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

Chicago Testbed Analysis Plan

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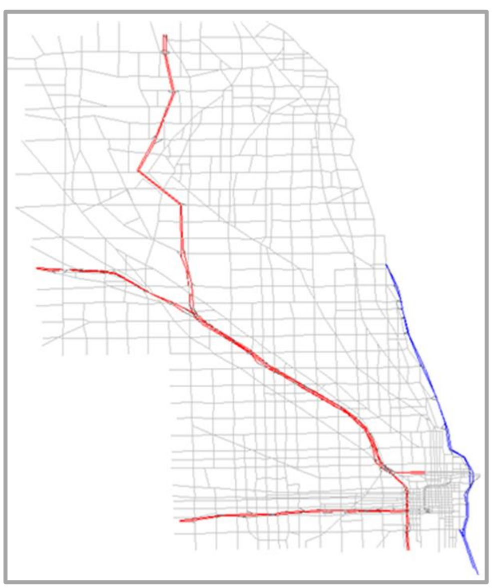

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16. Abstract

The primary objective of this project is to develop multiple simulation Testbeds/transportation models to evaluate the impacts of DMA connected vehicle applications and the active and dynamic transportation management (ATDM) strategies. The outputs (modeling results) from this project will help USDOT prioritize their investment decisions for DMA and ATDM programs.

The primary purpose of this report is to document the Analysis Plan for AMS Chicago Testbed. The report expands on detailed testbed description including the geographic location, modes, operational conditions and cluster analysis details. In addition, the plan also provides details on the analysis scenarios, DMA/ATDM applications and strategies that are evaluated using the Testbed and the plan to answer DMA/ATDM-specific research questions. The analysis plan provides details on the evaluation approach used to answer specific research questions. Additional data used for the testbed development and evaluation are provided in the Appendix.

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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. Capable, reliable AMS Testbeds provide valuable mechanisms to address this shared need by providing a laboratory to refine and integrate research concepts in virtual computer-based simulation environments prior to field deployments.

The foundational work conducted for the DMA and ATDM programs revealed 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 analysis plan helps to test the hypotheses of the DMA and ATDM Programs and evaluate the benefits and costs that may be anticipated through their implementation.

The primary purpose of this report is to document the analysis plan approach for the Chicago Testbed. The Chicago Testbed is developed for the Chicago core area, which covers around 15miles 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 sometime severe winter weather, particularly snow episodes which are commonplace for at least four months out 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 (I-90), the major road connecting downtown Chicago with O'Hare airport, the Edens Expressway (I-94), the major north-south highway connecting downtown Chicago with many of the suburbs and cities north of Chicago, the Dwight D. Eisenhower Expressway (I-290), 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 will be used to test several ATDM strategies and DMA bundles considering a proactive network management approach that adopts simulation-based prediction capabilities. Three types of ATDM strategies and one DMA application are proposed for this Testbed. The Active Traffic Management strategies considered consist of: 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 Preemption for Winter Maintenance Vehicles, Snowplow Routing and Anti-Icing and Deicing Operations). The DMA application to be 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.

This report is organized into ten chapters in addition to an Appendix as follows:

- Chapter 1 – Introduction: This chapter presents the report overview and objectives
- Chapter 2 – Testbed Description: This chapter presents the regional characteristics of the Testbed (e.g., geographic characteristic) and the proposed operational conditions.
- Chapter 3 – Analysis Hypotheses: This chapter identifies the hypotheses that will be tested by the Testbed. The hypotheses to be tested will, in many cases, determine the analysis approach and the operational scenarios to be considered for the specific Testbed.
- Chapter 4 – Analysis Scenarios: This chapter describes the analysis scenarios (combination of operational conditions, strategies and researched questions) to be evaluated, performance measurement for strategies evaluation, and analysis phases that we propose in this project.
- Chapter 5 – Data Needs and Availability: This chapter illustrates the data needs for the Testbed and describes sources of the available data and a detailed data collection procedure for Chicago Testbed network.
- Chapter 6 – Key Assumptions and Limitations: This chapter describes two main limitations in the proposed project and addresses potential solutions to these two limitations.
- Chapter 7 – Modeling Approach: This chapter details the modeling approach to test the hypotheses and generate performance measure statistics to evaluate and compare alternatives.
- Chapter 8 – Model Calibration: This chapter outlines the calibration procedures for parameters on both supply side, which includes traffic flow model and weather adjustment factor, and demand side, which refers to specific demand pattern that will be used in analysis scenarios.
- Chapter 9 – Evaluation Approach: This chapter presents the system evaluation plan to answer the ATDM and DMA research questions based on the analysis conducted and the sensitivity analysis.
- Chapter 10 – Execution Plan: This chapter presents the proposed schedule, budget and resources required to complete the analysis, and key roles and responsibilities of team members.
- Appendix – Cluster Analysis: This chapter documents the process used to identify four baseline scenarios, combining different levels of demand, incident, and weather conditions for testing the performance effects of Active Transportation and Demand Management (ATDM) Program improvements in the Testbed.

Chapter 2. Testbed Description

2.1 Regional Conditions

The Chicago Testbed network is 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 are bounding the Testbed network from south and north, respectively. Figure 2-1 depicts the original Chicago network and the extracted Testbed network, and Table 2-1 summarizes characteristics of the two networks.

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

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

Network	Original Chicago Network	Chicago Testbed Network
Description	▪ 40,443 links 1,400 freeways 201 highways 2,120 ramps (96 of them are metered) 36,722 arterials ▪ 13,093 nodes 2155 signalized intersections 1,961 zones 1,944 internal 17 external ▪ Demand period 5am -10am 5 minute interval demand (~4,100,000 total demand)	▪ 4,805 links 150 freeways 47 highways 247 ramps (59 of them are metered) 4,361 arterials ▪ 1,578 nodes 545 signalized intersections 218 zones ▪ Demand period 5am -11am 5 minute interval demand (~800,000 total demand)

The Chicago Weather Testbed is conducive to effective multi-climate congestion management approaches. Table 2-2 shows the relevant weather statistics based on weather data obtained from the Surface Weather Observation Stations (ASOS) O'Hare International Airport station in the past 5 years. The data is in 5-minute interval time resolution and preprocessed to exclude invalid or unrecorded data. It reveals that during the winter season, which stretches from late November to March, snow occurs much more than rain and its relative frequency was over 10% within the past 3 years. Northwestern University (NWU) is the primary developer of the Chicago Weather Testbed, and brings the expertise and experience required to enhance and evaluate weather-related strategies.

Table 2-2: Chicago Weather Event Statistics During Winter

	2009	2010	2011	2012	2013
Clear	80.56%	85.56%	85.91%	92.51%	82.09%
Rain	6.47%	3.77%	7.21%	2.91%	6.25%
Snow	12.40%	12.07%	7.93%	5.12%	11.67%

Both the original Chicago metropolitan region network and the Testbed network experience very large traffic demands during peak hours. As presented the Appendix, the congestion observed along the Edens Expressway in the morning peak is experienced with an average speed of about 25 miles per hour, even lower in the afternoon peak. The congestion becomes much worse in snow season, such that average speed could drop to 10 miles per hour in peak hours. Such conditions are commonly encountered on weekdays during winter. Even though drivers are generally used to driving in such conditions, the weather impact on the overall operational performance is still significant, and calls for innovative technology-enabled approaches to improve overall mobility and traffic congestion management.

