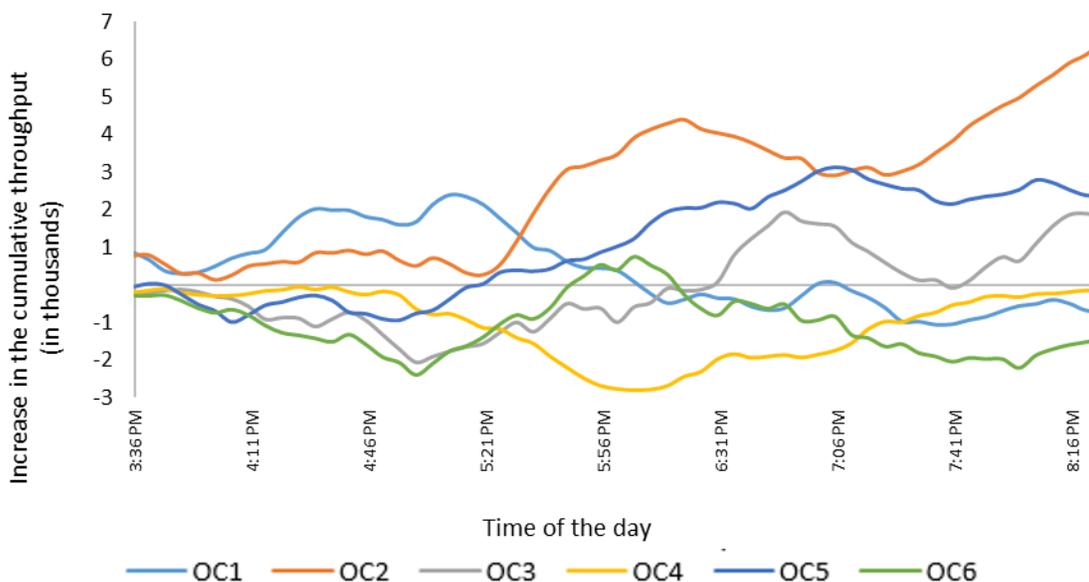


Figure 8-15: Impact of Speed Harmonization During Evening [Source: NWU]

Figure 8-14 gives a closer view to the impact of speed harmonization in the morning time. Figure 8-15 shows that in the evening time the impact is smaller compared to the morning time.

8.2.2.3 Impact of Speed Harmonization in a Connected Environment

The individual impact of speed harmonization with regular and connected vehicles was evaluated in the previous sections. In this section, the impact of speed harmonization is presented in a connected environment, namely, the connected vehicles are brought into the network and all the vehicles were subject to speed harmonization. As in previous analyses, 4 MPRs of connected vehicles in six OCs were evaluated.

Results of the analyses for connected vehicles with speed harmonization are presented in Figure 8-16 through

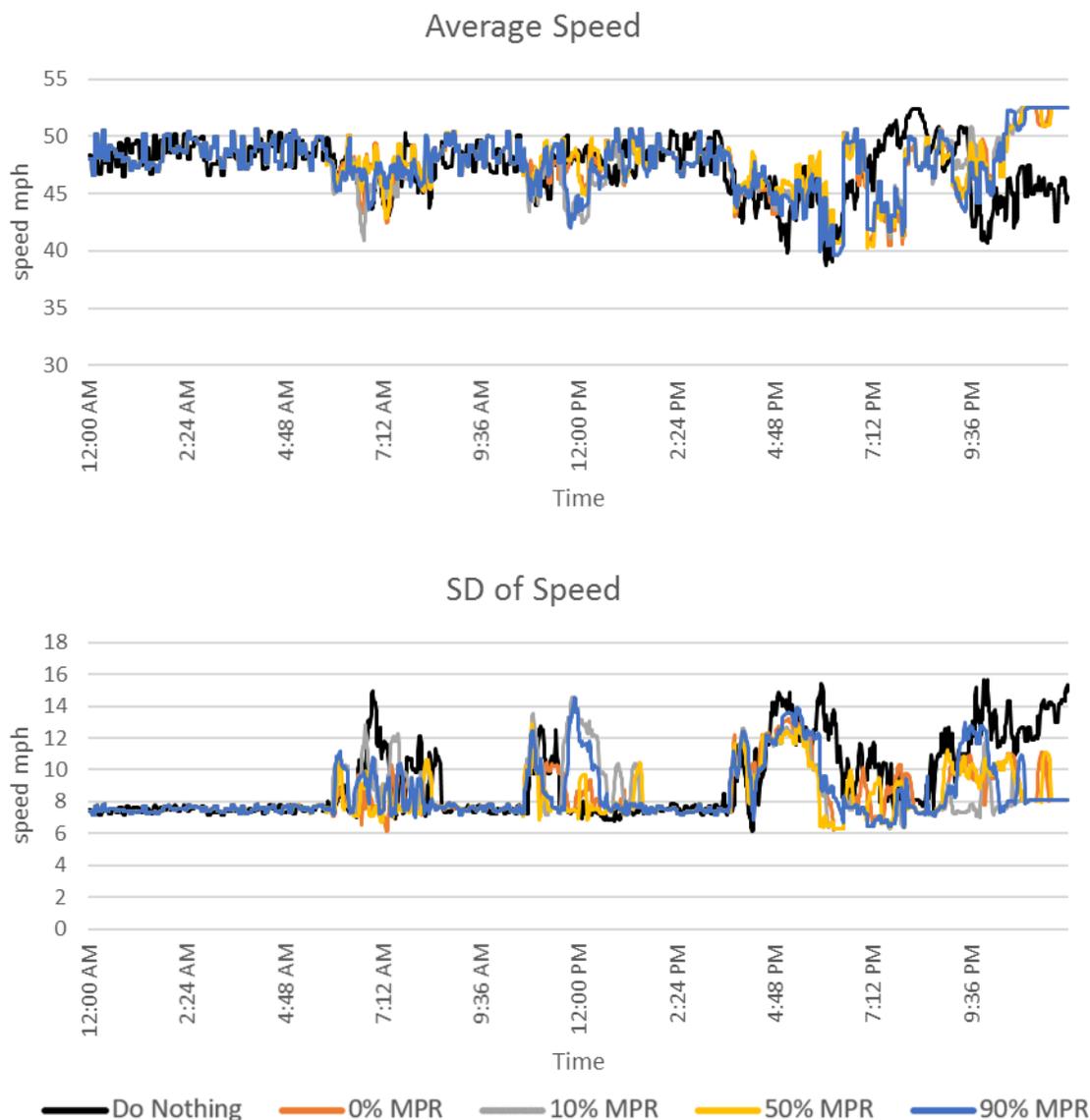
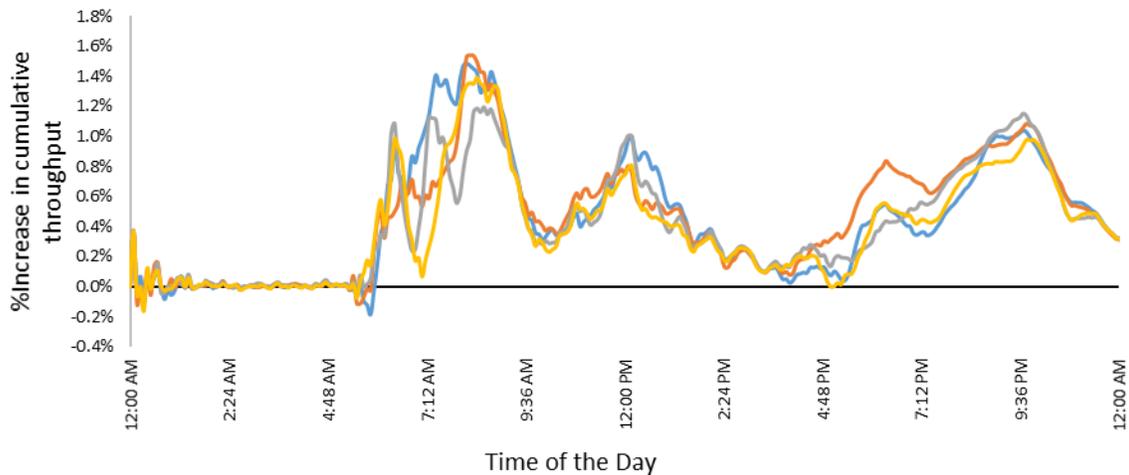
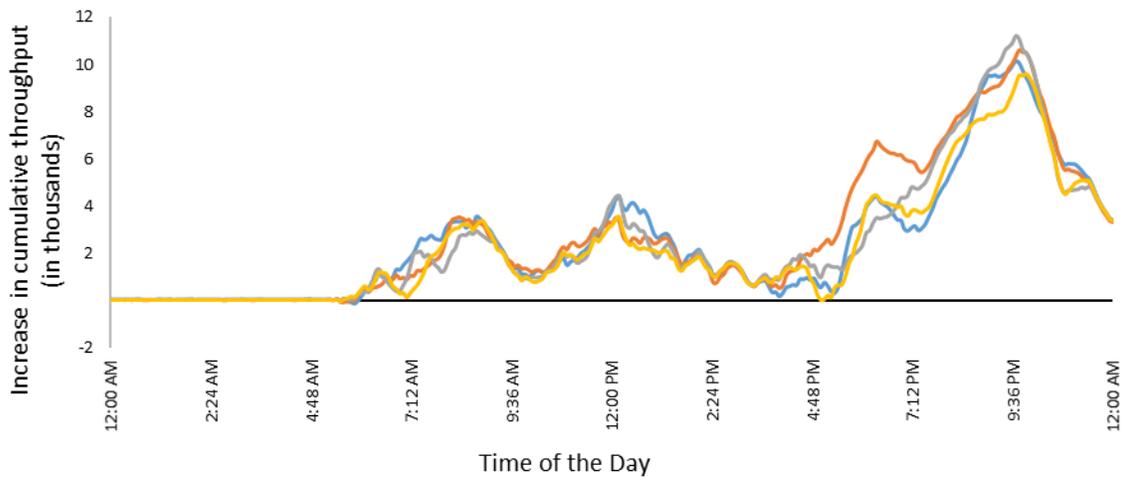
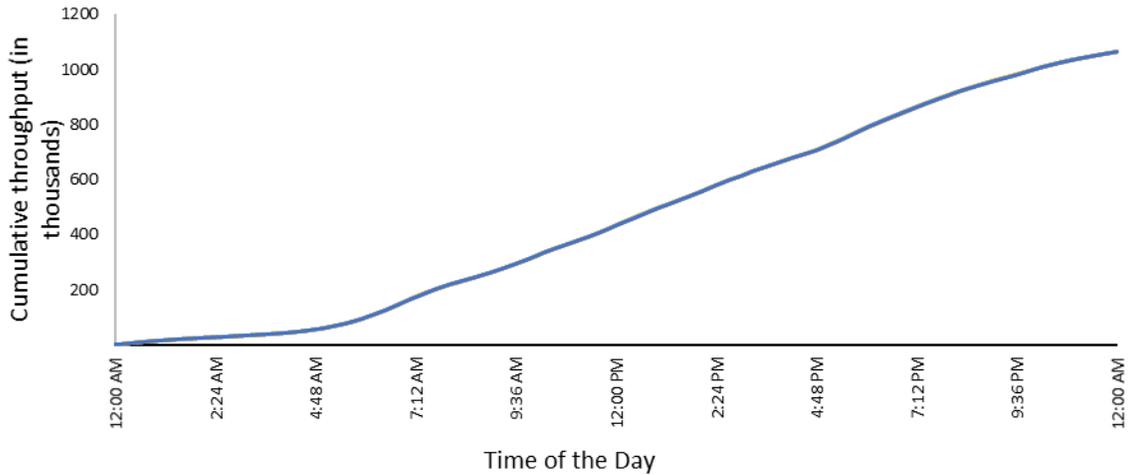


Figure 8-27 Figure 8-27 Four market shares of the connected vehicles were tested. Results show (1) cumulative throughput throughout the day, (2) improvement in the % cumulative throughput compared with the baseline scenario with no strategy implemented, (3) improvement in the actual number of the cumulative throughput compared with the baseline scenario with no strategy implemented, and (3) Average speed and standard deviation (SD) on the speed distribution in the day.

The impact of different market shares on the do-nothing case. 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. Only exception to this outcome is the OC4 (Figure 8-23). For OC4, the effect is very marginal or on the negative side. This is due to low demand and less improvement needed. With an intervention in this condition, instability is induced

Figure 8-16 and Figure 8-17 refer to the results for clear day scenario. It can be concluded that under clear day, where influence from weather effect is not significant, there is a slight decrease in the cumulative

throughput with 10%MPR. At other MPRs the throughput remains the same or increases slightly. Also, the average speed and the standard deviation remains the same with the implementation of the strategy in



— 0% MPR — 10% MPR — 50% MPR — 90% MPR

OC1.

Figure 8-18 and

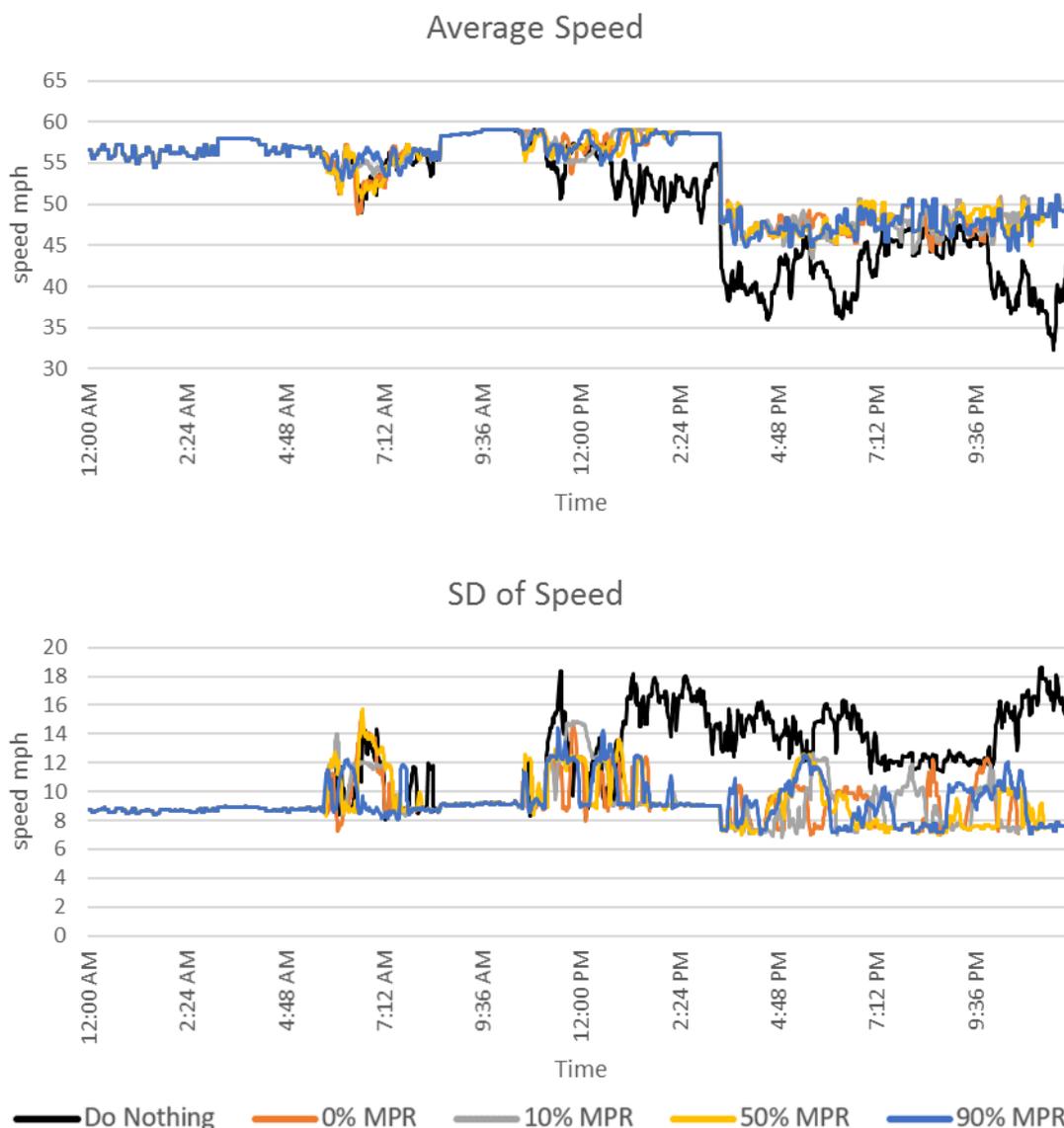


Figure 8-19 refer to the results for rain to snow scenario. It can be concluded that under rain to snow scenario, at all MPRs of the connected vehicles, the throughput increases especially in the morning and evening peak hours. Moreover, the average speed increases with reduction in the standard deviation. This is to say that the system is becoming more reliable with the strategy.

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. Only exception to this outcome is the OC4.

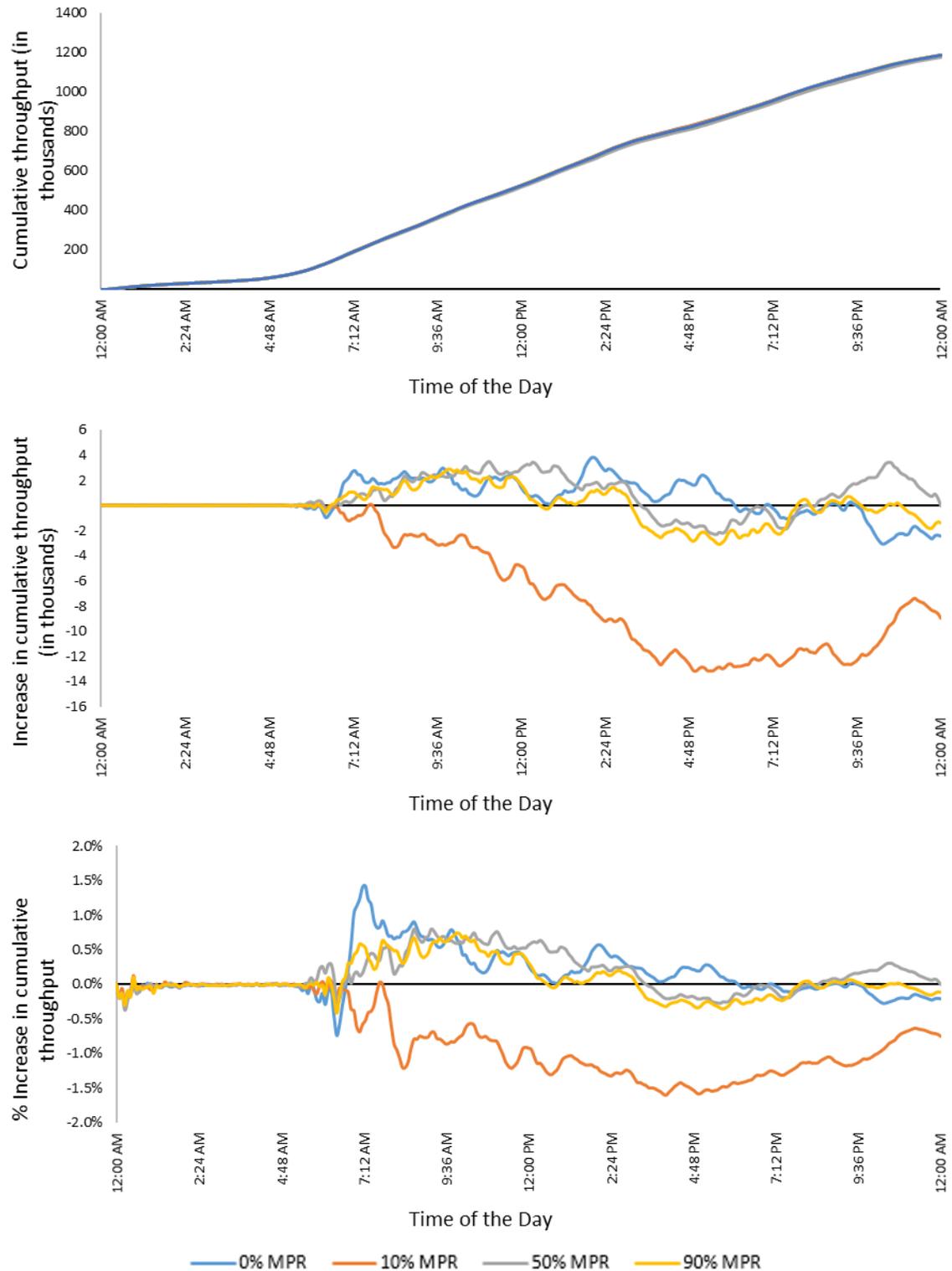


Figure 8-16: Impact of Speed Harmonization on Throughput at Different MPRs of CV in OC1 [Source: NWU]

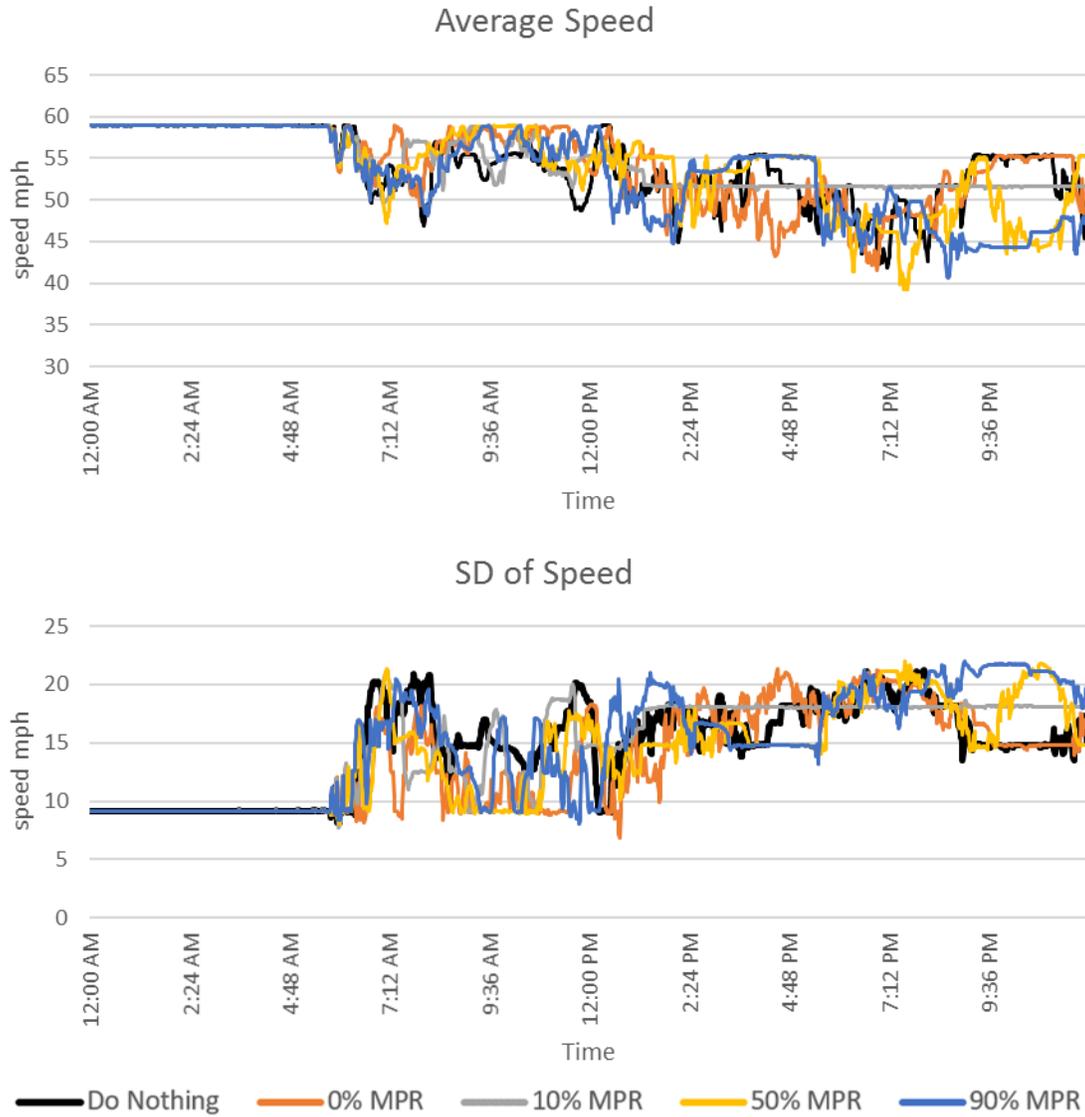


Figure 8-17: Impact of Speed Harmonization on Speed at Different MPRs of CV in OC1 [Source: NWU]

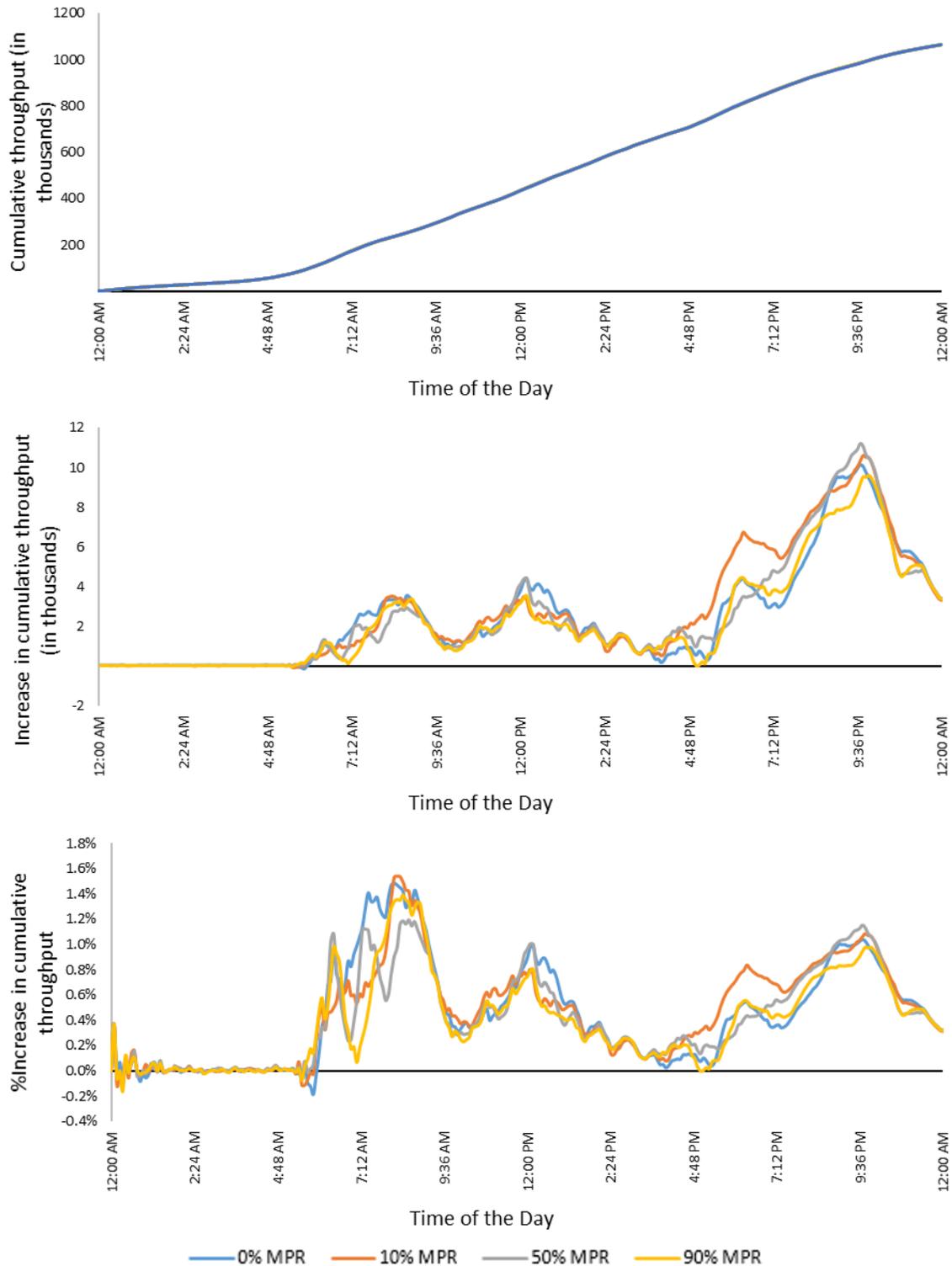


Figure 8-18: Impact of Speed Harmonization on Throughput at Different MPRs of CV in OC2 [Source: NWU]

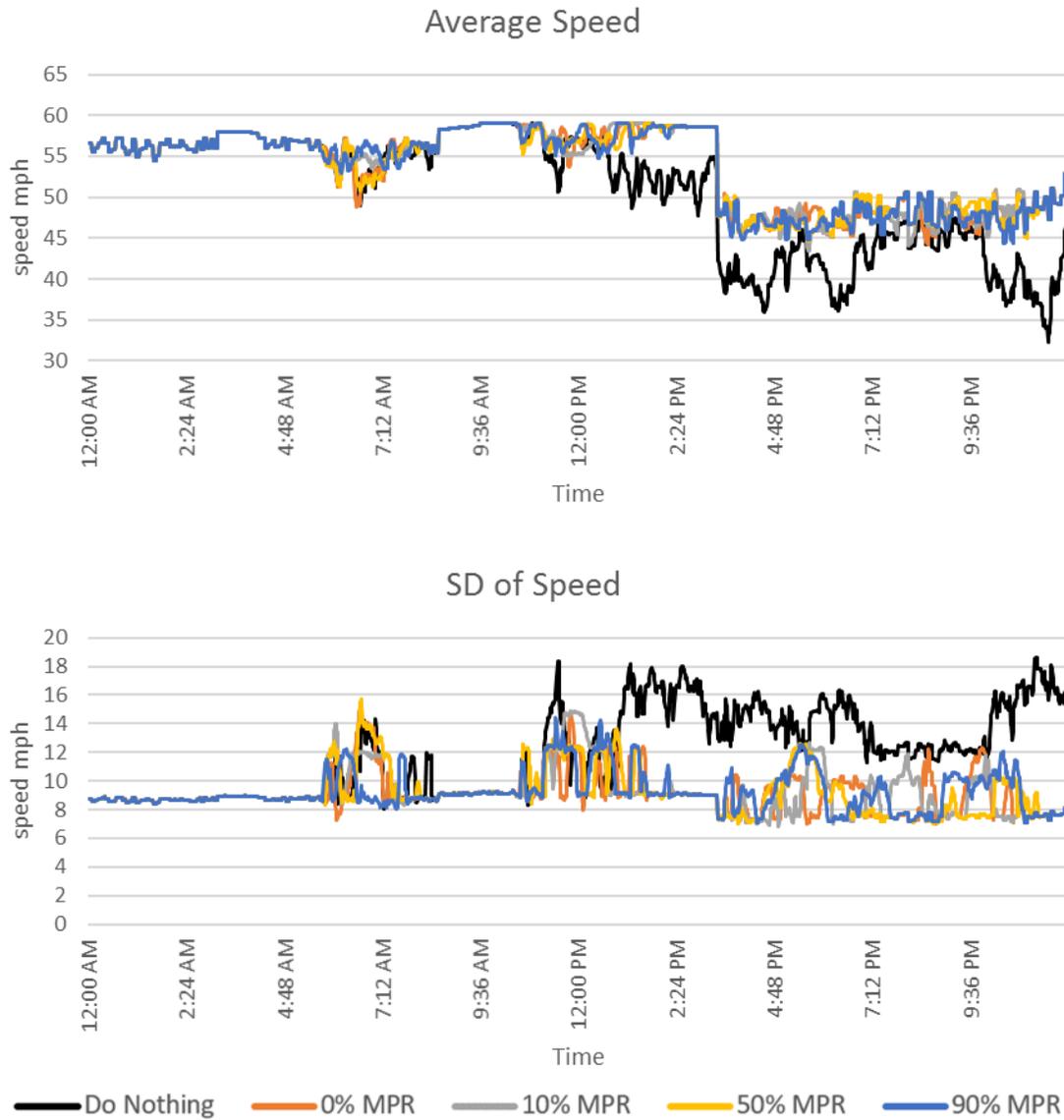


Figure 8-19: Impact of Speed Harmonization on Speed at Different MPRs of CV in OC2 [Source: NWU]

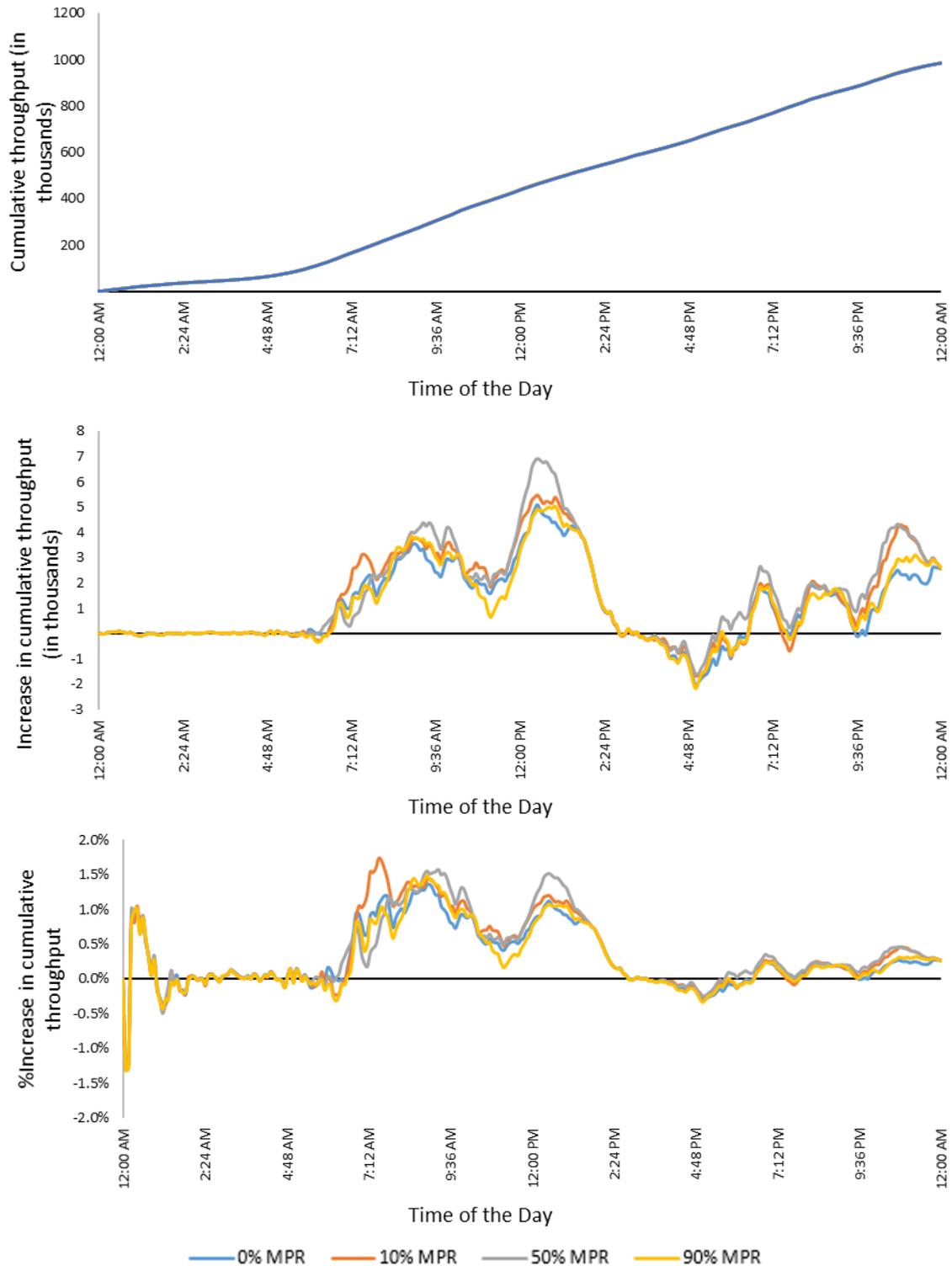


Figure 8-20: Impact of Speed Harmonization on Throughput at Different MPRs of CV in OC3 [Source: NWU]

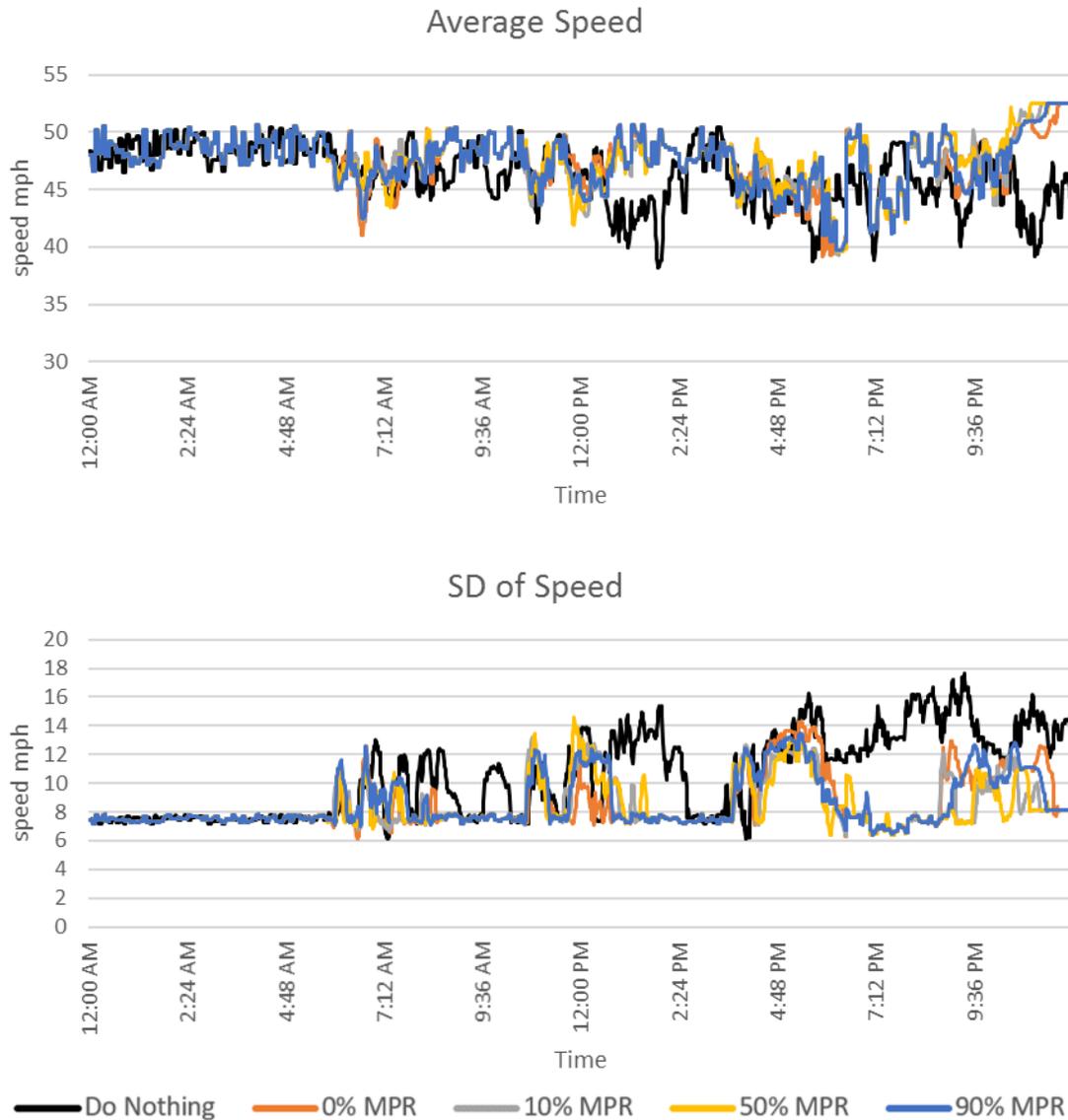


Figure 8-21: Impact of Speed Harmonization on Speed at Different MPRs of CV in OC3 [Source: NWU]