Several operational management strategies have been developed for the Chicago Testbed as part of previous or ongoing Northwestern University Transportation Center projects. These strategies focus primarily on (a) real-time traffic estimation and prediction system (TrEPS), incorporating field observations and traffic measures, as well as estimating and predicting network states to enable implementation and evaluation of on-line traffic management; (b) traffic flow model and Weather Adjustment Factor (WAF) calibration with multi-weather effects; and (c) implementation of the multi-modal dynamic network simulation of travelers and vehicles given predicted traveler information. Other strategies have also been developed and tested with DYNASMART on other metropolitan networks under analogous operational conditions: weather-related advisory and control measures for integrated real-time weather responsive traffic management (WRTM) with a Traffic Estimation and Prediction System (TrEPS). These strategies are designed to reduce the impacts of inclement weather events, prevent congestion, and extend the applicability to include sensitivity to dynamic network with predictive information provided.

The dynamics of traffic systems are complex, where many situations necessitate strategies that anticipate unfolding conditions instead of adopting a purely reactive approach. Simulation of the traffic network forms the basis of a state prediction capability that fuses historical data with sensor information under different operational conditions, uses a description of how traffic behaves in networks to predict future conditions, and accordingly develops control measures. A decision support system is needed to map the observed operational conditions to the suitable response plans. The simulation-based traffic performance evaluation and prediction system, DYNASMART, is used to quantify the potential benefits associated with deploying a response plan as recommended by the decision support system.

2.2 Operational Conditions

The experimental design to conduct the analysis entails identifying up to four operational conditions or baselines using the Cluster Analysis approach defined in Section 2.2.1. The details of the cluster analysis approach are described in the Appendix.

2.2.1 Generic Approach for Existing Operational Conditions

First we provide an overview of operational condition selection procedures using a two-step joint clustering approach, as illustrated in Figure 2-2. The two-step joint clustering approach is defined as following:

- **Step 1:** We first conduct weather condition recognition to identify significant weather patterns. We use ***K*-**means algorithm with historical weather index data, which represent different weather categories (see Table 2-3) to classify K different weather patterns identified as cluster 1 to cluster K.
- **Step 2:** Conditional upon each given weather cluster j, j=1...k (from Step 1), we then use the K-means algorithm on the corresponding historical traffic flow data for that cluster to generate traffic flow (sub)patterns under each identified weather condition. The traffic flow (sub) patterns are described as pattern M-j, where M=A, B… represents the traffic flow pattern, and j=1,…,k to represents the weather condition pattern. The M-j patterns are the joint clusters we seek to identify.

Note that it is possible to do a single step clustering, but an effective method or algorithm is required to evaluate the influence of weather on traffic in order to decide the weight of weather data, the weight of traffic data, and the weight for their combination. The selection of weights will be very critical to the results. The two-step joint model avoids this problem. Furthermore, weather is independent from traffic, but weather affects traffic. The interaction between weather and traffic is kind of hierarchical relationship. Therefore, the two-step joint approach, which is based on the logic of hierarchical clustering, is more suitable than single step approach. With the two-step joint clustering results, we calculate the frequency of each joint cluster, check the consistency between clustered operational conditions and the corresponding system performance with speed data, and select the high frequency and/or significant effecting one under identified weather conditions as our recommended operational conditions for the Chicago Testbed.

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2.2.1.1 K-Means Clustering Algorithm

Given a large scale dataset, it is difficult to discriminate between useful data set and ineffectual items. Some datasets may include redundant information or attributes, while others may hold unique information. Although it is possible to analyze each data element or subset one by one, such a task would be very time consuming and inefficient. Hence, clustering techniques (1) are widely used to determine the intrinsic grouping or structure in an unlabeled data set by classifying data into homogeneous groups where the within-group-object similarity is maximized and the between-group-object similarity is minimized. The K-means algorithm is a widely used procedure for this purpose.

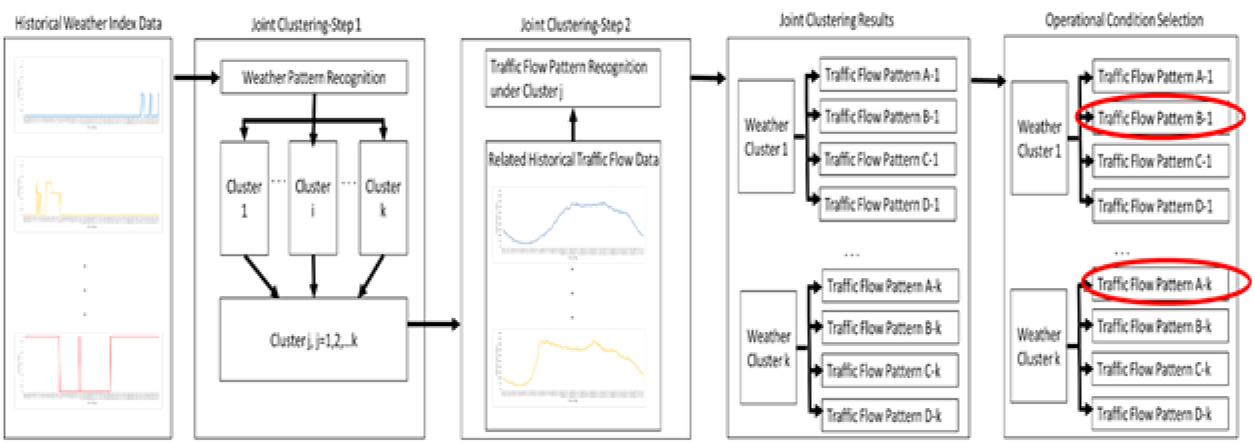

Figure 2-2: Operational Condition Selection with Joint Clustering Approach [Source: NWU]

However, the pure version of the K-means algorithm has some limitations in use, particularly with regard to the number of clusters K. The parameter K is known to be difficult to determine since it is sensitive to the initial partition's selection. If the number of clusters chosen is not appropriate for a given data set, poor clusters may result. Therefore, a criterion for choosing a reasonable K is adopted (Eq. (2-1)) (2) by examining final within-cluster sum of squares (WCSS) values J (K) (Eq. (2-2)).

$$R = \frac{J(K) - J(K+1)}{J(K)} \times 100\,\% \qquad (2\text{-}1)$$

where,

R = rate of change (decrease) in value of minimal WCSS as the number of clusters K increases (in percentage)

$$J(K) = \min_{S} \sum_{i=1}^{K} D(S_i) = \min_{S} \sum_{i=1}^{K} \sum_{X_n \in S_i} \left\| X_n - \mu_i \right\|^2 \qquad (2\text{-}2)$$

where,

K = number of clusters in the data set,

X_n=nth observation vector,

μ_i= the mean of points in S_i,

S_i= the cluster i,

$D(S_i)$ = the within-cluster sum of squares of cluster i,

$J(K)$ = the minimal within-cluster sum of squares.