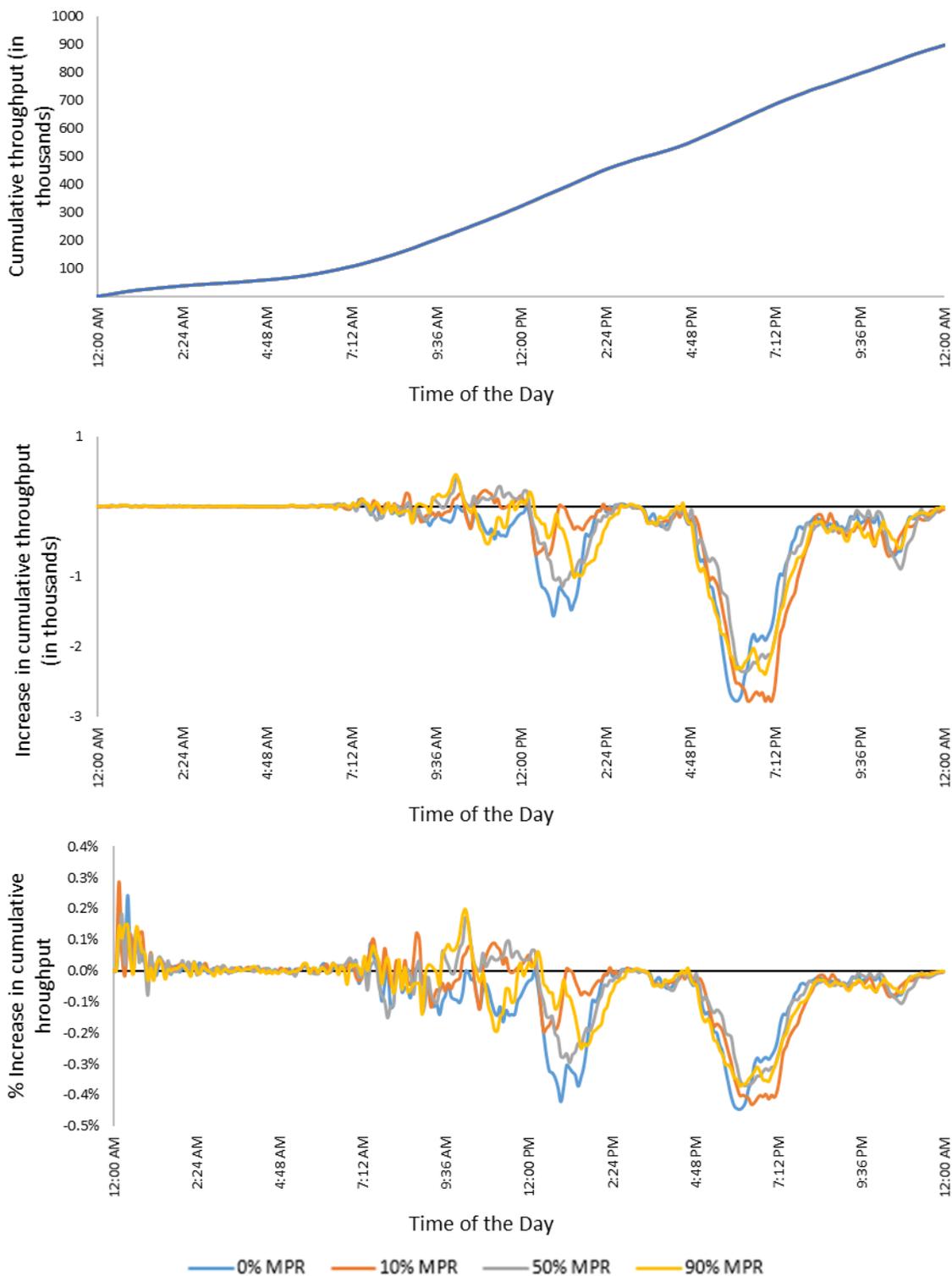


Figure 8-22: Impact of Speed Harmonization on Throughput at Different MPRs of CV in OC4 [Source: NWU]

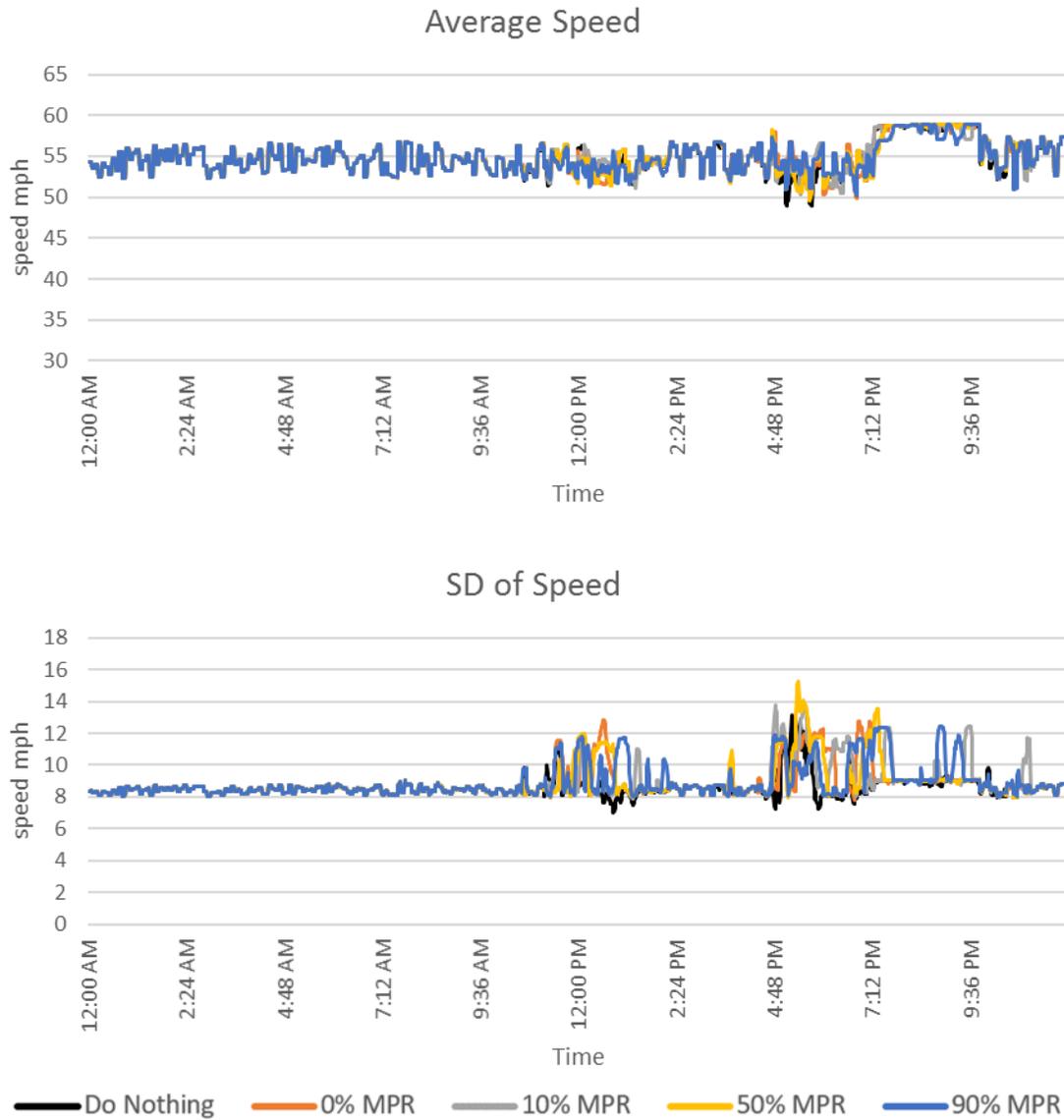


Figure 8-23: Impact of Speed Harmonization on Speed at Different MPRs of CV in OC4 [Source: NWU]

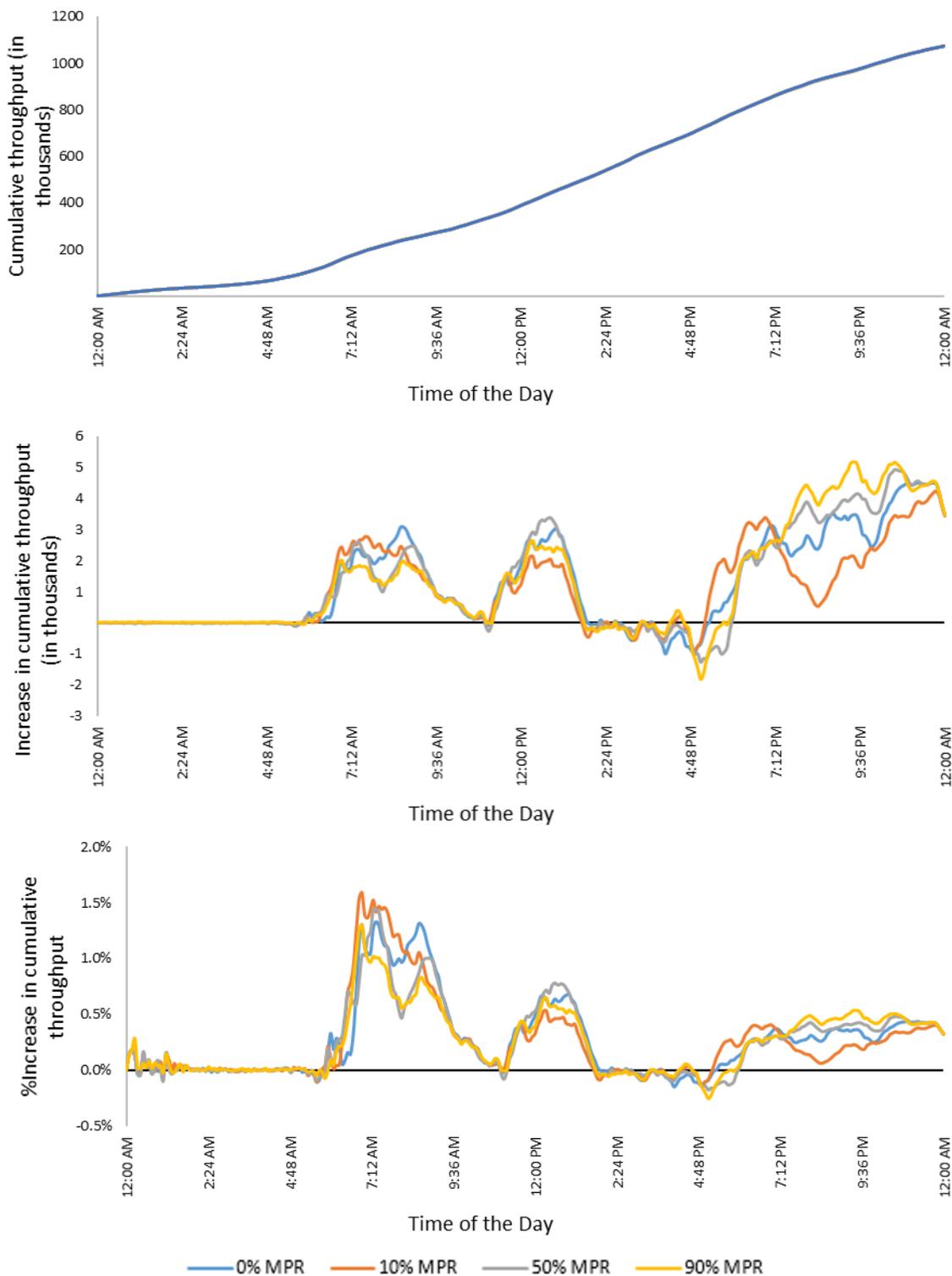


Figure 8-24: Impact of Speed Harmonization on Throughput at Different MPRs of CV in OC5 [Source: NWU]

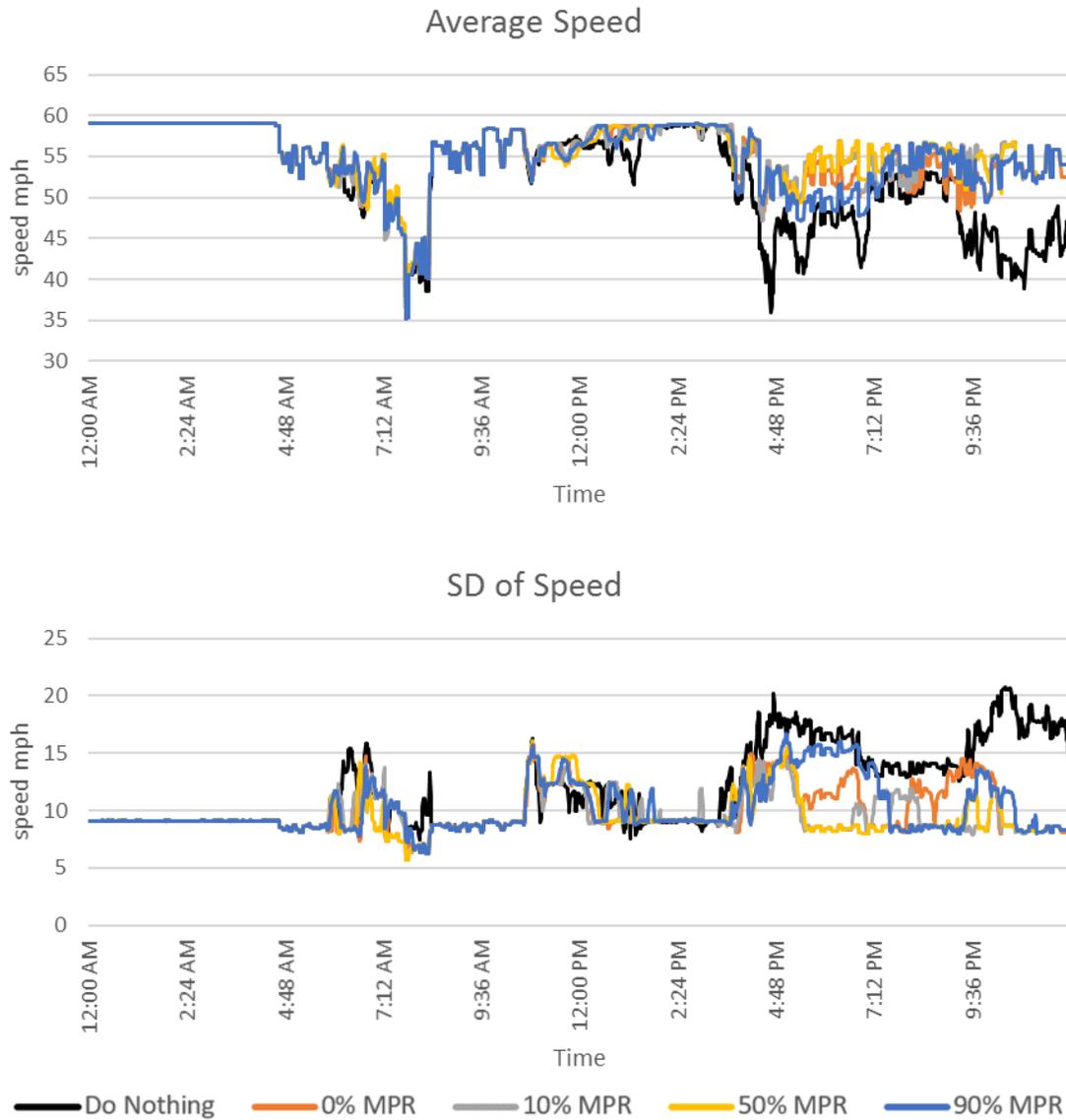


Figure 8-25: Impact of Speed Harmonization on Speed at Different MPRs of CV in OC5 [Source: NWU]

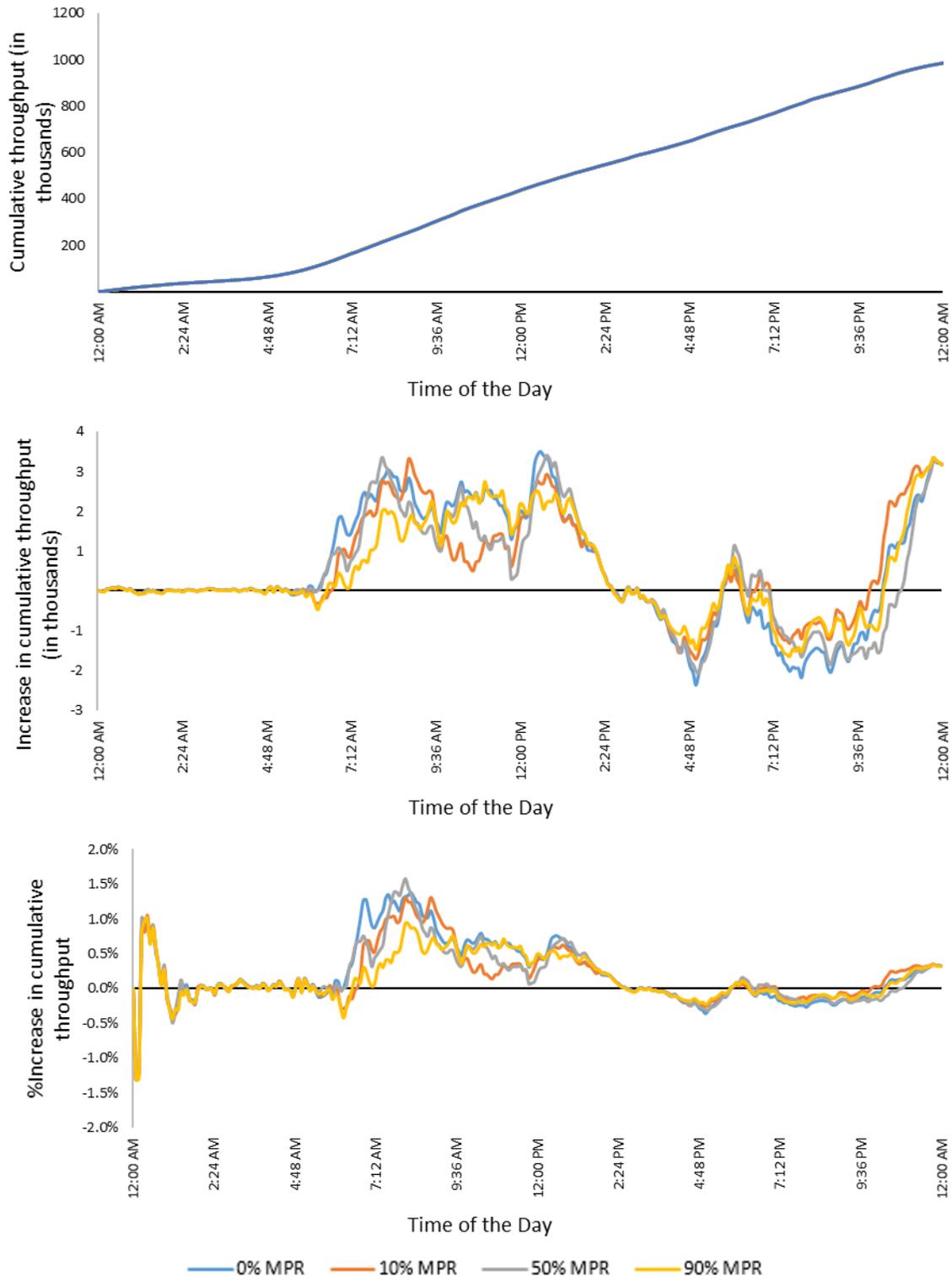


Figure 8-26: Impact of Speed Harmonization on Throughput at Different MPRs of CV in OC6 [Source: NWU]

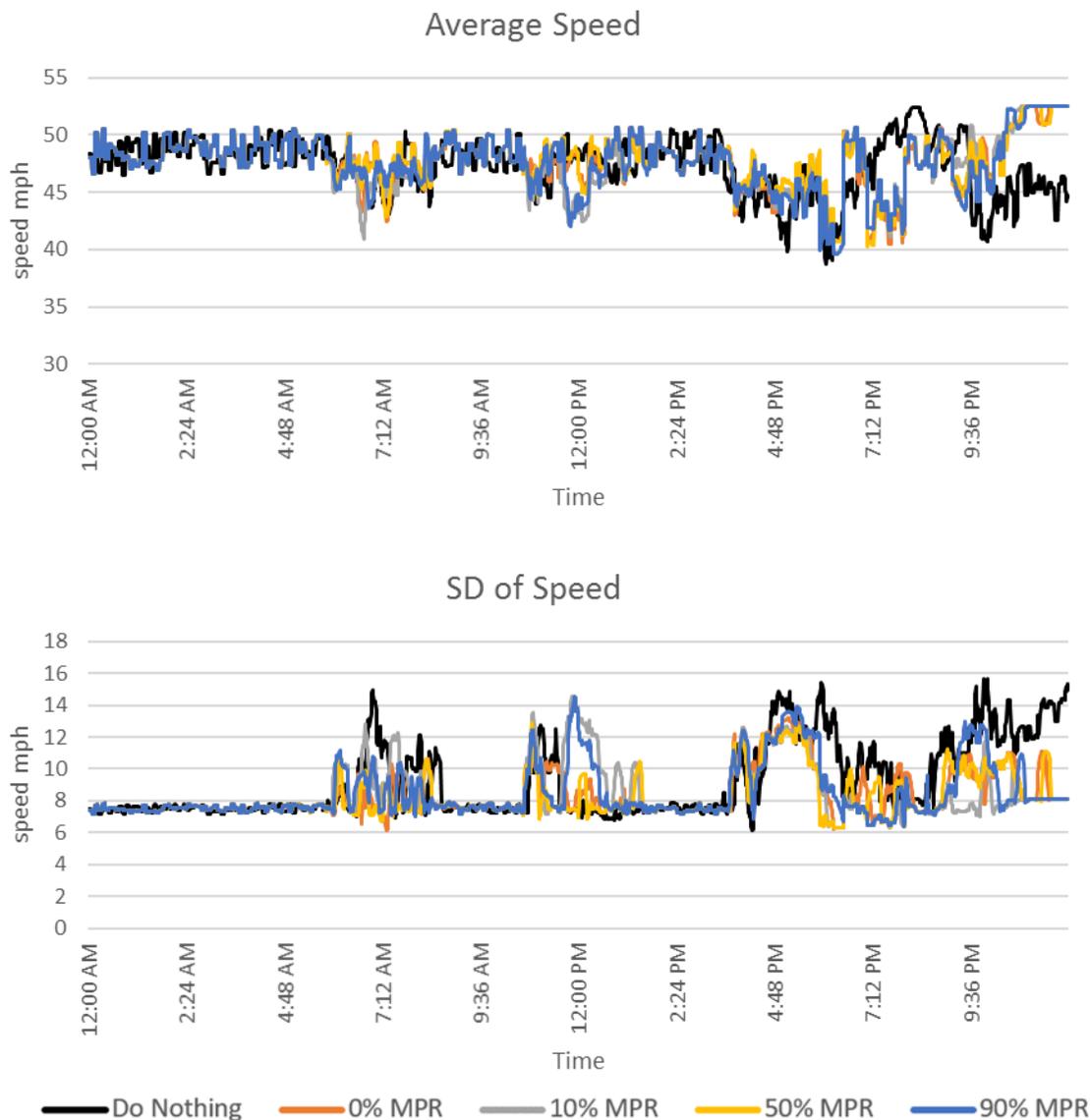


Figure 8-27: Impact of Speed Harmonization on Speed at Different MPRs of CV in OC6 [Source: NWU]

8.3 Summary of Results

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.