Since J(K) decreases monotonically with increasing number of clusters K, the procedure starts with a small value of K (e.g., K=1) and checks the rate of decrease R by incrementally increasing K (by +1). The process continues until the rate of decrease R falls below a certain threshold, suggesting that adding clusters would not meaningfully improve the objective function. The steps of the K-means clustering procedure used in this project are listed below:

S1. Initialization:

Randomly assign an initial set of means $\mu_1^{(t)},\ldots,\mu_K^{(t)}$, iter = 0, t=1 and $J(K) = \infty$.

S2. Searching optimal allocation and centroid for K clusters:

S2.1.Checking iteration condition: if iter < 10, then go to **S2.2**; otherwise, **S3**

S2.2. Allocating samples to clusters:

If t=1, $\mu_1^{(t)},\ldots,\mu_K^{(t)} = \mu_1^{(1)},\ldots,\mu_K^{(1)}$; otherwise, $u_i^t = \frac{1}{\left|S_i^{(t-1)}\right|}\sum_{X_j \in S_i^{t-1}} X_j$

For each $\boldsymbol{X}$, if $\left\| X_j - \mu_i^{(t)} \right\| \le \left\| X_j - \mu_l^{(t)} \right\| \; \forall 1 \le l \le K$, then assign $\boldsymbol{X_j}$ into cluster $S_i^{(t)}$. Go to **S2.3.**

S2.3. Checking convergence:

If $S_i^{(t)} = S_i^{(t-1)}$ for all i, then calculate $J(K)\_new$ and go to **S2.4**; otherwise, t=t+1, go back to **S2.2**.

S2.4. Checking optimization:

If $J(K)_{new} < J(K)$, then $J(K) = J(K)\_new$ and results are $S_i^{(t)}$; otherwise, iter = iter + 1, go back to **S2.1.**

S3. Checking threshold:

If $R \le 5\%$, K is selected as a desirable number of clusters and $S_i^{(t)}$ is accepted, the procedure stops; otherwise, K=K+1 and go to **S1**.

After the two-step joint clustering process is completed, a traffic flow and weather condition library reflecting the cluster results will be built, and will serve as the reference for creating associated demand files and weather condition files used as input scenarios for the traffic simulation model and/or as initial matrix in an online implementation.

2.2.1.2 Data Description

Traffic Flow Data

The primary source of traffic data is loop detectors installed on freeway lanes. Historical data with the 5-minute interval is obtained from the Illinois DOT in 2009, where the daily 24-hour traffic flow demand profile is described in a vector, which includes 288 5-minute intervals of flow volume. Figure 2 3 shows a map of the 13 selected detector locations in Chicago. The clustering data is aggregated from these 13 detector datasets. At each location, traffic data from north- or southbound directions are obtained. Before the clustering procedure is executed, the dataset is filtered according to the percentage of observations and those days with less than 90% valid observations are excluded from the dataset. The total of 321 days' aggregated daily traffic flow data labeled from 1 to 321 comprise the test dataset.

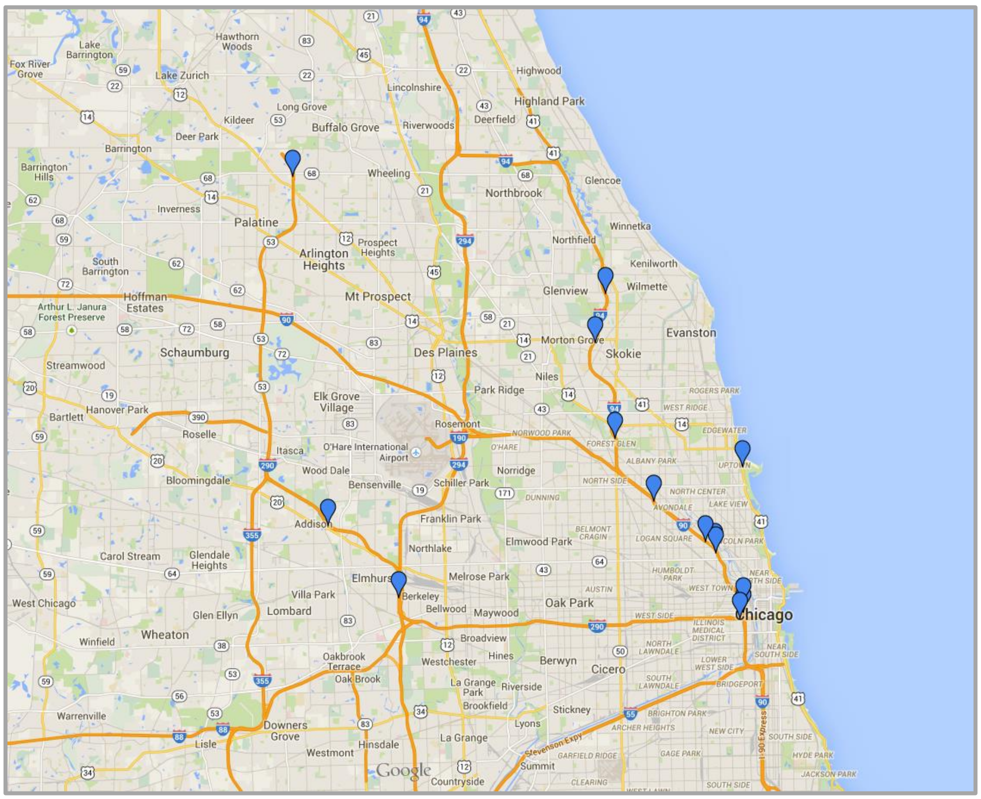

Figure 2-3: Selected Detector Locations in Chicago [Source: Google Maps]

Weather Time-Series Data

ASOS data with the 5 minute resolution will be used in conjunction with traffic detector data collected and aggregated over a 5-minute interval. ASOS 5-minute weather data are available on the NOAA National Climatic Data Center (NCDC) website (ftp://ftp.ncdc.noaa.gov/pub/data/asos-fivemin). In this cluster analysis study, we are using the ASOS data obtained from O'Hare International Airport, Chicago, IL in 2009.

With the same data structure of traffic data, the daily 24-hour weather condition is described in a vector, which includes 288 5-minute intervals. The data contains information on various weather parameters such as visibility, precipitation type and intensity, temperature, wind speed and direction (3). Among these, precipitation type and intensity are used as the main attributes to represent a different weather condition in each interval. The following seven categories are identified based on the combination of these attribute values in Table 2-3: Clear, Light Rain, Moderate Rain, Heavy Rain, Light Snow, Moderate Snow and Heavy Snow(4). The main focus of the index definition is on capturing a relative order of precipitation intensity within the same precipitation type (e.g., Light, Moderate and Heavy). Given the fact that other weather parameters are typically highly correlated with these two attributes (e.g., visibility decreases as precipitation intensity increases), we assume that the proposed seven weather categories can cover the majority of weather conditions that commonly occur in daily driving situations. These categories are those adopted in previous FHWA projects for incorporating the effect of weather in traffic modeling tools (4; 5).

Table 2-3: Weather Condition Index

Weather condition	Condition Index	Precipitation Type	Precipitation Intensity (in/hr)
Clear	0	None	0
Light Rain	1	Rain	(0,0.1]
Moderate Rain	2	Rain	(0.1,0.3)
Heavy Rain	3	Rain	>= 0.3
Light Snow	4	Snow	(0,0.05]
Moderate Snow	5	Snow	(0.05,0.1)
Heavy Snow	6	Snow	>=0.1

2.2.1.3 Joint Clustering Results

Weather Pattern Identification

After filtering clear days, that is the days without any precipitation of either rain or snow identified as **cluster 0**, a total of 187 weather scenarios labeled from 1 to 187 is created according to historical weather data. Figure 2-4 presents a plot of the minimized objective function value from historical weather data, *J(K),* as a function of *K*. It can be calculated that the rate becomes lower than the 5% when *K=5*. Therefore, *K=5* is selected as the number of clusters.

For the purpose of investigating between group dissimilarities across clusters, the cluster centers of the obtained five clusters are depicted in Figure 2-5, which plots the centroid value (i.e., mean) of the weather condition indices (i.e., $I_m(t)$) of the members of each cluster under weather clustering. One can observe distinct characteristics of five weather scenario clusters, where Clusters 1 represent light rainy days, Cluster 2 shows the days with moderate and/or heavy rain changing to light rain, Cluster 3 presents the days with gradual changing process from (moderate) rain to moderate snow, Clusters 4 represents mostly moderate snow days which might end with snow or rain, and Cluster 5 displays the days starting with light rain and changing into moderate or heavy rain in the evening. The five identified weather patterns are used for weather effected traffic flow pattern recognition as Step 2 of joint clustering approach.

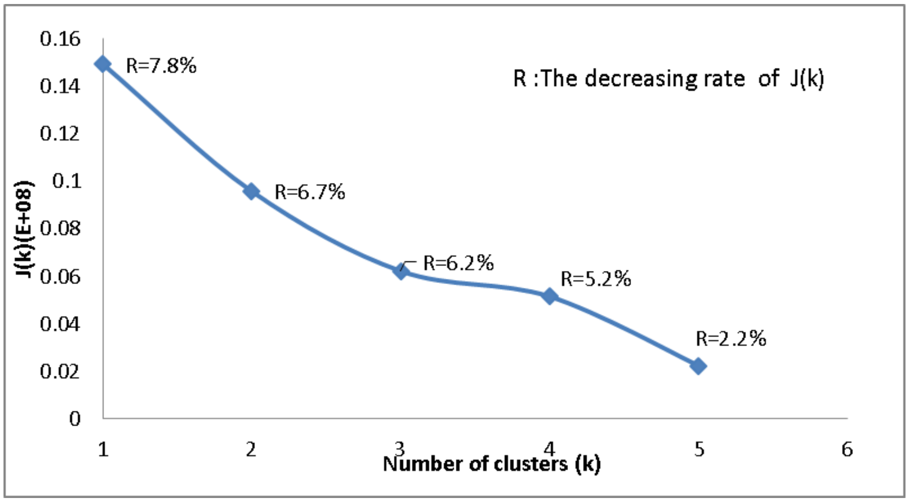

Figure 2-4: Minimized Within-Cluster Sum of Squares (WCSS) Value with Respect to the Number of Clusters. [Source: NWU]

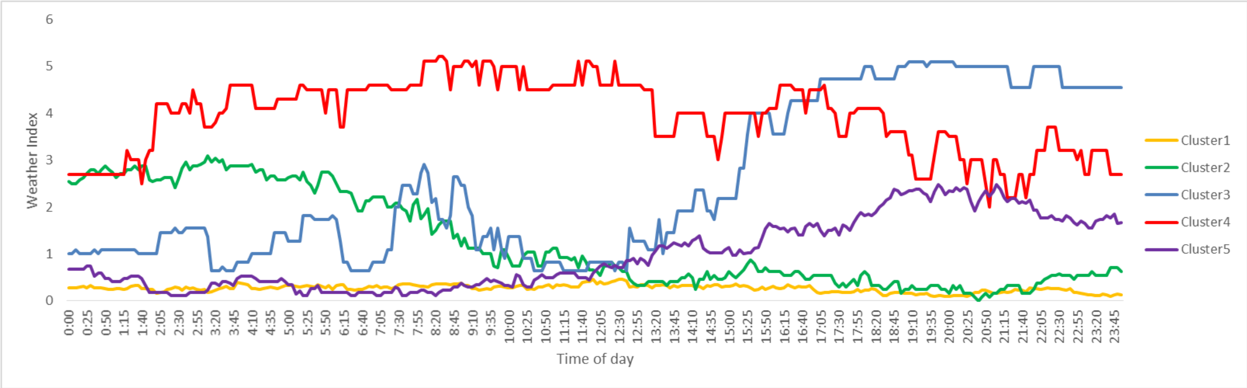

Figure 2-5: Temporal Profiles of Weather Condition Cluster Centroids [Source: NWU]

Traffic Flow Pattern Recognition Given Weather Condition

Figure 2-6 presents a plot of the minimized objective function value from the historical traffic flow data under each weather condition, J(K). The decreasing trend becomes slow after K=3. The rate reaches the 5% threshold when K=4. Therefore, K=4 is selected as the number of clusters. These four general clusters are Monday-Tuesday pattern (cluster A), Wednesday-Friday pattern (cluster B), Saturday pattern (cluster C) and Sunday pattern (cluster D). It is also found that most national holidays display a pattern similar to Saturday. The details of the cluster analysis results are described in the Appendix.

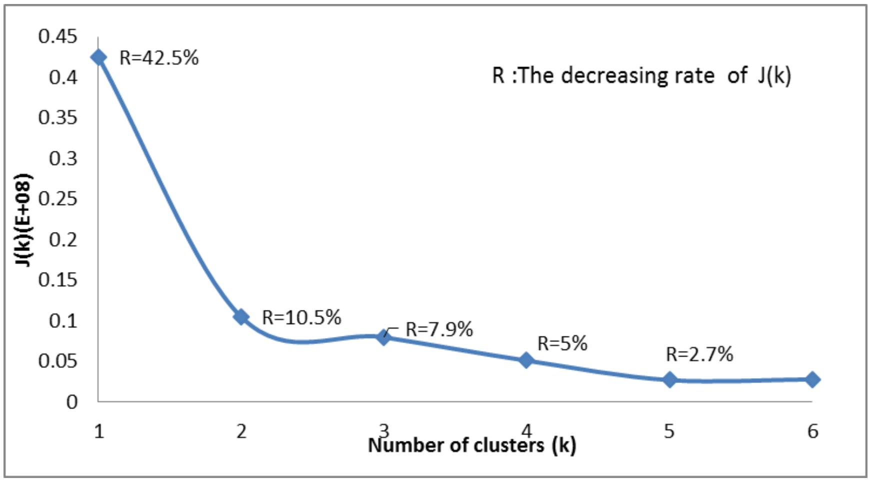

Figure 2-6: Minimized Within-Cluster Sum of Squares (WCSS) Value with Respect to the Number of Clusters. [Source: NWU]

Table 2-4 represents the frequency of traffic flow pattern (A to D) under different weather conditions (0 to 5) calculated based on joint clustering results. We selected the most frequently occurring joint cluster under each weather condition as the candidates of the recommended existing operational conditions, which are Cluster B-1, Cluster A-2, Cluster B-3, Cluster B-4, Cluster B-5 and Cluster B-0.