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 of speed was reduced.

Chapter 9. Synergies and Conflicts

9.1 Research Questions

In this chapter, we addressed the following three research questions, which are related to the synergies and conflicts:

- Are ATDM strategies more beneficial when implemented in isolation or in combination (e.g., combinations of ATM, ADM, or weather-related strategies)?
- What ATDM strategy or combinations of strategies yield the most benefits for weather related operational conditions?
- What ATDM strategies or combinations of strategies conflict with each other?

The hypothesis is that some ATDM strategies could create synergy when deployed together, while other strategies could be conflicting with each other; resulting in a reduction in the overall benefits. Under different weather scenarios, the extent of synergy or conflict among strategies may vary.

9.2 Analysis Approach

The simulation testbed is configured to emulate the traffic management operations for the identified operational conditions defined above. To explore the answers to the three research questions above, details of the logic design for the experiment scenarios and evaluation of the resulting system performance are described below.

9.2.1 Scenarios

Table 9-1 shows the design of experiment tests. The average travel time on the Chicago testbed is no more than 30 minutes, and the shorter roll period is expected to provide more accurate predictive information. In the tests for the first two research questions, the default settings for prediction features were applied, with a prediction horizon of 30 minutes, and a roll period of 5 minutes. The experiments to test the research questions on Synergies and Conflicts are designed to test all possible combinations of strategies. Note that the Weather-related strategies are only applicable to OC 3 through OC6, as the snow accumulation cannot reach the threshold to trigger the Weather-Related strategies in OC2.

However, in order to select the optimized setting of the percentage of vehicles which have access to predictive information, the net penetration level of 0% (do nothing), 30% and 50% are tested in OC 1 (a clear day scenario) before conducting the test scenarios to address questions for Synergies and Conflicts. Note that the net penetration rate in the test scenarios for the experiment factor of combination of strategies is set at 30% in the table. This choice is made according to the simulation tests for the network penetration, which is described in detail in the section 9.2.2. The ADM net penetration rate means what percentage of vehicle have the access to prediction information. They will make decision according to the information that they get and the individual behavior rule.

Table 9-1: Experiment Scenarios for Research Questions of Synergies and Conflicts

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 %	-	-	-
	OC1 (Clear Day) → ADM	30 %	5	30	0
	OC1 (Clear Day) → ADM	50 %	5	30	0
Combination of strategies	OC1 (Clear Day) → Do nothing	0 %	-	-	-
	OC1 (Clear Day) → ADM	30%	5	30	0
	OC2 (Rain to Snow) → ATM	0%	5	30	0
	OC2 (Rain to Snow) → ADM + ATM	30%	5	30	0
Combination of strategies	OC3, 4 (Moderate Snow) → Do nothing	0 %	-	-	-
	OC3, 4 (Moderate Snow) → ADM	30%	5	30	0
	OC5 (Heavy Snow) → ATM	30%	5	30	0
	OC6 (Moderate Snow + Incident) → WR	30%	5	30	0
	OC6 (Moderate Snow + Incident) → ADM + WS	30%	5	30	0
	OC6 (Moderate Snow + Incident) → ADM + ATM + WS	30%	5	30	0

9.2.2 Results

Several observations can be made on the results shown on Figure 9-1 to Figure 9-7. First, for the net penetration effect in Figure 9-1, the penetration rate of 30% yields more benefits than the rate of 50% in terms of system performance for the entire day, but the higher rate contributes more benefits on the morning peak traffic. This phenomenon was also verified in literature (see (Zockaie, Chen, & Mahmassani, 2014) where the traffic network with high penetration rate requires coordination in vehicle routing to achieve maximal effect; otherwise, conflicts among route choices may occur, leading to a less improved traffic state.

To test the scenarios in terms of Synergies and Conflicts, 3 operational conditions were plotted, including (1) improvement in the % cumulative throughput compared with the baseline scenario with no strategy implemented, (2) improvement in the actual number of the cumulative throughput compared with the baseline scenario with no strategy implemented, and (3) the actual number of cumulative demand and cumulative throughput under the baseline scenario and the scenario with the most beneficial strategy or combination of strategies.

Figure 9-2 and Figure 9-3 refer to the results for clear day and rain to snow scenario. It can be concluded that under clear day or rain to snow scenario, where influence from weather effect is not significant, the

combination of ATM and ADM shows considerable synergies, especially for peak hours, where the effect is better than just the sum of the individual strategies. For example, ATM brings 3% improvement, ADM brings 5% when implemented individually. If ATM + ADM are implemented together, they bring 10% improvement (rather than 5%+3%). Note that ATM brings some negative effect around noon, when the shoulder lane is not available to provide more supply. Meanwhile, due to the continuously high demand, dynamic speed limit is always functional on the main highway segments, limits the traffic volume and thus leads to the network throughput drop. The throughput gets recovered after 3PM when dynamic shoulder lane is open again.

Under the snow affected scenarios, the tests of ATM + ADM and ATM + WS were not included in the experiments. Because (1) WS is always needed for OC 3-6, and thus ATM+ADM is not an option; (2) WS provide dynamic snowplow routing and it is more desired to test with dynamic routing strategy (in ADM) +WS. (3) ATM has been proved with most synergies with ADM, and it is only needed to test "ATM+ADM" with WS. If the travel demand is high (e.g. OC 3 and OC 5) in Figure 9-4 and Figure 9-6, the best strategy comes from the Weather-related strategy described in section 2.1 and 4.3, and it is compatible with ADM and ATM with most synergies.

If the travel demand is low (i.e., OC 4) in Figure 9-5, ATM and the Weather-related strategy can bring negative effect when implemented individually. The reasons could be (a) dynamic shoulder lanes are not functional on weekend for OC 4, producing no extra capacity, (b) speed limits due to safety issue under snow may reduce the network throughput in a less congested network when demand is low, and (c) the recovered capacity from the Weather-related strategy is not effective for OC 4 due to low demand, but it brings disadvantages from lane closure during implementation.

Under the snow and incident affected scenario (OC 6) in Figure 9-7, ATM shows the most benefits as an individual strategy since it brings more capacity with dynamic shoulder lanes and controls local demand with speed limit. Meanwhile, compared with OC 3 do-nothing scenario, the loss of capacity due to incident is observed, and the combination of strategies contributes to not only recovering the capacity but improving it compared with pre-incident capacity.

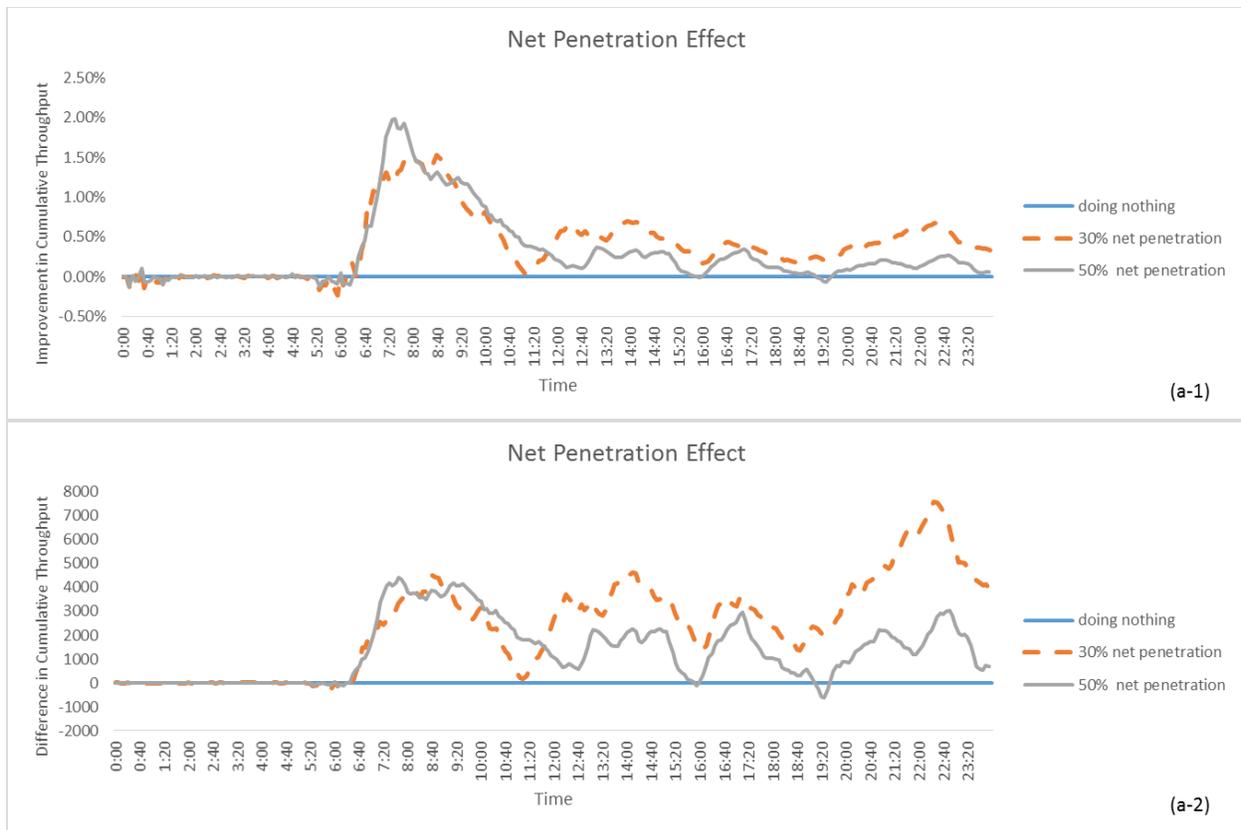


Figure 9-1: Simulation Tests for CV Market Penetration [Source: NWU]



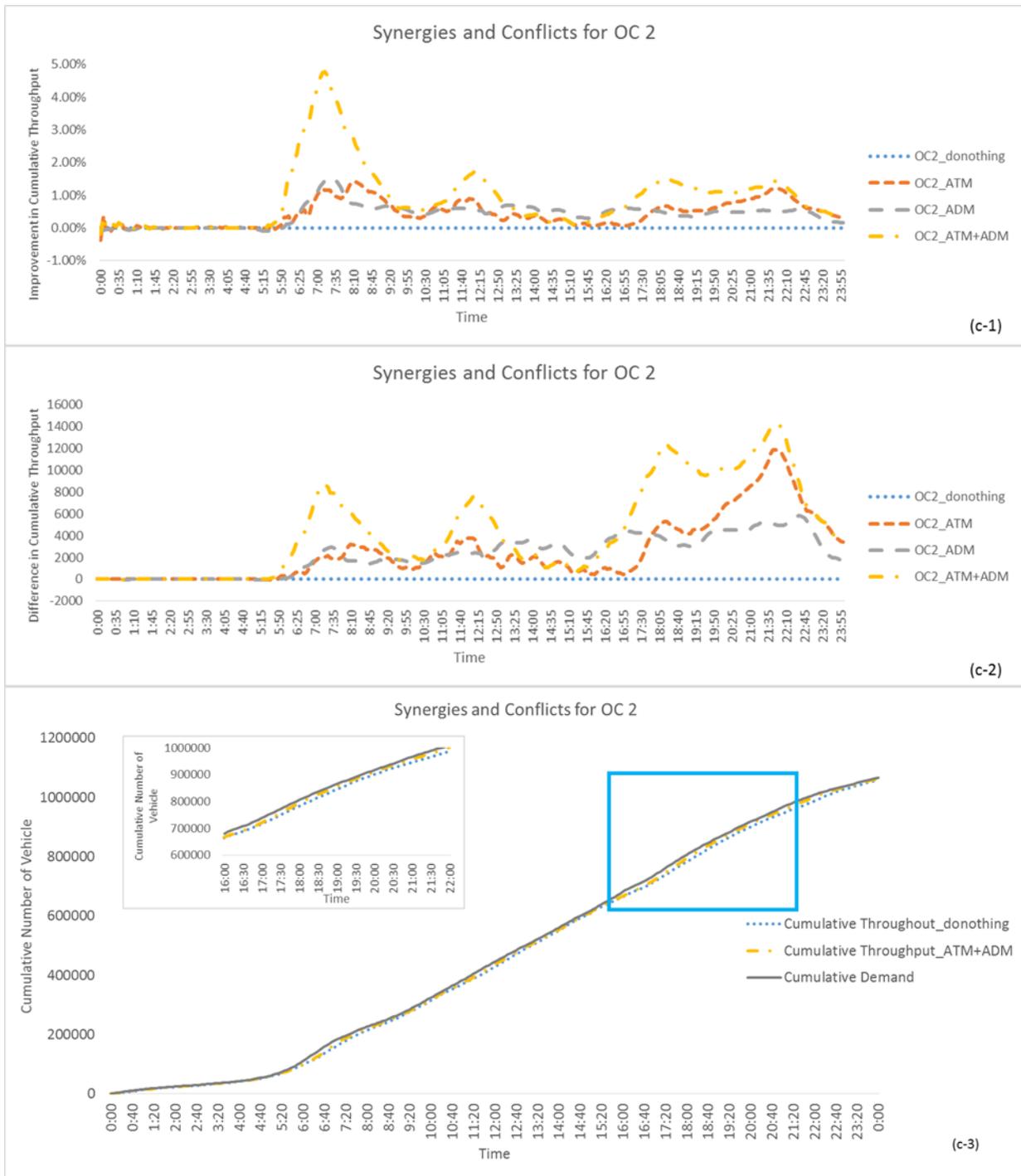
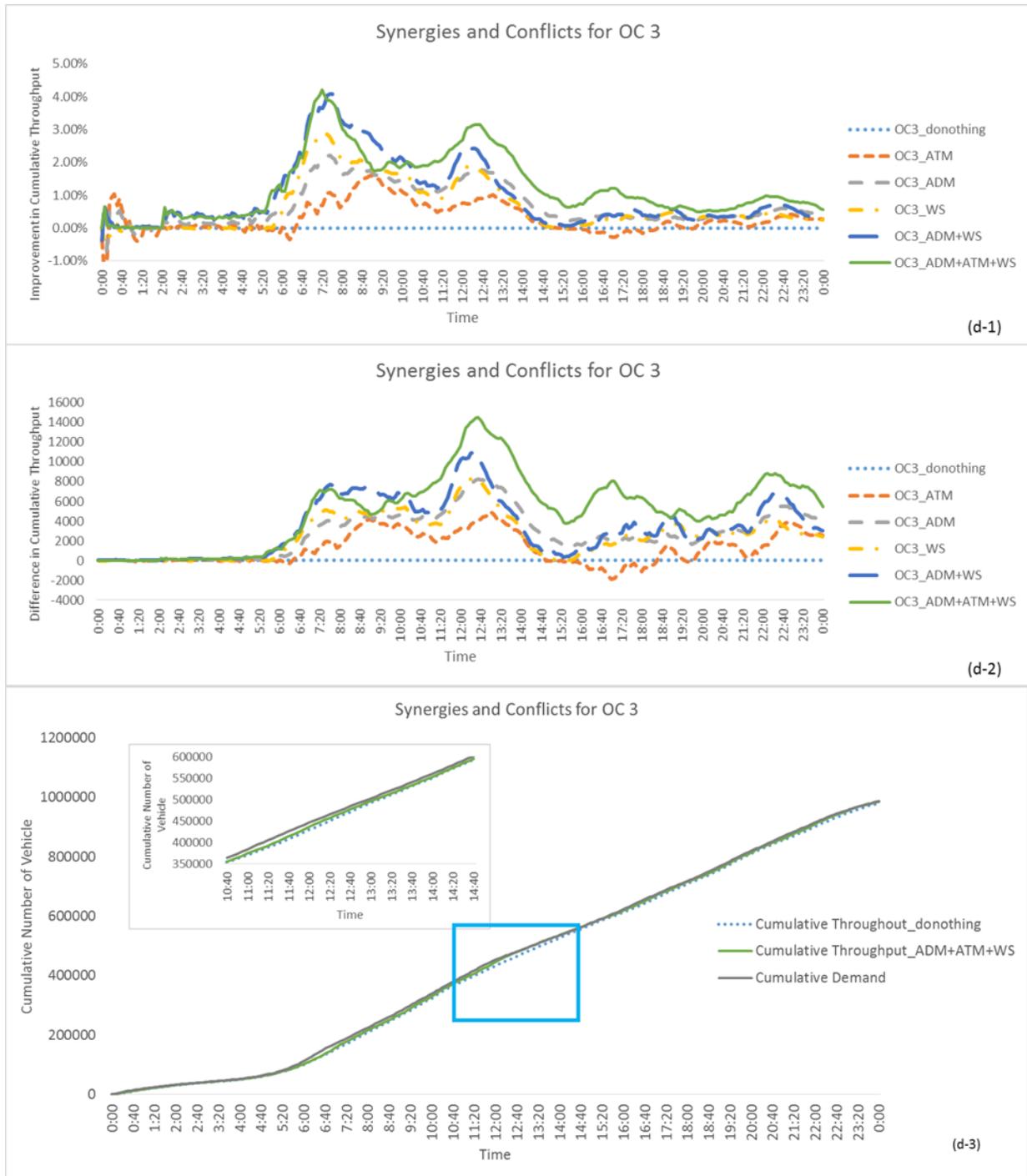


Figure 9-3: Simulation Tests for Synergies and Conflicts for OC2 [Source: NWU]



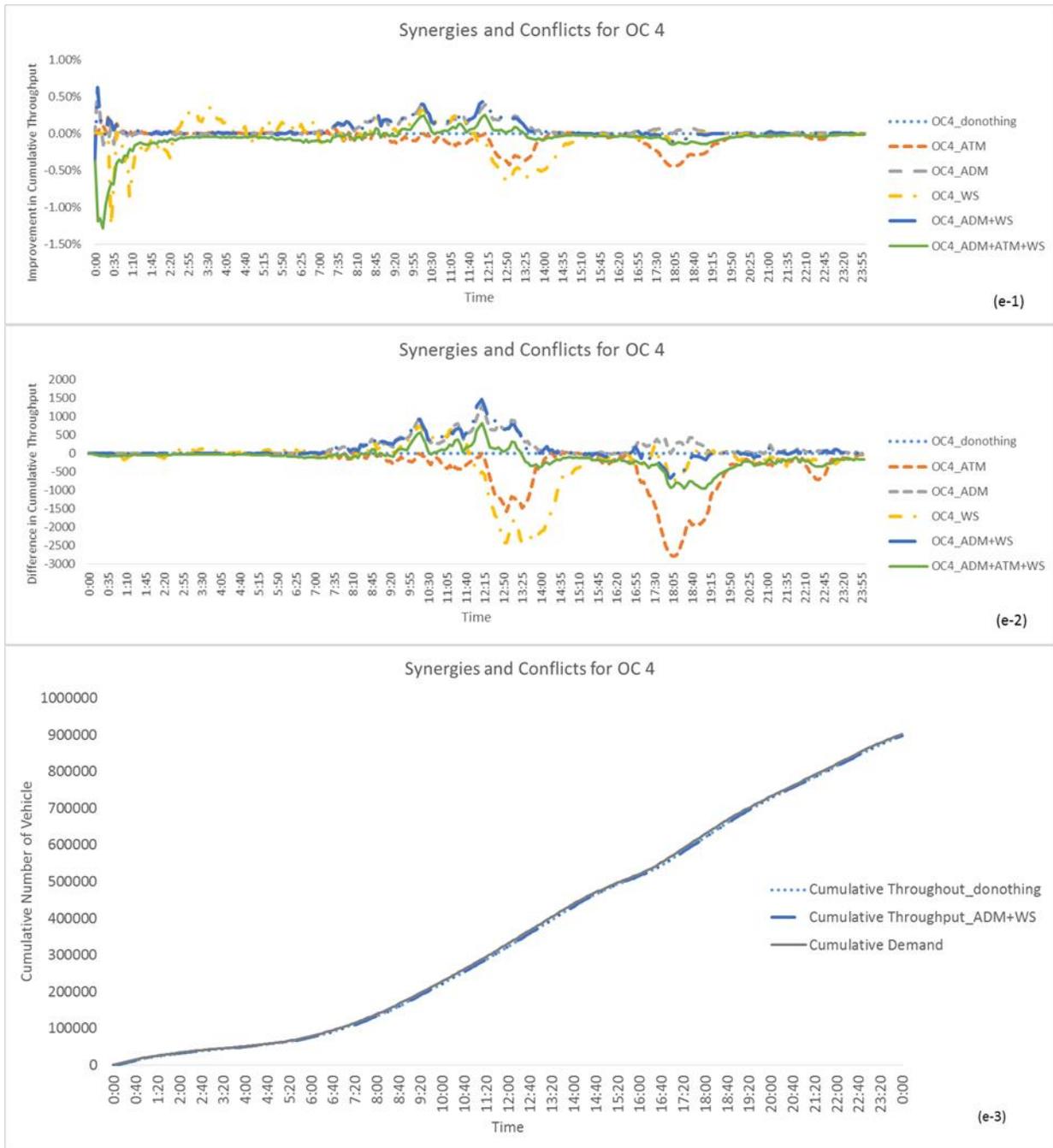


Figure 9-5: Simulation Tests for Synergies and Conflicts for OC4 [Source: NWU]

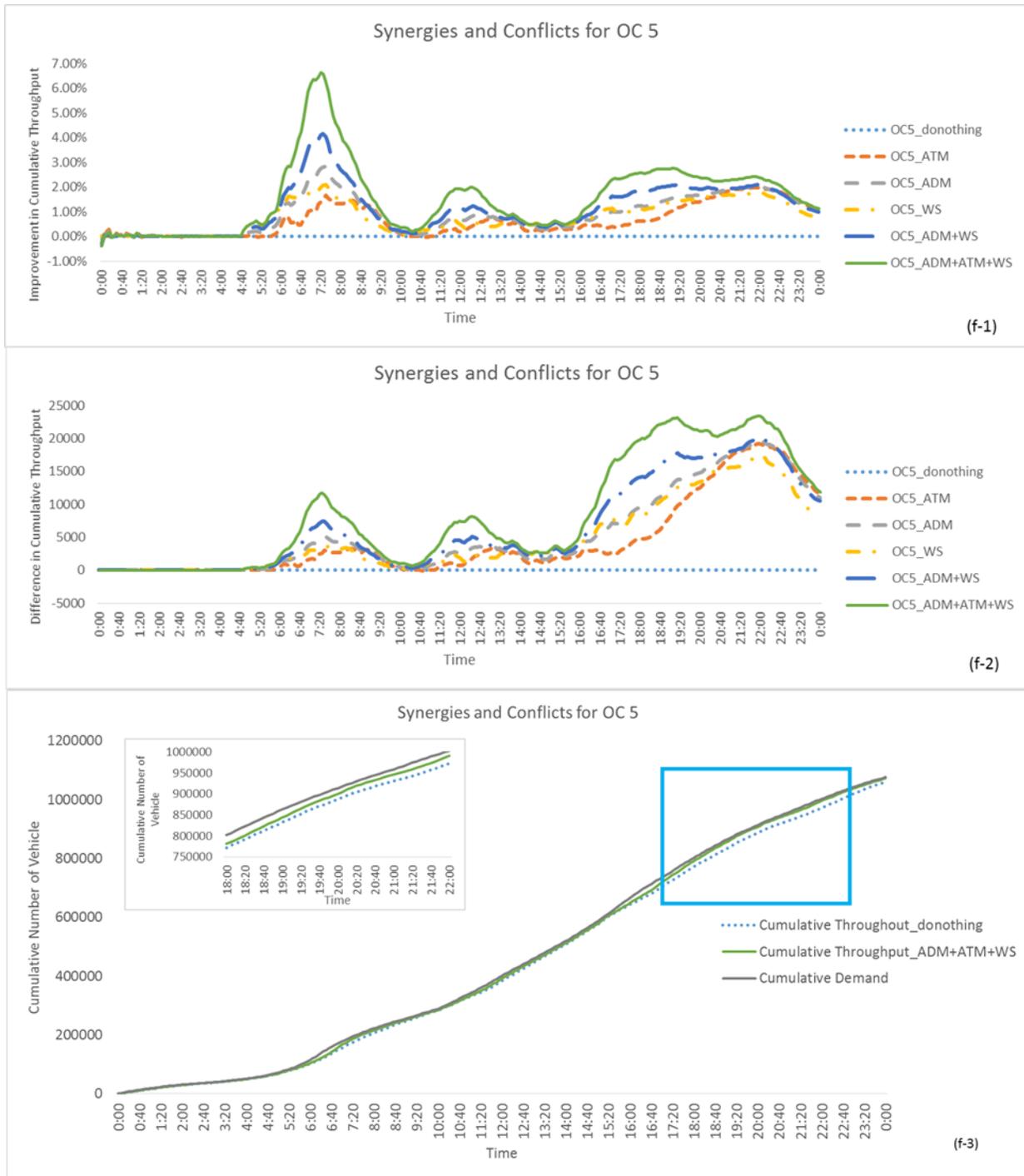


Figure 9-6: Simulation Tests for Synergies and Conflicts for OC5 [Source: NWU]

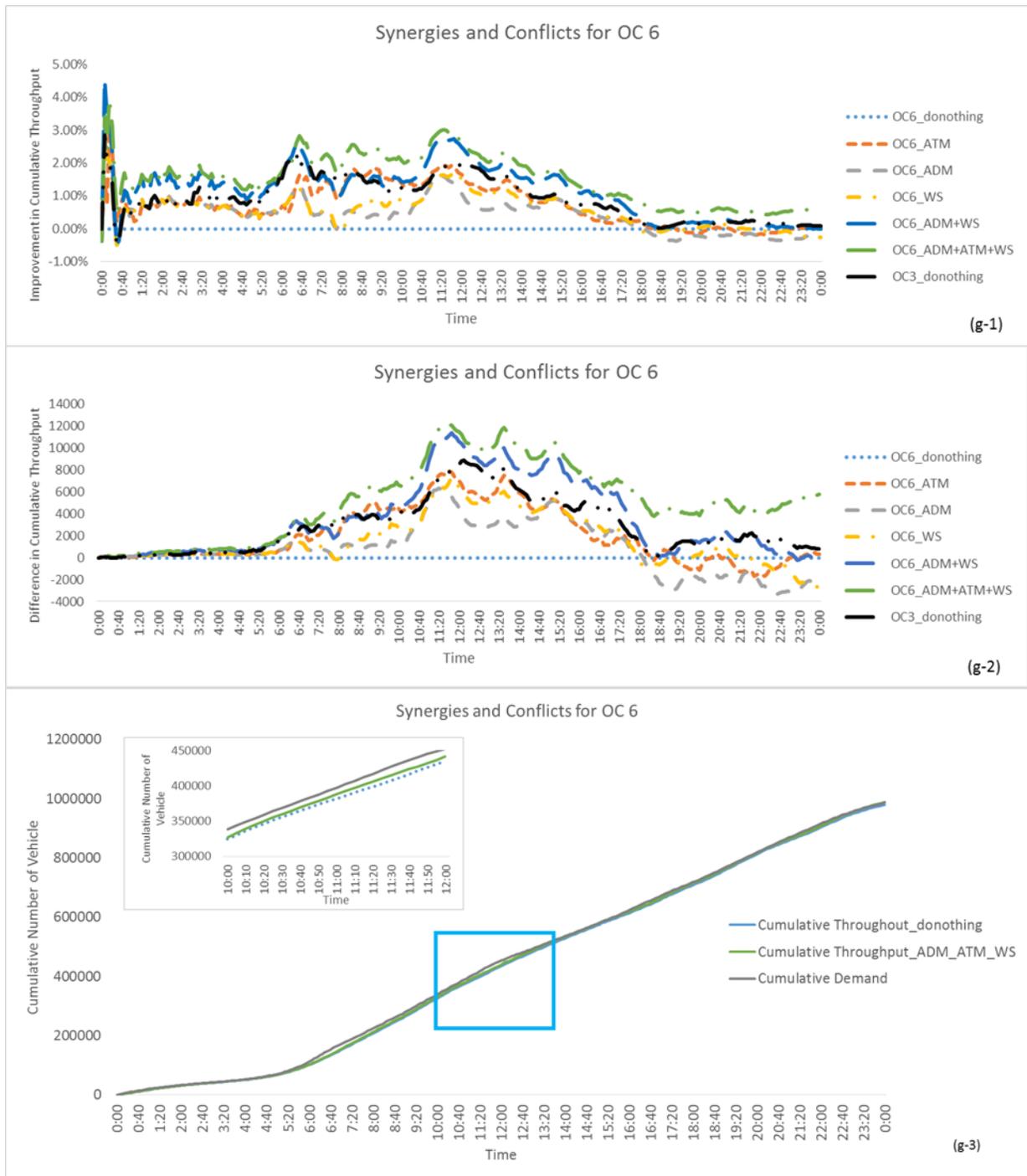


Figure 9-7: Simulation Tests for Synergies and Conflicts for OC6 [Source: NWU]

9.3 Summary of Results

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. 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.

Chapter 10. Prediction and Latency

10.1 Research Questions

This chapter addresses the following research questions related to prediction accuracy, latency and the tradeoffs between them:

Prediction Accuracy

- Which ATDM strategy or combination of strategies will be most beneficial in terms of increased prediction accuracy?
- Are all forms of prediction equally valuable, or which attributes of prediction quality are critical (e.g., length of prediction horizon, prediction accuracy, prediction speed, and geographic area covered by prediction) for each ATDM strategy?

The hypotheses are that the value of prediction will be higher under inclement weather conditions, and will vary depending on the operational conditions experienced in the system.

Active Management or Latency

- Which ATDM strategy or combinations of strategies will be most beneficial in reducing latency?

The hypothesis is that the most beneficial combination of strategies through reduced latency may vary under different weather related operational conditions.

Prediction, Latency, and Coverage Tradeoffs

- What is the tradeoff between improved prediction accuracy and reduced latency with existing communications in terms of their combined effect on resulting benefits?
- What is the impact of increased prediction accuracy, more active management, and improved robust behavioral predictions on mobility, safety, and environmental benefits?

The hypotheses are: (1) increased communication level with less prediction accuracy could lead to similar results as less communication level with higher prediction accuracy, (2) increased prediction accuracy, more active management (reduced latency), and more robust behavioral predictions result in significant mobility, safety, and environmental benefits, and (3) key attributes of prediction quality (e.g., prediction horizon, prediction accuracy, speed of prediction, and geographic prediction coverage) vary critically depending on ATDM strategies considered and weather related operational conditions encountered.

10.2 Analysis Approach

10.2.1 Scenarios

Table 10-1 shows the experimental design to test the research questions related to the prediction and latency. Note the many factors included in the experimental design, each pertaining to a significant research question.

The main strategy bundle sensitive to prediction quality includes ADM strategies, especially dynamic routing. Also, it was assumed that the prediction accuracy is influenced by the roll period and prediction horizon. As the roll period gets shorter, the prediction state gets updated more often and becomes more

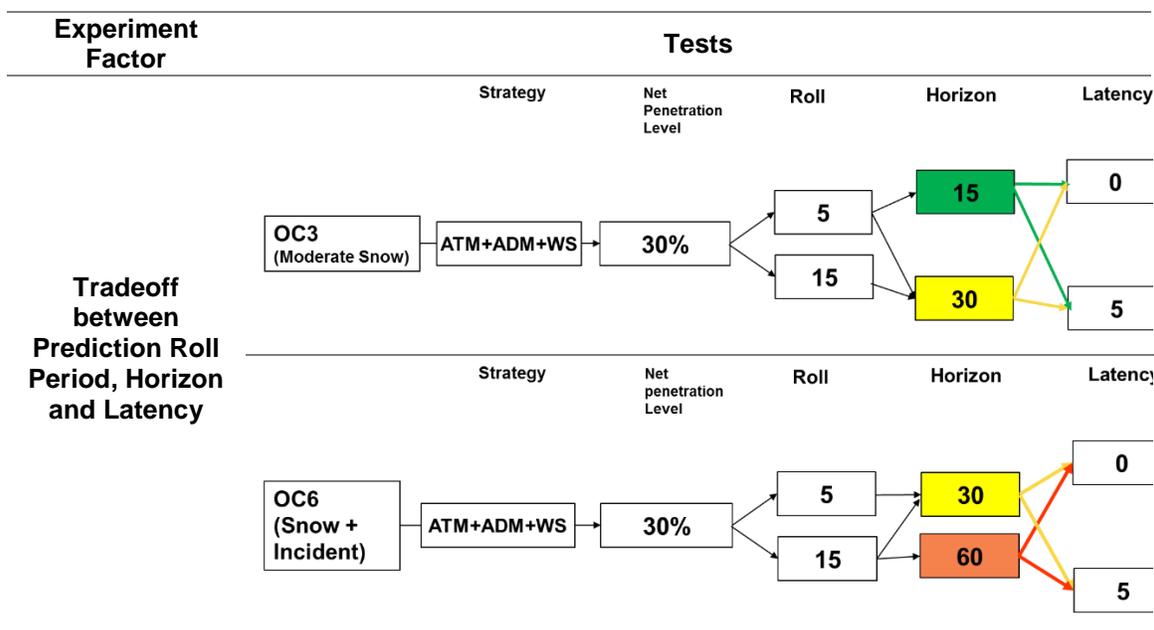
accurate. As with the prediction horizon, it was assumed that the accuracy might be less for the long prediction compared to the short prediction. Therefore, two sets of tests were conducted to capture the sensitivity of the system performance to roll period and prediction horizon with the ADM strategy bundles implemented under OC1. In these tests, the latency was not taken into account.

For the latency related question, the roll period and prediction horizon were fixed while the communication latency was varied in three levels, no latency (0 minute), moderate latency (3 minutes), and large latency (5 minutes). According to the overall framework, latency determines when the predictive information is received by the simulation system (as input to the decision or control logic to be applied). Although 5-minute latency seems not long, but it is large enough compared with the 5-minute roll period. Prior to that time, the latest received prediction remains in effect and the predictive information gets updated after latency. So if the current prediction stage is triggered at interval 15th minute with prediction horizon 30 minutes. The system can only receive information at 20th minute. If the system needs to make decision between 15th to 20th minute, it can only use the information from previous prediction stage.

The experiments to examine the tradeoff between prediction and latency are designed to test sensitivity of the system performance to the changes of prediction quality when the combination of strategies yielding to the most benefits are implemented. Since the focus of this study is weather-affected conditions, OC 3 and OC 6 were tested. As OC 6 is an incident-related scenario, it is tested with a longer prediction horizon than OC 3, because the incident is expected to lead to longer travel time.

Table 10-1: Experiment Scenarios for Research Questions of Prediction and Latency

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



10.2.2 Results

Figure 10-3 shows the test results for the sensitivity analysis of the entire network performance to the prediction quality, including prediction accuracy when roll period, prediction horizon, and the communication latency are changed.

Figure 10-1 shows the results related to the prediction accuracy when the roll period is varied and prediction horizon is fixed with no latency. It is observed that short roll period contributes to better prediction accuracy and leads to higher throughput compared with the simulation results with long roll period. Especially for the morning peak, the improvement from short roll period can be twice that from the long roll period. However, in the afternoon, the improvement from both scenarios are very similar, as the travel demand is not very high after morning peak and the system could maintain its stability so that vehicles may not require very often updated travel information for dynamic routing. As the simulation of the implementation of strategy with short prediction roll period requires more memory and involves more computational cost, when implementing the strategy in the real world a short roll period can be used for peak hours and moderate long roll period for off peak hours.

Figure 10-2 shows the results related to the prediction accuracy when the prediction horizon is varied and prediction horizon is fixed with no latency. The short prediction horizon results in a more accurate prediction. However, with short prediction horizon, the prediction information for dynamic routing may not be fully captured, which means that the travel time or travel cost after the prediction horizon is omitted from prediction. For example, if the vehicle needs 30 minutes to arrive at destination, but we only provide 15-minute predictive information, this driver may only get accurate information for the first 15 minutes of his trip, the rest 15-minute information are omitted at the current prediction stage. This driver can still get information updated within a rolling horizon framework. However, this may lead to less accurate dynamic routing every time and updating route every roll period. On the other hand, the long prediction may lead to less accuracy even though it can produce more traveler information. Therefore, it is necessary to check the time-dependent sensitivity of the system to the prediction horizon. From the test results, it is observed that during the morning peak, the system prefers shorter prediction horizon with more accuracy, but the opposite is true in the afternoon.

Figure 10-3 shows the results related to the latency when the prediction roll period and horizon are fixed. The results show that the system prefers no latency, especially during peak hours. If there exists a little latency which is much less than the prediction roll period, the system under off peak can still perform well. However, if the latency is no less than the roll period, which means that the system always get some predictive traveler information from the previous prediction stage, it will bring some negative effect to the system performance.