Table 2-4: Joint Clustering Results Statistics

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 0
Cluster A	26	**10**	3	1	5	42
Cluster B	**37**	5	**5**	**4**	**13**	**67**
Cluster C	17	5	3	3	4	26
Cluster D	10	2	1	2	5	23

With the results statistics, we notice that neither weekend traffic pattern nor heavy snow weather condition are among the candidates of the recommended existing operational conditions. But we also want to capture the impact of heavy snow, which is identified as Cluster 6, and it includes the days with any heavy snow record. Among the two days with heavy snow records, ID=9, January 9 (Friday) and ID=50, February 22(Sunday), 2009, we select the weather condition and traffic flow pattern of January 9, 2009, as the heavy snow operational condition. The reasons to do so are 1) the heavy snow precipitation occurred in morning peak hours, which is expected to have much effect on traffic, and 2) it could be compared with the Cluster B (Wednesday to Friday) in other selected candidates and its traffic demand pattern is then defined as cluster B-6. Accordingly, we remove these two days from Cluster 4 and recalculate the centroid of Cluster 4 in Figure 2-7.

Besides, a weekend weather event scenario also belongs to our interests and we are going to include one in our recommended operational conditions to differentiate from weekday patterns. With the emphasis on snow effect and the most frequency selection principle, we are going to include cluster C-4 in our operational condition lists. Accordingly, due to small effect, two rain scenarios are to be excluded, i.e. cluster B-1 and cluster A-2. For the purpose of investigating between group dissimilarities across clusters, the cluster centers of the obtained modified selected clusters are depicted in Figure 2-7. The details of System Performance Consistency Checking are described in the Appendix.

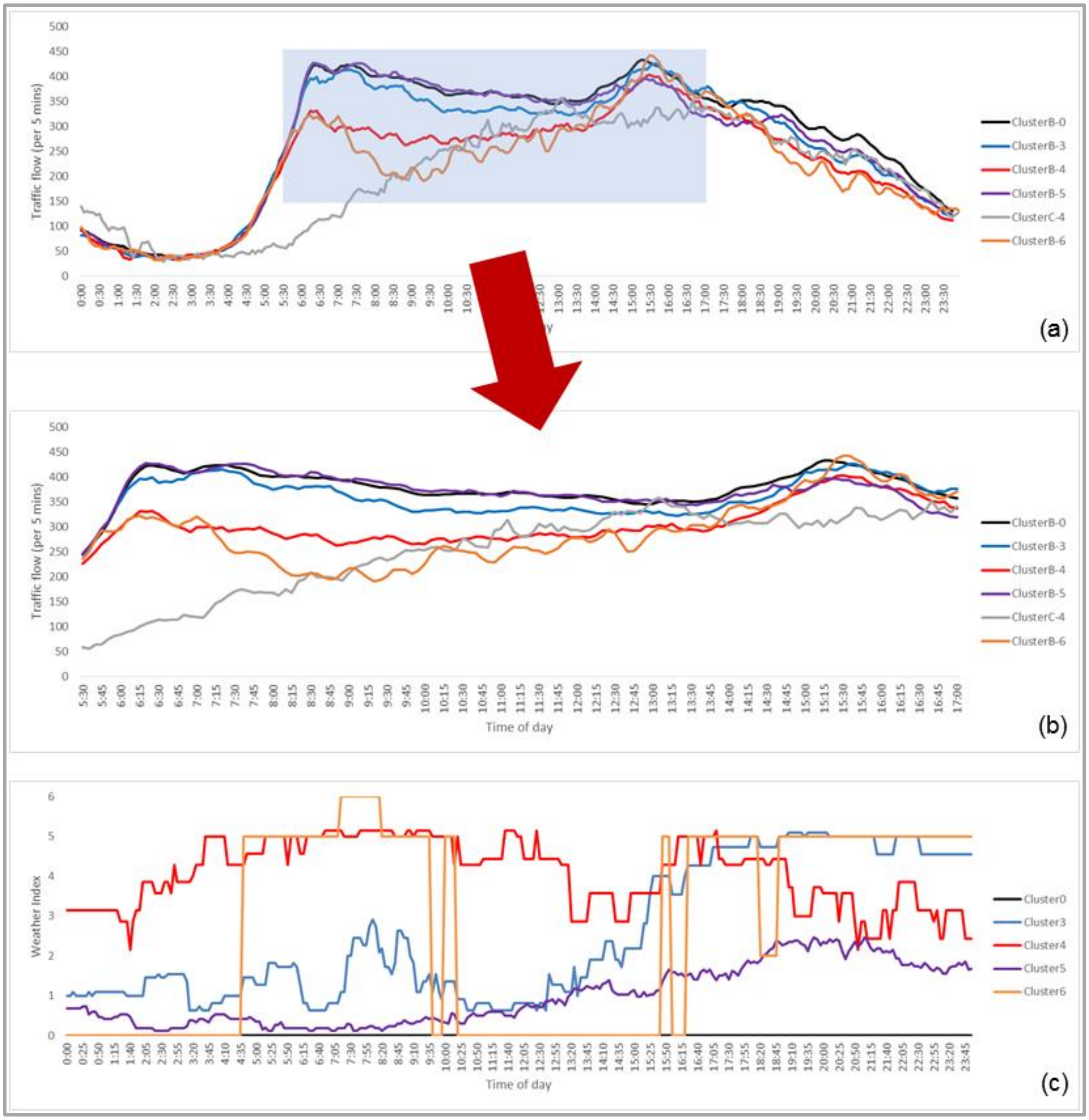

Figure 2-7: Temporal Profiles of Selected Operational Conditions: (A) 24-Hour Pattern Traffic Demand Pattern, (B) Day-Time Pattern Traffic Demand Pattern, (C) 24-Hour Weather Condition. [Source: NWU]

2.2.1.4 Recommended Existing Operational Conditions

To summarize, the team recommends original selection of the frequently occurring and significantly impacting operational conditions in Figure 2-7. These include 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 to be useful in the cluster analysis, but we still want to include the incident-related delay and compare it with weather effect, we recommend to remove Cluster B-5, which shows least system performance changes in section 4.3.2 and to add Cluster B-7, which is a weather-incident mixed scenario. Table 2-5 finalizes the operational condition candidates, which will be used to test weather related strategies in the Chicago Testbed.

Table 2-5: Existing Operational Condition Candidates

Variables	All	Cluster B-0	Cluster B-3	Cluster B-4	Cluster C-4	Cluster B-6	Cluster B-7 (hypothetical)
Number of 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

2.2.2 Hypothetical Operational Conditions

Since there are 6 existing operational conditions recommended to be tested on Chicago Testbed according to the clustering analysis results, which already cover heavy snow and heavy rain scenarios, any other weather-related scenarios are not to be added in hypothetical operational conditions. However, the hypothetical scenario Cluster B-7 with incident interruption might be considered for Chicago Testbed. We propose modeling a snow-weather scenario with incident in which multiple roadways in the network are fully or partially closed. In the scenarios, the local congestion and speed drop are expected to occur, and the change in the drivers' behavior given predictive information to reroute will be represented in the model.

Figure 2-8 shows the location of car crashes and traffic accidents during the month of January, 2010 on selected highways in Chicago.