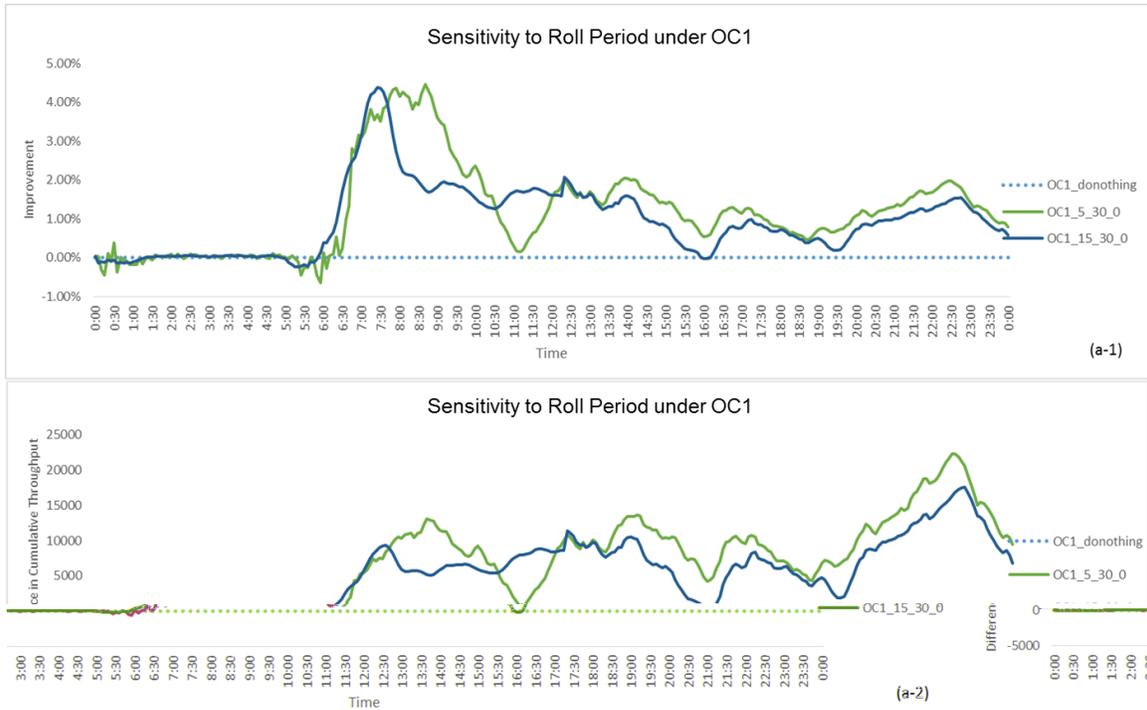


Figure 10-1: Sensitivity Analysis of System Performance to Roll Period [Source: NWU]

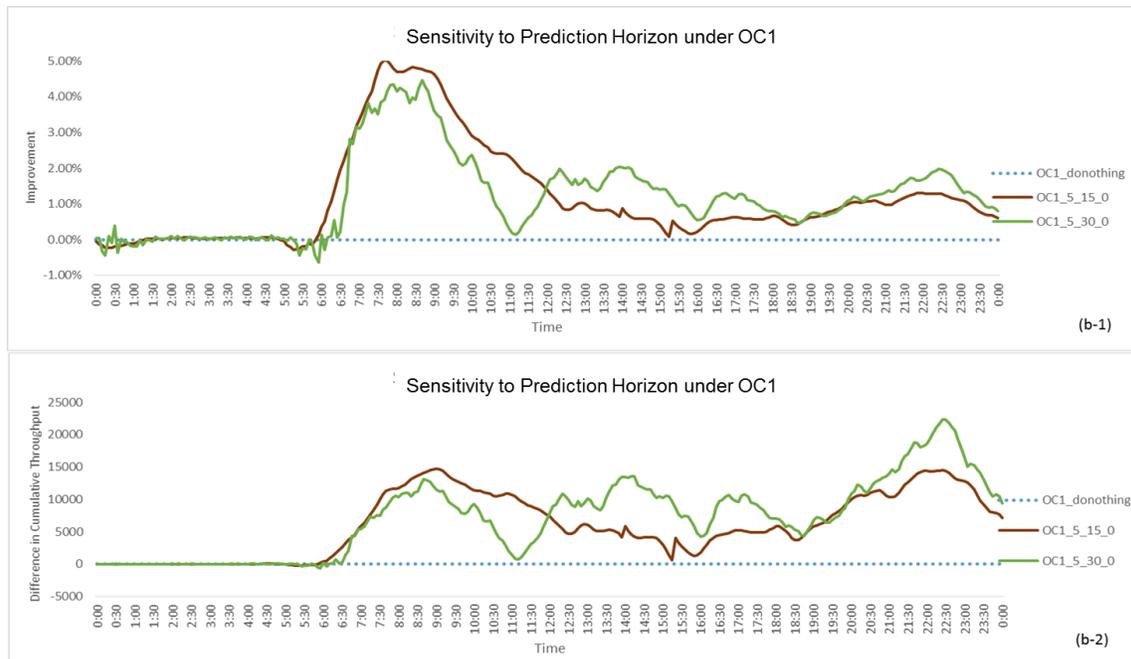


Figure 10-2: Sensitivity Analysis of System Performance to Prediction Horizon [Source: NWU]

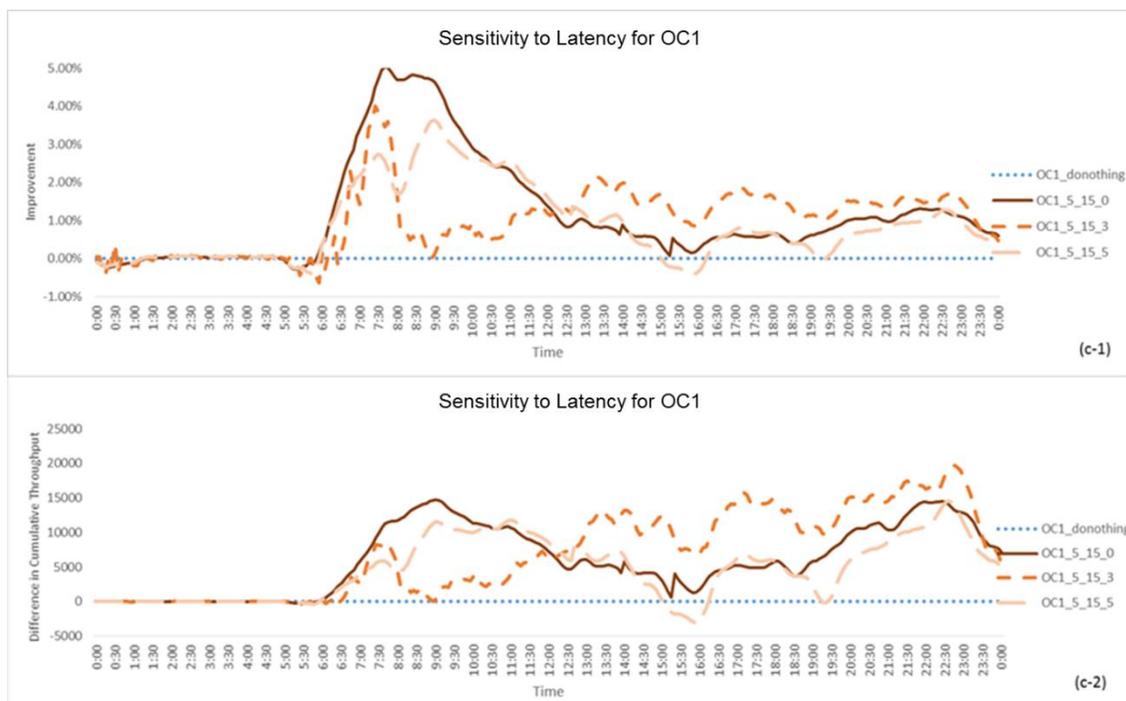


Figure 10-3: Sensitivity Analysis of System Performance to Communication Latency [Source: NWU]

Figure 10-4 shows the test results for the tradeoff analysis of the entire network performance with the prediction quality and the communication latency under the selected weather-related scenarios (i.e., OC 3). Only the best combination of strategies identified from the analyses of Synergies and Conflicts were tested.

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 for 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.

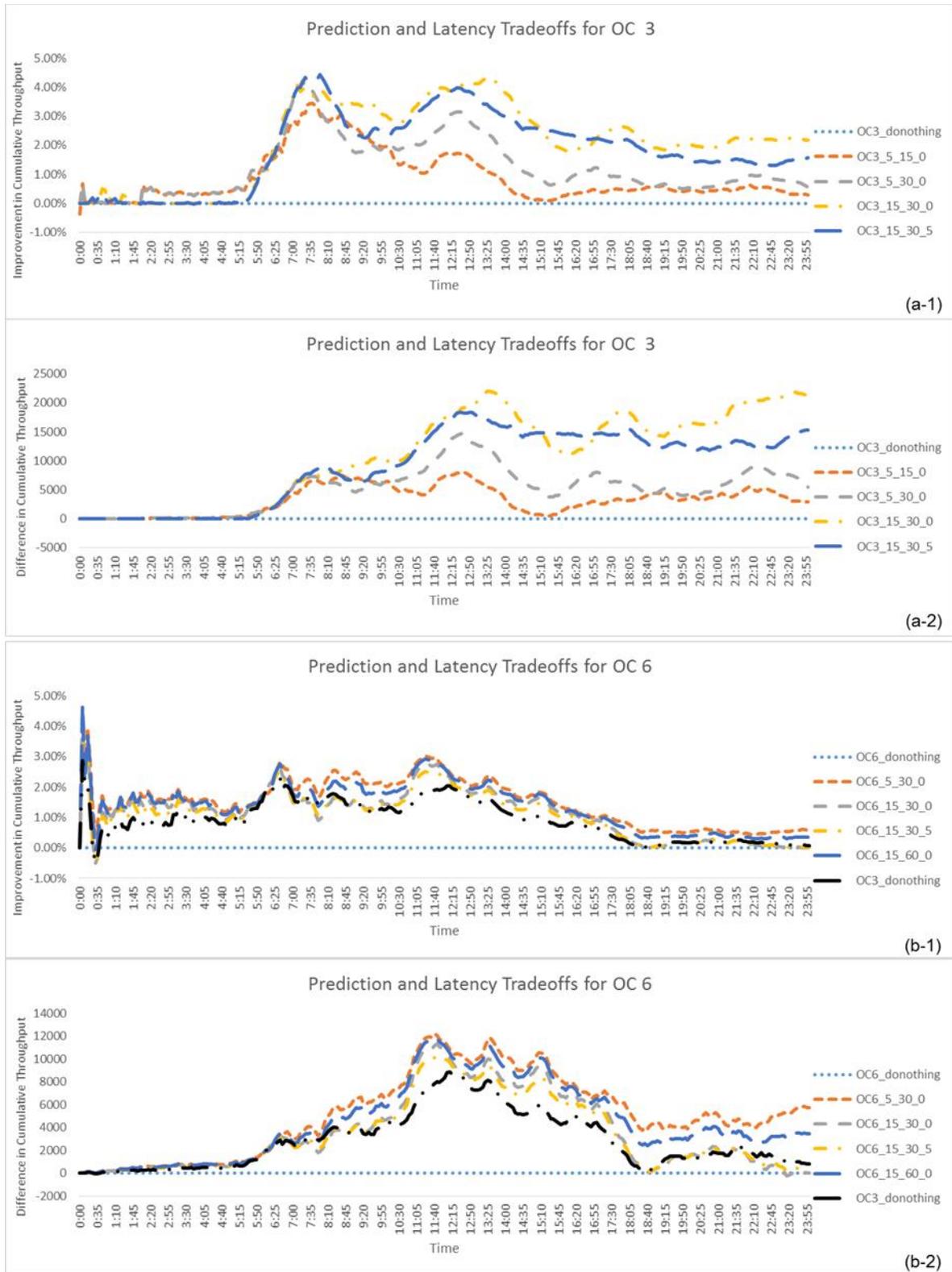


Figure 10-4: Tradeoff Analysis of System Performance to Prediction Quality and Communication Latency [Source: NWU]

10.3 Summary of Results

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, 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.

Chapter 11. Operational Conditions and Facility Types with Most Benefit

11.1 Research Questions

In this chapter, the following three research questions were addressed, which are related to the operational conditions and facility types with most benefit:

- Which ATDM strategy or combinations of strategies will be most beneficial for certain facility types (freeway vs. arterial) and under which kind of weather related operational conditions?
- Which ATDM strategy or combinations of strategies will have the most benefits for individual facilities versus system-wide deployment versus region-wide deployment and under which kind of weather related operational conditions?

The hypotheses to the research questions are: (1) most benefits will be achieved in the high congestion and inclement weather scenarios, (2) some weather-responsive ATDM strategies are focused on arterial streets more than freeways, and (3) the benefits of ATDM strategy or combination of strategies will vary by region, facility type and system.

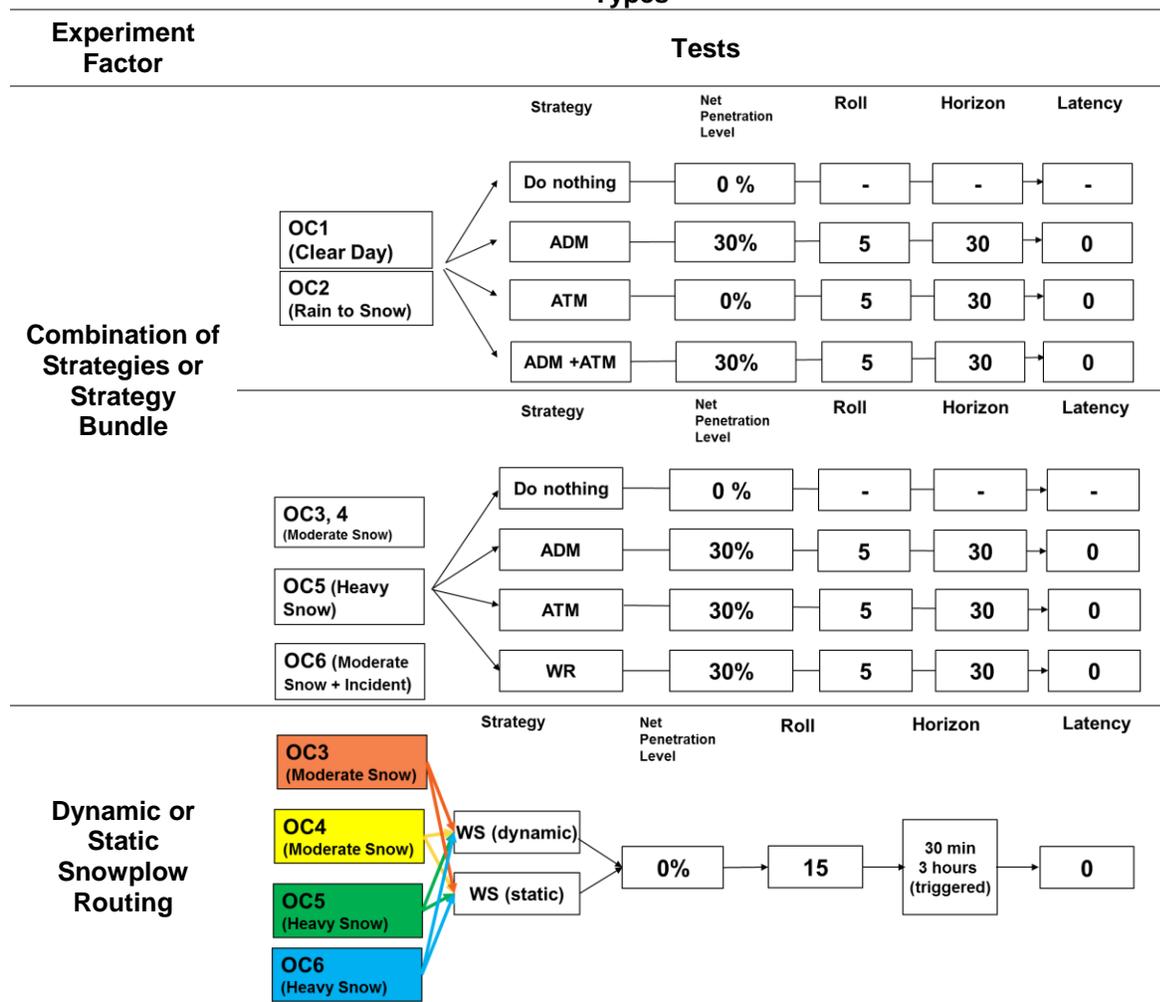
11.2 Analysis Approach

11.2.1 Scenarios

Table 11-1 shows the experimental design to test the research questions related to the operational conditions and facility type. To examine the best combination of strategies or strategy bundles for certain facility type, including freeway segments and arterial roads, four combinations of strategies for OC 1 and OC 2 were tested, each not taking the weather-related strategies into consideration. For the snow-affected scenarios (i.e., OC 3 to OC 6) we test the individual strategy bundle compared with the do-nothing baseline scenario to find the most effective strategy bundle.

In addition, another set of experiments were designed to test the effectiveness of different snowplow routing plans. As stated in section 7.3, the dynamic snowplow routing plan was proposed which is generated according to the predicted travel demand for each link, also referring to the link volume. The routing plan may vary by time of day and under different scenarios due to the dynamic traffic assignment. On the other hand, there is another way to generate snowplow routing, which only depends on the link travel time or link length in the network, which is called static snowplow routing plan in this study. When the static routing plan is selected, the operators do not need to update the plan according to the travel demand or the snow intensity, they only need to decide when the snowplow vehicles depart from the depot. Therefore, the question is what kind of operational conditions prefer dynamic routing plan versus static plan. In this set of tests, three snow-related operational and traffic conditions were simulated, comparing the unit travel time and travel time reliability. Both static and dynamic plans analyzed were optimized according to the objective functions

Table 11-1: Experiment Scenarios for Research Questions of Operational Conditions and Facility Types



11.2.2 Results

11.2.2.1 Combination of Strategies or Strategy bundle for Different Operational Conditions and Facility Types:

In order to verify the best combination of strategies for each facility type, two representative corridors from each facility type were selected as target segments. The performance measurement for this research question category is the corridor speed profile over the entire simulation horizon on each target segment. The two corridors are displayed in Figure 11-1, where the I-90 freeway segment and the Peterson Avenue are selected.

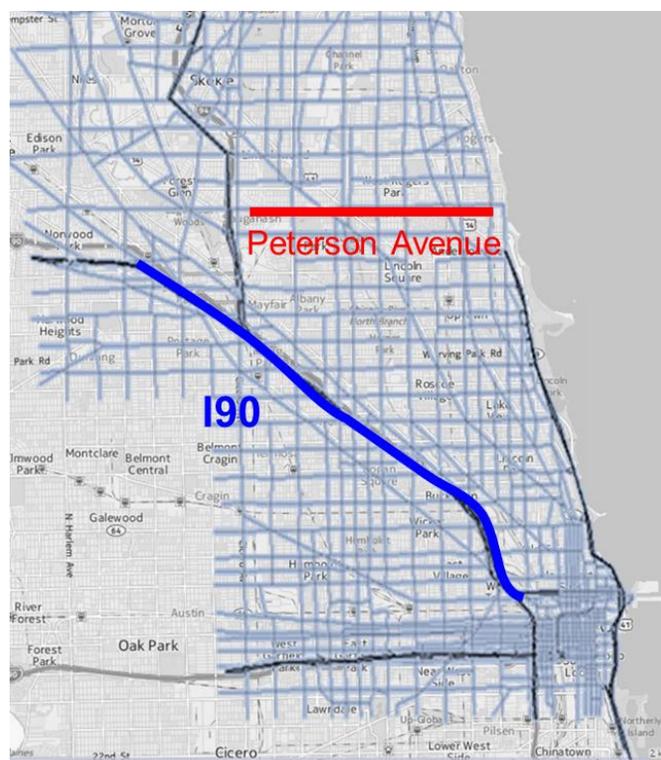


Figure 11-1: Representative Corridors of Freeway Segments and Arterial Roads [Source: NWU]

Figure 11-2 shows the speed profiles that were extracted from I-90 segment and the Peterson Avenue from different scenarios. On the I-90 segment, the dynamic shoulder lanes and dynamic speed limit were implemented, while on the Peterson Avenue the adaptive signal control was implemented on the corridor.

Figure 11-2 (a) shows that both ATM and ADM strategy bundles improve the corridor performance on both facility type, but if ADM strategy is implemented in conjunction with ATM, the corridor speed is increased the most over the entire horizon. Figure 11-2 (b) shows the results for the OC 2 where there was some influence from the rain and light snow. It is observed that the ATM strategies shows more effectiveness on the freeway segment than the ADM strategies, and it also generates more benefit when implemented together with the ADM strategies. But for the arterial road, the scenarios with the ATM, ADM and the combination of both strategy bundles show similar performance.