Table 2-6 presents the attributes of the car crashes, which include routes for accident locations, case ID, time (year, month, day and hour), weather and other conditions. The hypothetical operational scenario could be developed from these datasets.

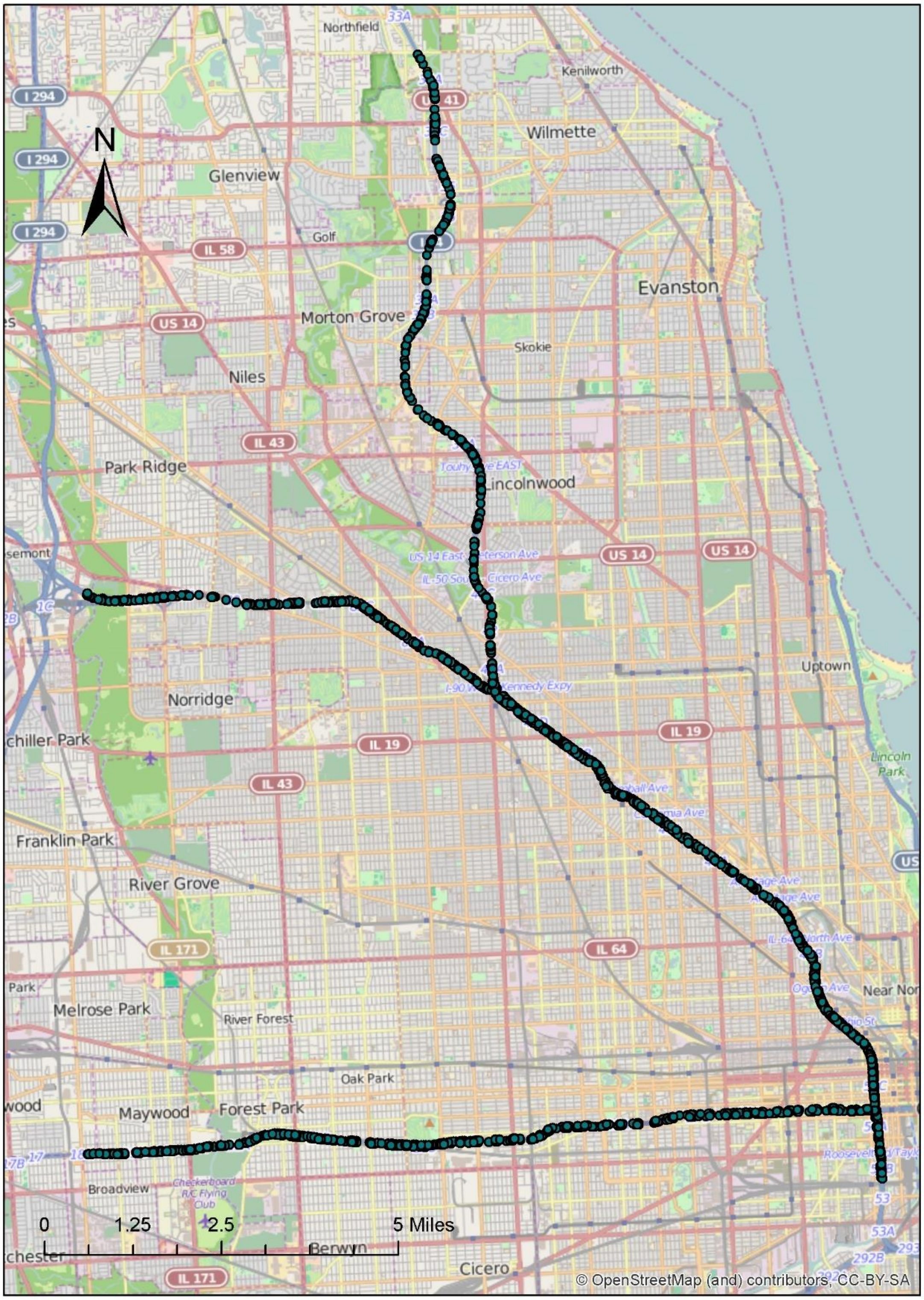

Figure 2-8: Locations of Car Crashes of I-90, I-94, I-290 and I-294 in January 2010 [Source: Open Street Map]

Table 2-6: Attribute Table of Car Crash Data

FID	ROUTE	CASE_ID	YEAR	MONTH	DAY	HOUR	DAY_O_WEEK	NUM_VEH	WEATHER	LIGHTING	SURF_COND
2	I 090	201001010113	10	01	02	15	Sat	2	Clear	Daylight	Dry
12	I 290	201001010143	10	01	02	18	Sat	2	Clear	Darkness/Lighted road	Dry
28	I 094	201001010178	10	01	03	02	Sun	1	Clear	Darkness/Lighted road	Dry
63	I 094	201001010295	10	01	01	18	Fri	1	Clear	Daylight	Dry
79	I 290	201001010337	10	01	03	15	Sun	1	Clear	Daylight	Dry
80	I 090	201001010339	10	01	04	06	Mon	3	Clear	Daylight	Dry
82	I 094	201001010342	10	01	04	08	Mon	2	Clear	Daylight	Dry
100	I 290	201001010381	10	01	04	14	Mon	1	Clear	Daylight	Dry
107	I 290	201001010398	10	01	03	20	Sun	1	Snow	Darkness/Lighted road	Dry
147	I 290	201001010555	10	01	02	10	Sat	3	Clear	Daylight	Dry
152	I 094	201001010573	10	01	04	17	Mon	2	Clear	Darkness/Lighted road	Dry
153	I 094	201001010574	10	01	04	18	Mon	3	Clear	Darkness/Lighted road	Dry
165	I 094	201001010603	10	01	03	23	Sun	3	Clear	Darkness/Lighted road	Dry
184	I 290	201001010641	10	01	07	04	Thu	1	Snow	Darkness/Lighted road	Snow or slush
200	I 094	201001010668	10	01	02	03	Sat	1	Clear	Darkness/Lighted road	Dry
212	I 290	201001010706	10	01	06	21	Wed	1	Clear	Darkness/Lighted road	Dry
242	I 094	201001010754	10	01	06	13	Wed	2	Clear	Daylight	Dry
302	I 290	201001010863	10	01	02	18	Sat	2	Clear	Darkness/Lighted road	Dry
303	I 094	201001010865	10	01	02	22	Sat	1	Clear	Darkness/Lighted road	Dry
309	I 290	201001010875	10	01	07	09	Thu	2	Snow	Daylight	Snow or slush
320	I 290	201001010897	10	01	07	10	Thu	1	Clear	Daylight	Snow or slush
398	I 094	201001011033	10	01	08	10	Fri	1	Snow	Daylight	Snow or slush

2.3 Existing Testbed Modeling and Tools Capabilities

The operational condition scenarios with some default controls will be generated using a Scenario Manager. It consists of a scenario generation and management tool that serves as an interface between the simulation engine (both offline and online) and a human user or decision maker. The role of the Scenario Manager is to facilitate the process of developing and preparing input scenarios for the simulation tool and the exchange of information between DYNASMART and traffic management operators. Scenarios generated by the Scenario Manager are mainly weather and basic operational strategies, and incident is also an option if the hypothetical operation conditions are to be included. The Scenario Manager is also able to extract performance measures from the simulation output and present to the operator a side-by-side comparison of network states with different strategies or interventions.

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. Offline model (DYNASMART-P) includes dynamic network analysis and evaluation, and 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 (both 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.

It is noted 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 inter-connection between these components and the basic data flow model are illustrated in Figure 2-9. 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.

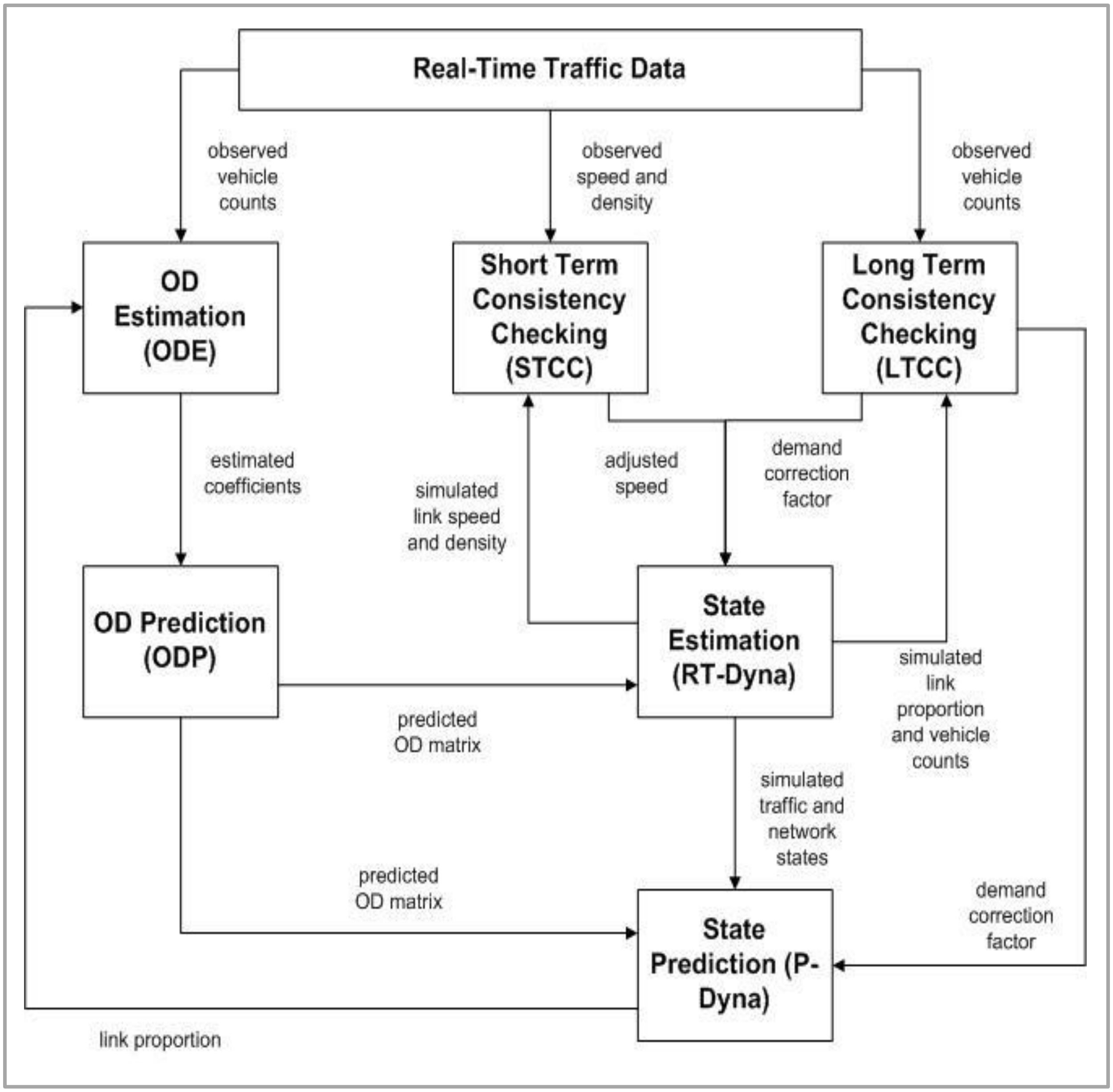

Figure 2-9: System Structure of DYNASMART-X and Data Flow [Source: NWU]

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 2-10 presents a snapshot of DYNASMART-X system running for an example network of Chicago Testbed. The three windows in the user interface display the current prevailing traffic conditions, a predicted traffic condition without implementing traffic management strategy, and a predicted traffic condition with management strategy.

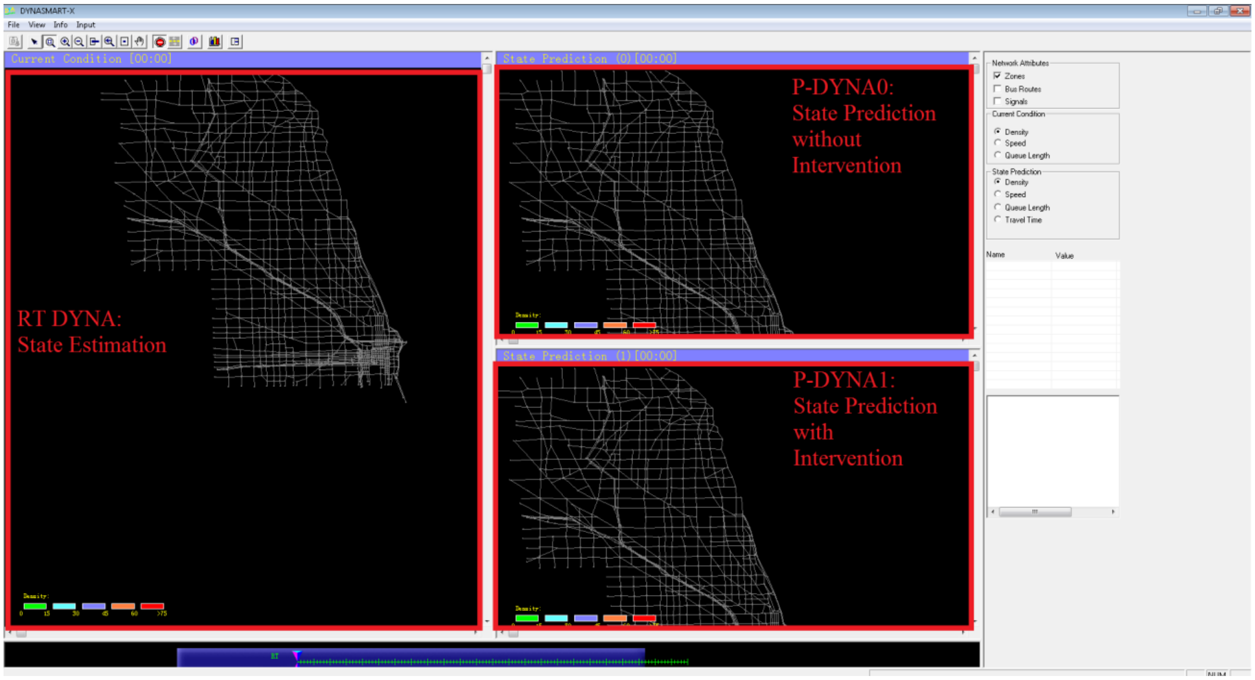

Figure 2-10: Chicago Testbed Network as Displayed in DYNASMART-X GUI [Source: NWU]

Chapter 3. Analysis Hypotheses

The Chicago Testbed analysis will focus on the ATDM and DMA applications evaluation. This section details the analysis hypotheses to address the different ATDM research questions for the Chicago Testbed. Table 3-1 and Table 3-2 present the general hypothesis corresponding to each ATDM and DMA research questions, respectively. The ATDM and DMA strategies that will be analyzed and evaluated using the Chicago testbed are listed in Chapter 4, Table 4-1.