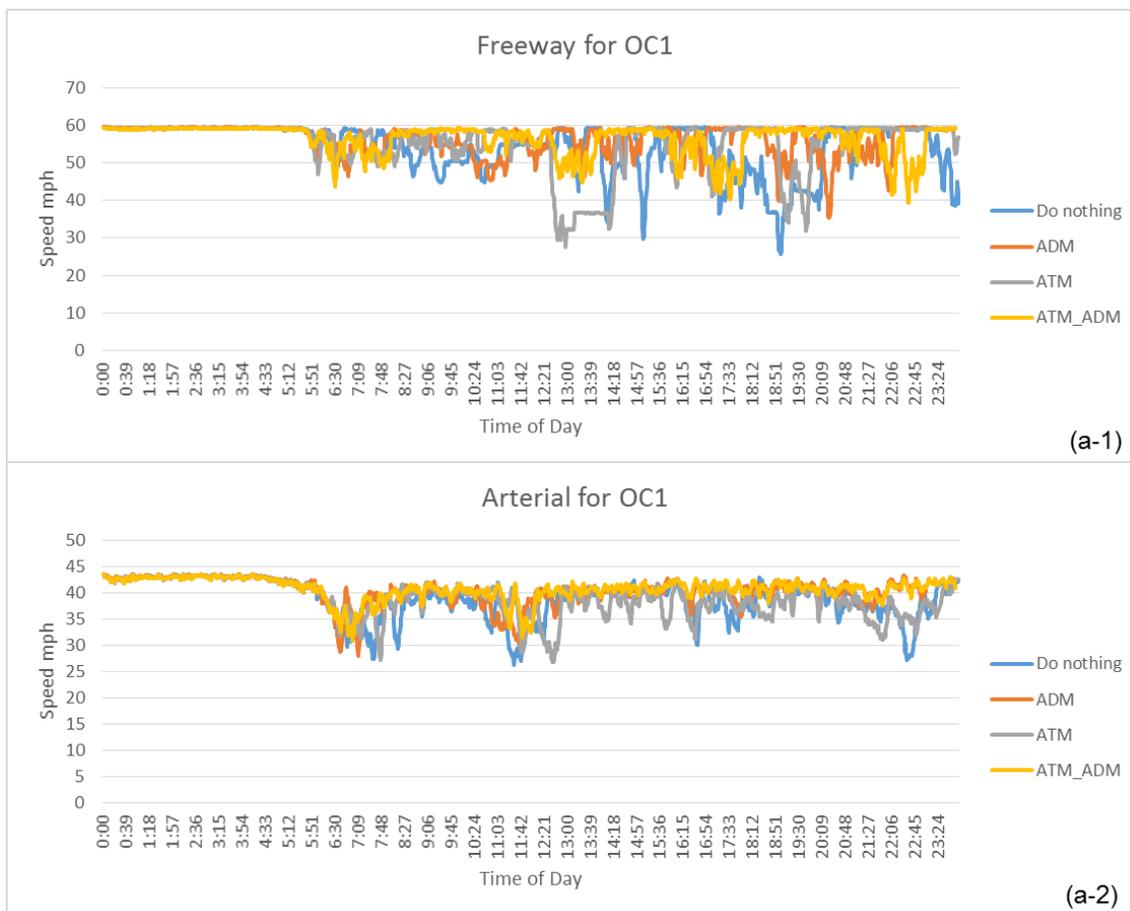
Figure 11-2 (c-f) shows the results for the snow-related scenarios with three individual strategy bundles implemented. For OC 3 where the demand is medium high and the snow intensity is moderate and uniform over the entire simulation horizon, the best strategy is the Weather-related strategy for both freeway segment and the arterial road, and the ADM strategy bundle also shows significant improvement for the corridor performance. Due to the dynamic speed limit control, one of the ATM strategies implemented on I-90 segment, the speed profile under ATM strategy, is the lowest among the test scenarios. However, as the speed limit is generated according to the speed harmonization principle, it can also be observed that speed changes within a smallest range under ATM strategies compared with the other scenarios. This phenomenon is also described in Chapter 8 where the speed harmonization helps to control the speed variance and maintain the stability of the corridor. Therefore, from the aspect of reliability, ATM strategy is also very beneficial to the I-90 freeway corridor.

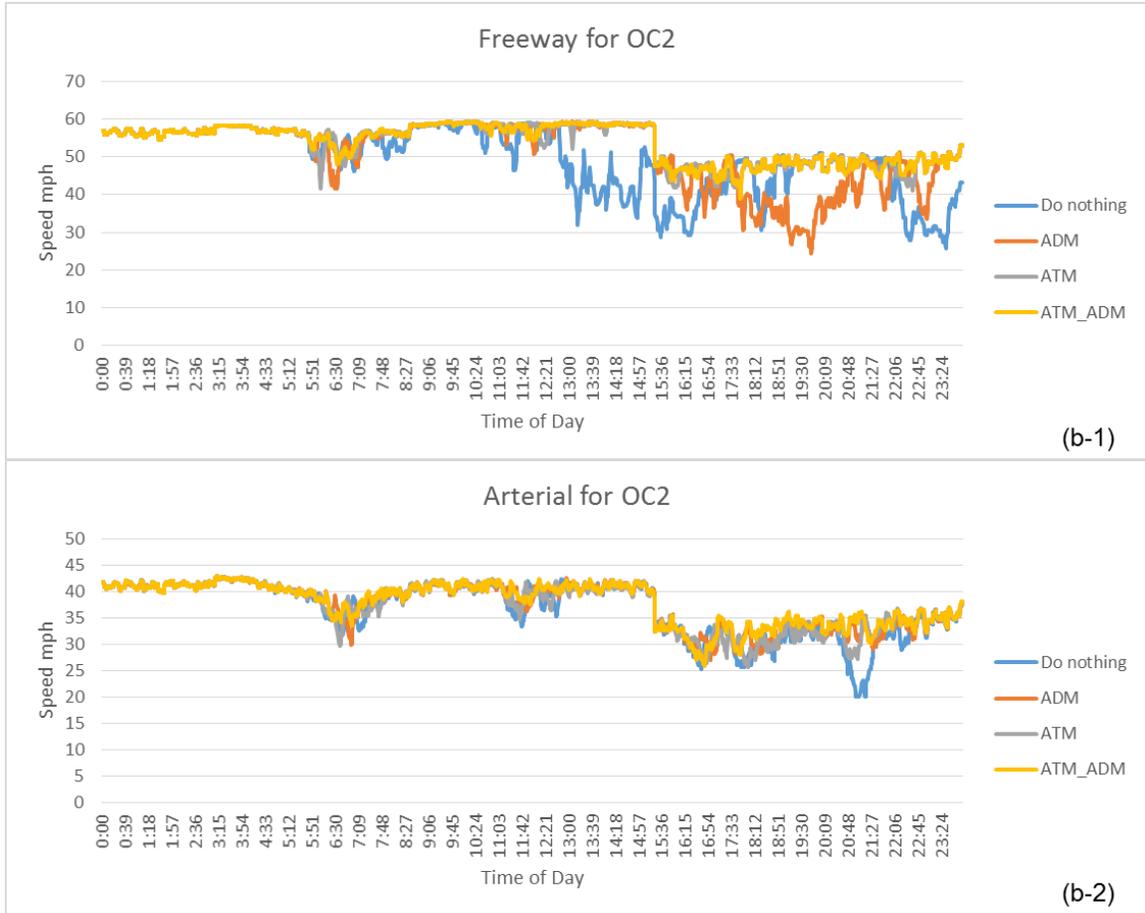
For OC 4 shown in Figure 11-2 (d), the most beneficial strategy bundle is the ADM strategy instead of the Weather-related strategy. This is due to the low demand pattern under this operational condition so system may not have serious congestions even under the baseline scenario which has been confirmed in the

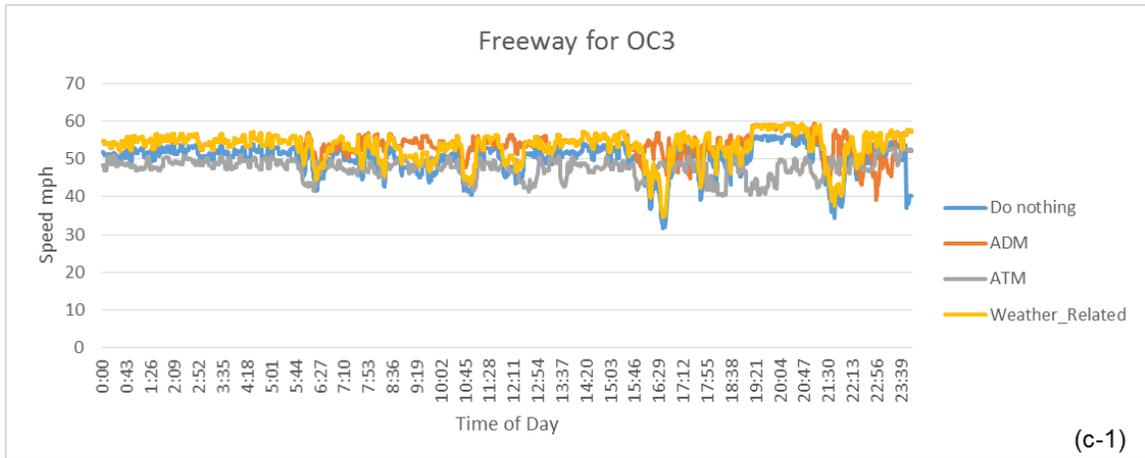
baseline scenario performance in section 3.2. Likewise, the negative impact from the ATM strategy on both freeway segment and the arterial corridor, and from the Weather-related strategy during some period, has been also observed from the tests for Synergies and Conflicts in section 9.2. The reasons could be that: (a) dynamic shoulder lanes are not functional on weekend for OC4, producing no extra capacity, (b) speed limits may reduce the network throughput in a less congested network when demand is low, and (c) the recovered capacity from the Weather-related strategy is not effective for OC4 due to low demand, but it brings disadvantages from lane closure during implementation.

Like OC 5 in Figure 11-2 (e), for OC 3 the best strategy is the Weather-related strategy which helps to reduce the snow accumulation impact and is most beneficial especially for the heavy snow scenario. The ATM strategy helps to maintain travel speed within a small range, keeping travel time in the corridor reliable and stable.

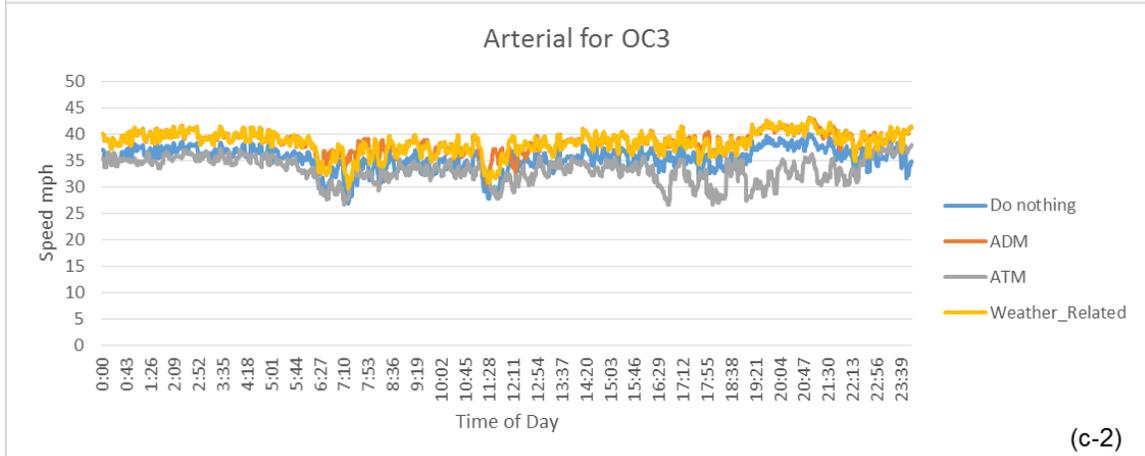
For OC 6, which shares the same demand and weather pattern as OC 3 and is an incident-snow mixed scenario, the best strategy is the ADM strategy which helps vehicle choose the best routes and avoid the impact from the incident-related delay. The ATM strategies also lead to a reliable corridor especially from 16:00 to 18:00 when the ADM strategy is less effective.



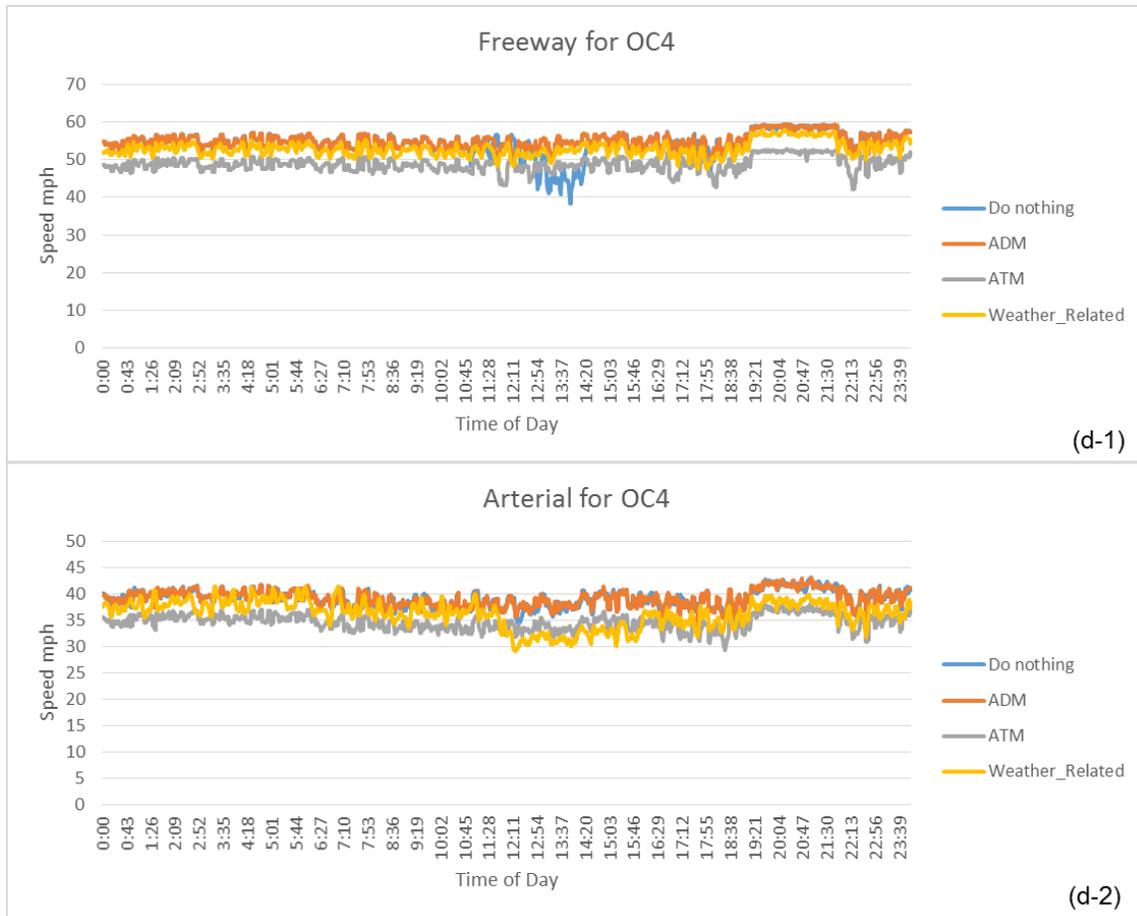


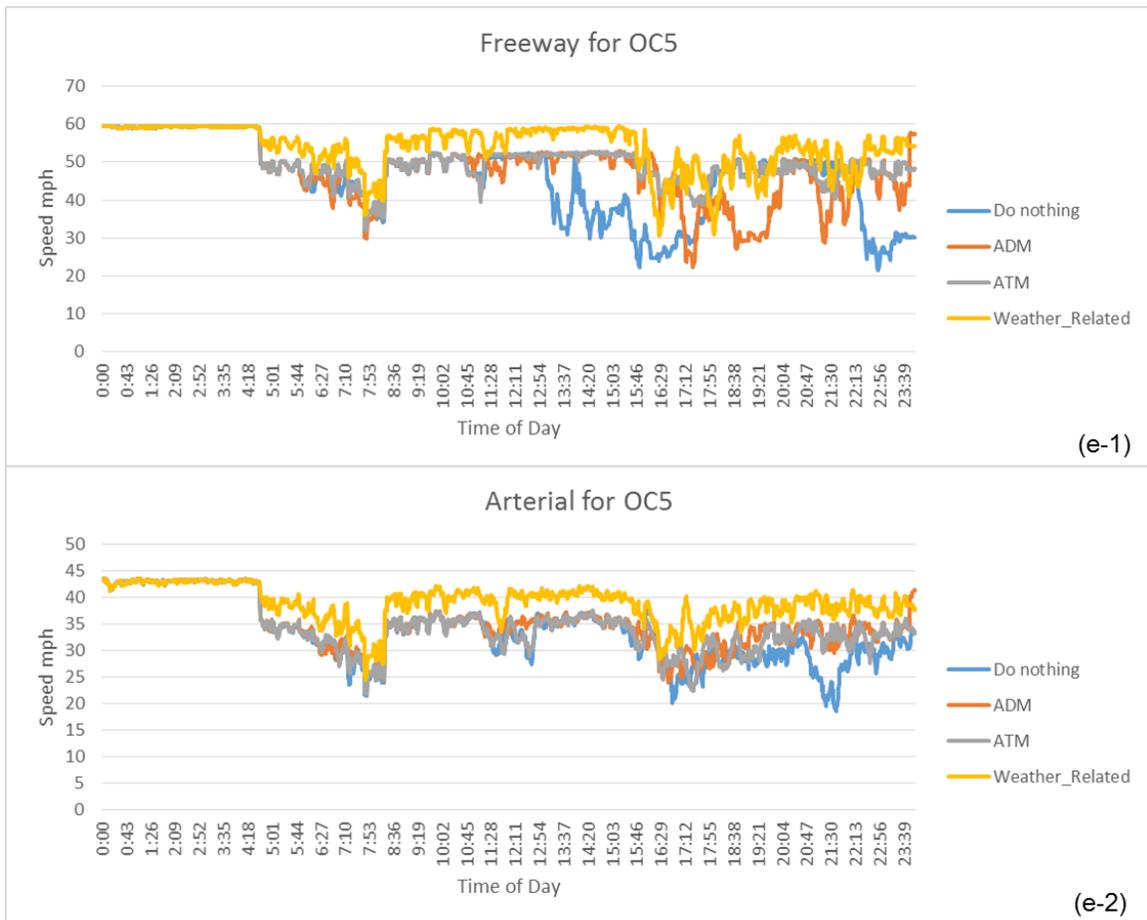


(c-1)



(c-2)





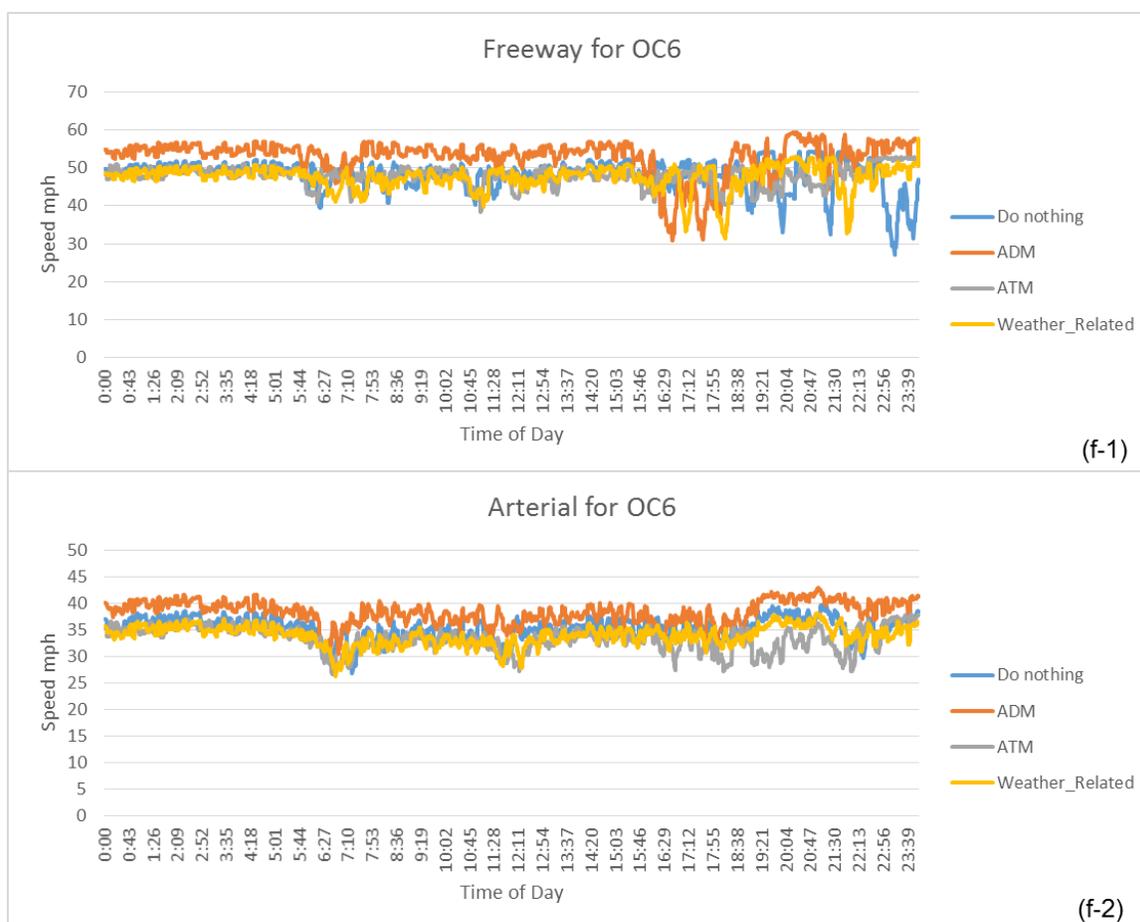


Figure 11-2: Traffic Speed Profiles for Different Facility Types and Operational Conditions [Source: NWU]

11.2.2.2 Dynamic or Static Snowplow Routing Under Different Operational Conditions:

The snowplow routes generated by the model proposed in section 7.3 are called dynamic snowplow routes because the model uses dynamic and predictive weather and traffic information. Another set of routes, static snowplow routes, was generated by dividing the whole network into small clusters and solving the Chinese Postman Problem for each cluster. While the dynamic routing plan incorporates the benefit of plowing in the objective function, the static routing plan aims to minimize the deadheading cost. The static snowplow routes served as the benchmark against which to evaluate the performance of the dynamic snowplow routes.

We use the average travel time, average stop time, average unit travel time and 95% unit travel time to evaluate the performance of the routing plan. The 95% unit travel time is used as the travel time reliability measurement. The improvement of unit travel time is defined as:

$$\frac{\text{unit travel time with static routing plan} - \text{unit travel time with dynamic routing plan}}{\text{unit travel time with static routing plan}}$$

A positive improvement value indicates the dynamic routing plan has a better result, negative value indicates otherwise. Because OC1 has no snow and OC2's snow fall is too light, these two operational conditions do not have weather-related strategies. Only OC3, OC4 and OC5 results are included in this chapter.

Figure 11-3 illustrates the performance of plowing under OC3. Both routing plans, static and dynamic, have two rounds of plowing at 7:23 am and 3:58 pm respectively. Compared with the scenario using the static snowplow routes, travelers' average travel time is **3%** shorter and average stop time is **8%** less in the case of the dynamic snowplow routes. The dynamic routing plan leads to improvement in the morning and evening peak hours. Figure 11-3 (a) compares the unit average time in both scenarios and shows the dynamic snow plowing routes scenario has a lower unit travel time during most intervals of planning horizon. As shown in **Error! Reference source not found.** (b) the dynamic routing plan performed slightly better in terms of 95%-unit travel time. Figure 11-3 (c) shows the difference in terms of percentage improvement. At the beginning of each plowing operation, dynamic routing always lead to a better result as the most important links are plowed first. However, towards the end of the plowing operation, one could see the fluctuation in the improvement. Because the dynamic plow plan aims to minimize the snow's impact on traffic, it has more deadheading trips and longer routes comparing with the static plan. As discussed in section 7.3, the snowplow's presence on a link would reduce the link capacity and increase link density and travel time. Therefore, these extra trips cause a reduction in the performance of the dynamic plans.

Figure 11-4 shows the performance of different strategies under OC4. Because the weather under OC4 is the same as OC3, both the static and dynamic plow plan have two rounds of plowing starting at 7:23 am and 3:58 pm respectively. Compared with the scenario using the static snowplow routes, travelers' average travel time is **4.32%** shorter and average stop time is **11%** less in the case of the dynamic snowplow routes. Since OC4 has low demand during the morning peak, the dynamic routing plan has a similar performance compared to the static routing plan. However, during the PM peak, when the demand increases, the dynamic routing plan has improvement in both unit travel time and 95% unit travel time.

Figure 11-5 illustrates the OC5 scenario, with high snow intensity during the morning peak hour and moderate snow at night. It needs two rounds of plowing at 8:15 am and 10:10 pm respectively. Although OC5 is the only scenario with heavy snow in terms of intensity, and the duration of heavy snow is less than 1 hour. Therefore, the total snow accumulated on the road surface is no more than the other scenarios. Similar to OC3, Figure 11-5 (c) shows that at the beginning of each plowing session, the dynamic routing plan always has a shorter unit travel time because the most important links are plowed.

Figure 11-6 demonstrates the performance of the two plowing plans under OC6. OC6 is almost identical to the OC3, except that OC6 has four incidents. The dynamic snowplow routing is regenerated with the updated link volume and speed information. Comparing with the OC3, dynamic routing plan leads to a larger improvement in unit travel time. With the incidents, the network is more congested. The dynamic snowplow plan performance better in terms of alleviating congestion as it serves the relevant links first.

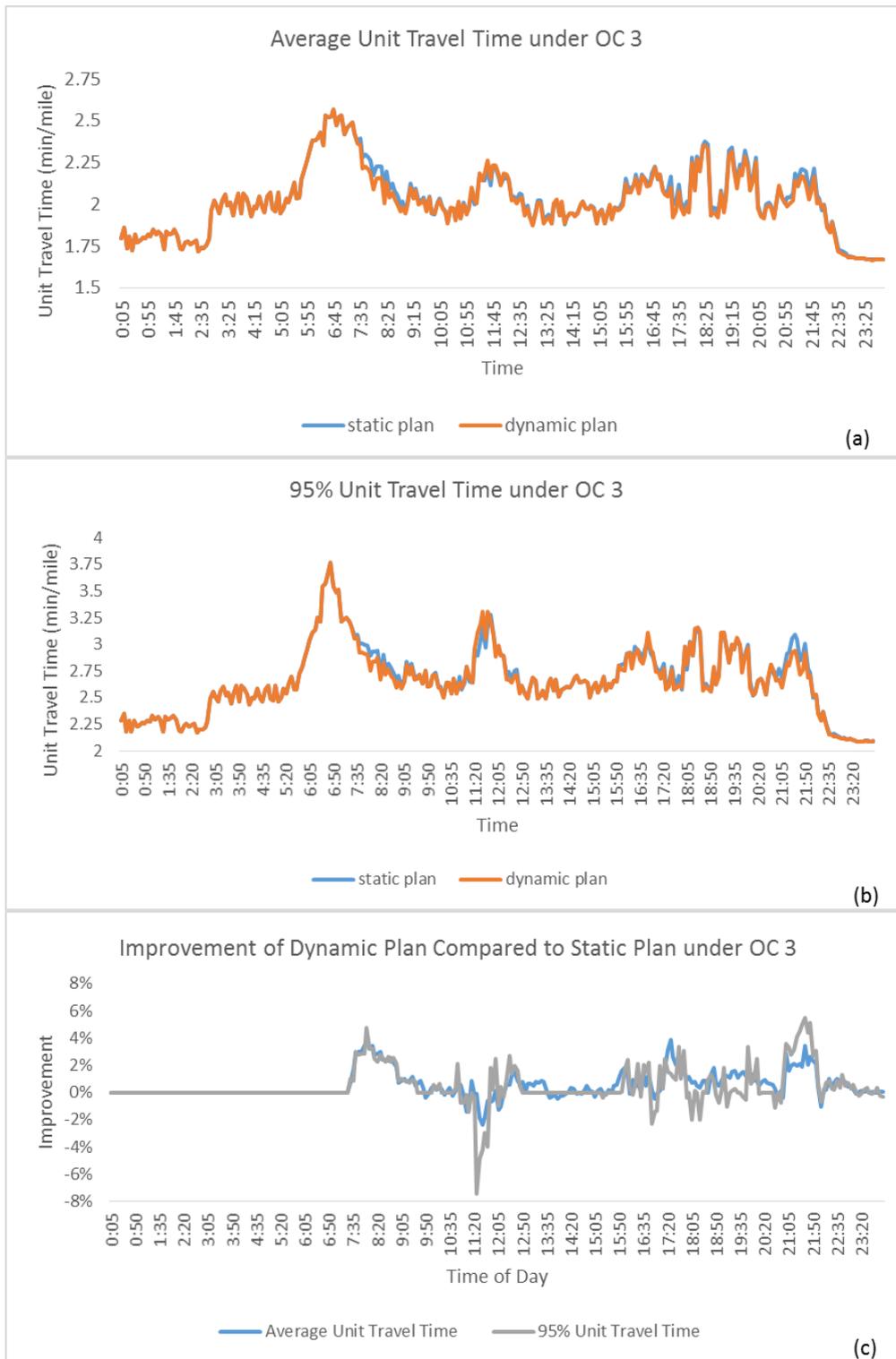


Figure 11-3: Comparison of Unit Travel Times Under Different Snowplow Routing Plans for OC 3 [Source: NWU]

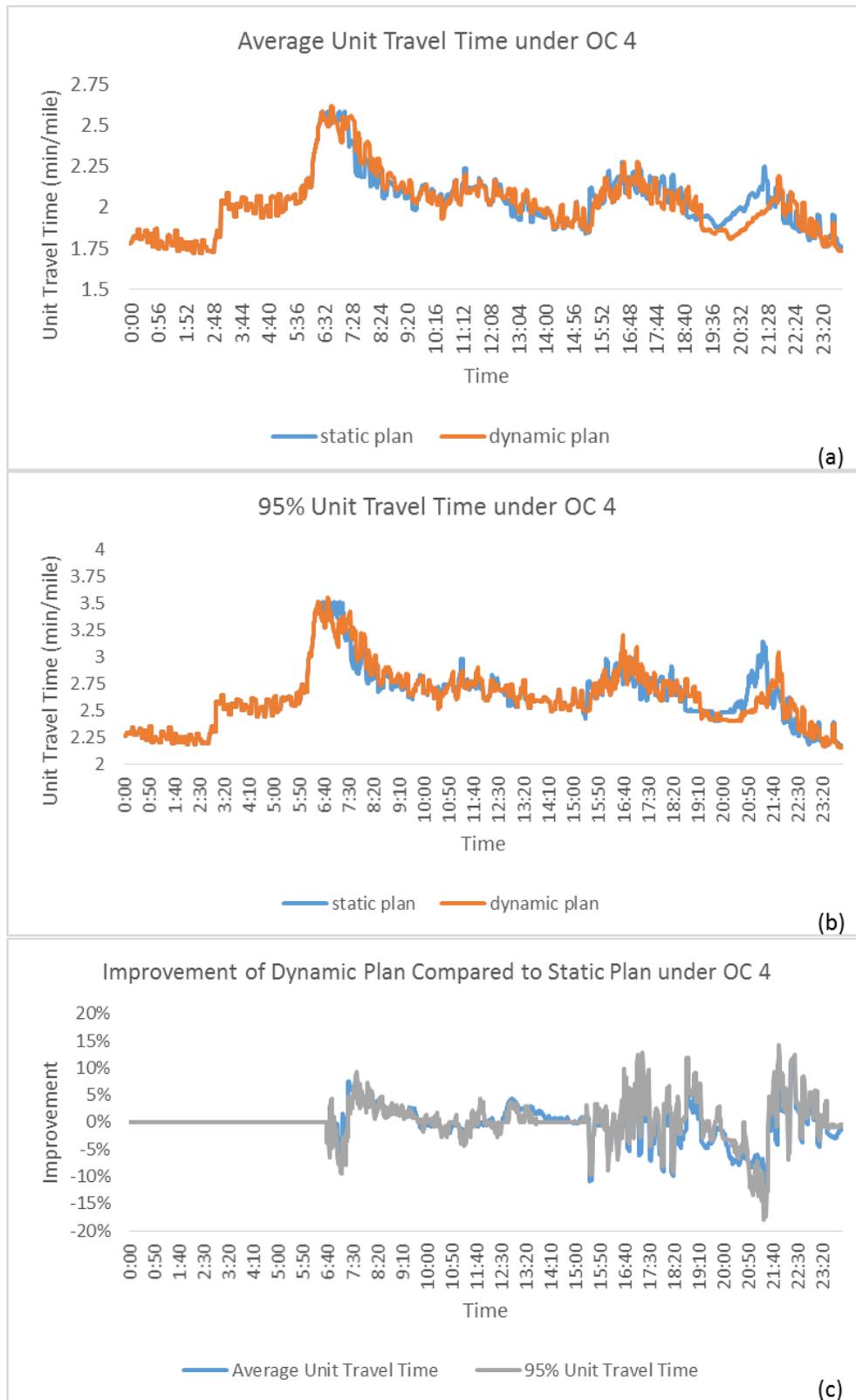


Figure 11-4: Comparison of Unit Travel Times Using Different Snowplow Routing Plans for OC 4 [Source: NWU]

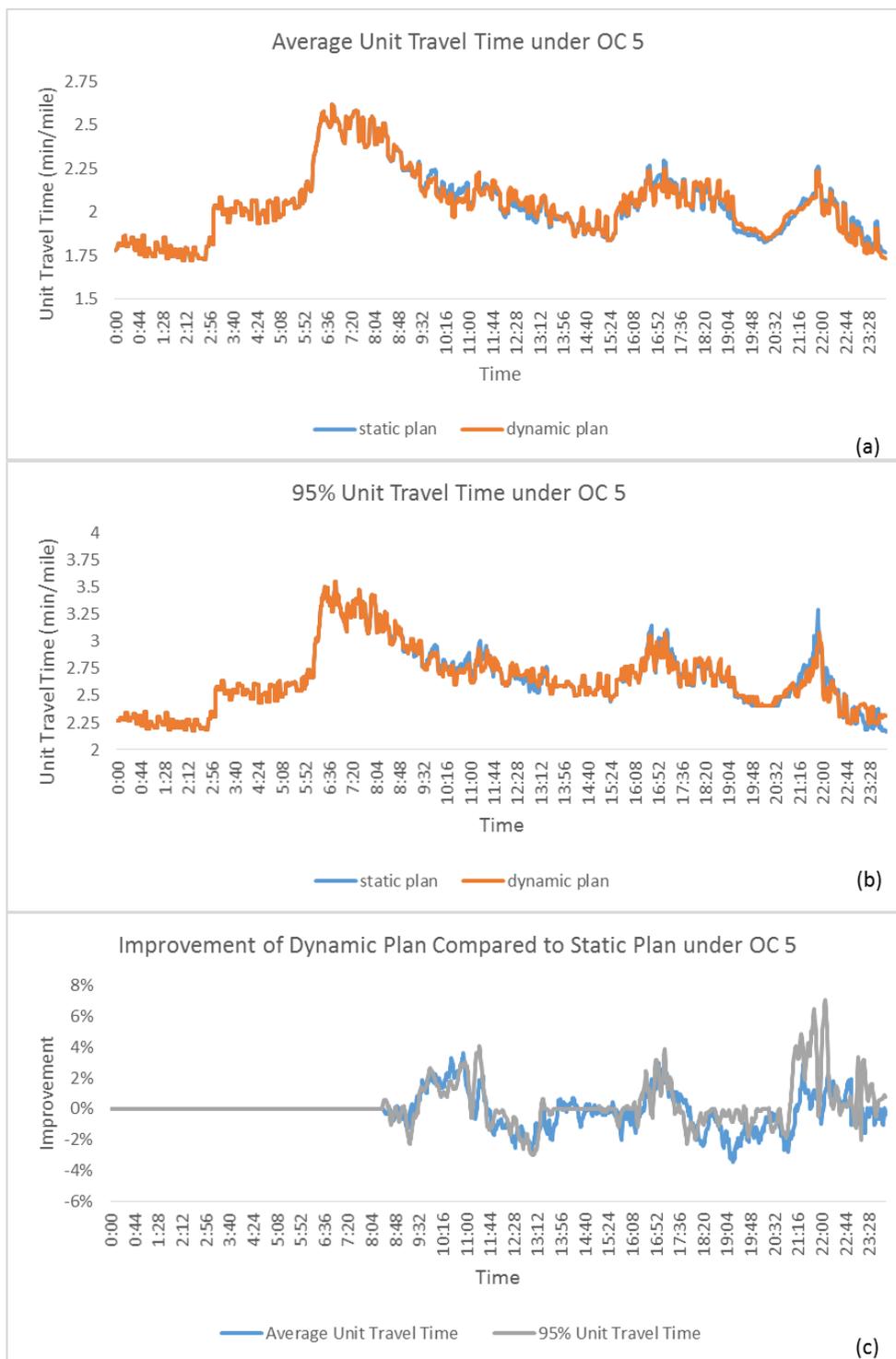


Figure 11-5: Comparison of Unit Travel Times from Different Snowplow Routing Plans for OC 5 [Source: NWU]

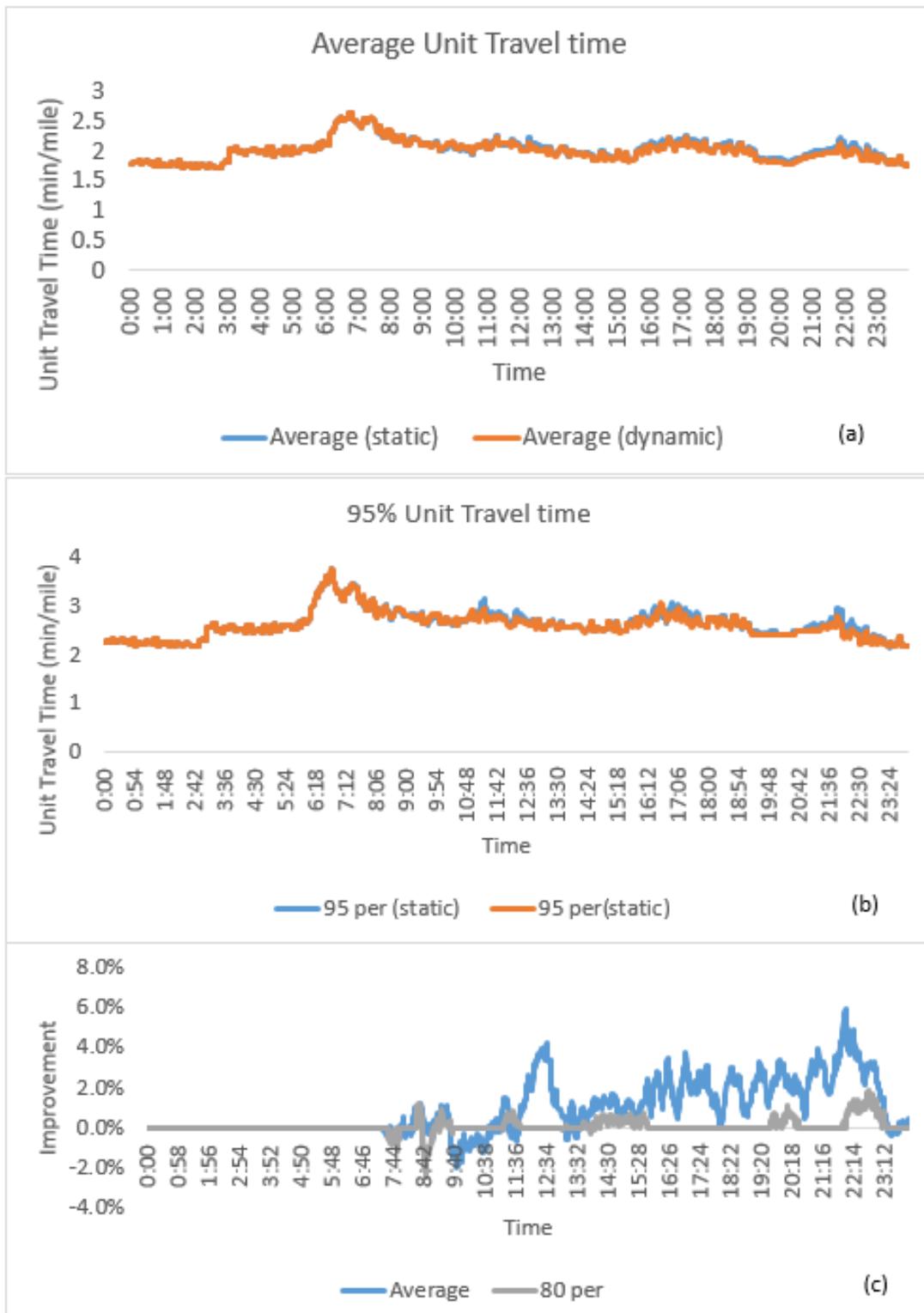


Figure 11-6 Comparison of Unit Travel Times from Different Snowplow Routing Plans for OC 6 [Source: NWU]

11.3 Summary of Results

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 exception, 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 less impacted by the plowing operation. Therefore, the weather-related strategy can 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. One should pay close attention to the operational conditions when selecting the plan to deploy.

Chapter 12. 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 vehicles 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. These 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 generates 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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