Table 3-1: ATDM Research Questions and the Corresponding Hypothesis

ID	Research Question Category	ATDM Research Question Category	Hypothesis
1	Synergies and Conflicts	Q1. Are ATDM strategies more beneficial when implemented in isolation or in combination (e.g., combinations of ATM, ADM, or APM strategies)? Q2. What ATDM strategy or combinations of strategies yield the most benefits for weather related operational conditions? Q3. What ATDM strategies or combinations of strategies conflict with each other?	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.
2	Prediction Accuracy	Q4. Which ATDM strategy or combination of strategies will benefit the most through increased prediction accuracy, and under which kind of weather related operational conditions?	The value of prediction will be higher under inclement weather conditions.
		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?	The value of prediction will vary depending on the operational conditions experienced in the system.

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 and under which kind of weather related operational conditions?	The most cost-effective strategy or combination of strategies 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? 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? 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?	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. The benefits of ATDM strategy or combination of strategies will vary from regions, facility types and systems.

ID	Research Question Category	ATDM Research Question Category	Hypothesis
5	Prediction, Latency, and Coverage Tradeoffs	Q11. What is the tradeoff between improved prediction accuracy and reduced latency with existing communications for maximum benefits? Q12. What is the tradeoff between prediction accuracy and geographic coverage of ATDM deployment for maximum benefits? Q13. What is the tradeoff between reduced latency (with existing communications) and geographic coverage for maximum benefits? Q14. What will be the impact of increased prediction accuracy, more active management, and improved robust behavioral predictions on mobility, safety, and environmental benefits? Q15. What is the tradeoff between coverage costs and benefits?	Increased communication level with less prediction accuracy could lead to similar results as less communication level with higher prediction accuracy. Increased prediction accuracy, more active management (reduced latency), and improved robust behavioral predictions result in significant mobility, safety, and environmental benefits. Key attributes of prediction quality (e.g., prediction horizon, prediction accuracy, speed of prediction, and geographic prediction coverager) vary criticality depending on ATDM strategies considered and weather related operational conditions encountered. Longer execution time is expected (i.e., prediction latency) with increasing the prediction horizon and the size of the coverage area.
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?	Weather and traffic prediction can be most effective when coupled with real-time data capture and communications technologies to obtain motion and state of mobile entities, and enable active exchange of data with and between vehicles, travelers, roadside infrastructure, and system operators.

ID	Research Question Category	ATDM Research Question Category	Hypothesis
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?	Real time traveler information will enable travelers to better estimate their travel time and change their behavior related to route, mode, departure time choices for short-term behaviors. Other weather-related strategies will enable travelers to better estimate their travel time and change their behavior related to route, mode, departure time choices for long-term behaviors.
		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?	Real time traveler information will enable travelers to better estimate their travel time and change their behavior related to route, mode, departure time choices.

Table 3-2: DMA Research Questions and the Corresponding Hypothesis

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? Q2. What is the marginal benefit if data from connected vehicle technology are augmented with data from legacy systems? Q3. What is the marginal benefit if data from legacy systems are augmented with data from connected vehicle technology?	Compared to legacy systems, INFLO DMA applications 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.
II	**Synergies and Conflicts**	**Not to be addressed**
VIII	**Prediction and Active Management Investment**	

ID	DMA Research Question	Hypothesis
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.

Chapter 4. Analysis Scenarios

This section describes the analysis scenarios to test the different DMA/ATDM applications. An analysis scenario is defined as “a combination of operational conditions, applications (or combination of applications) and the alternatives to be used to test hypotheses”.

Scenarios should be developed for the range of operational conditions of greatest interest (to be determined using historical data) for the Testbed site in light of analysis objectives and based on current conditions. This chapter presents a description of the analysis scenarios to be created in addition to the baseline scenario.

4.1 DMA Applications to be addressed by Testbed

This section presents the proposed applications to be evaluated by the Testbed. The Chicago Testbed will only focus on the DMA/ATDM applications summarized in Table 4-1. Active parking management strategies are excluded from our analysis because they are not relevant to the purpose of Chicago Testbed, especially not related with weather-responsive strategies.

Table 4-1: DMA/ATDM Applications to be Evaluated/Addressed by the Chicago Testbed

DMA/ATDM	Type/Bundle	Application
ATDM Strategies	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 Preemption for Winter Maintenance Vehicles Snowplow Routing Anti-icing and Deicing Operations
DMA Applications	INFLO Bundle	Speed Harmonization (SPD-HARM) (Basic)

4.2 Performance Measures

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

- Mobility and System Efficiency – travel time and delay; flow breakdown and throughput;
- Reliability – variability and predictability in experienced travel time;
- Traffic Flow quality (user experience) – flow regimes, stopped time, and average travel speed;
- Energy Impact – fuel consumption;
- Safety – crash likelihood, hazard rate

4.3 Analysis Phases

We propose dividing the analysis effort for the Chicago Testbed into three main phases. These phases are structured such that they allow the incorporation of the gained knowledge and lessons learned from one phase into the subsequent phase(s). The multi-phase approach also enables knowledge sharing among the different Testbeds, and facilitates the integration of any newly developed models/methodologies generated from other ongoing related projects.

The first phase, which we propose from October 2014 to February 2015, is devoted to preparing Testbed network with the preliminary data collection, clustering analysis and defining operational conditions, identifying strategies and devising the analysis plan. We propose to have 10 ATDM strategies and 1 DMA application (Table 4-1) to be tested in 6 operational conditions (Table 4-2) to address the research questions (Table 3-1 and Table 3-2). One additional operational condition might be added to the selected scenarios in order to test incidents in the Chicago Testbed.

The second phase, from March 2015 to May 2015, is devoted to answering research questions related to quantifying the synergy and conflict among the different ATDM strategies, also quantifying these benefits for the different facilities and modes considering different operational conditions, and checking and comparing prediction accuracy and latency with the operational conditions and strategies considered in Phase 2 (Table 4-3).

In the third phase, from June 2015 to October 2015, the modeled scenarios are devoted to testing connected vehicle technology and prediction, and also quantifying the synergy and conflict among the different ATDM strategies. These benefits will be quantified for the different facilities and modes considering different operational conditions. In addition, we will check and compare prediction accuracy and latency using three strategies from Phase 2, the snow-related strategies and one DMA application (Table 4-4). The hypothetical operational condition with incident and snow will be modeled for more tests for only partial ATDM strategies. Results from these hypothetical scenarios would provide insight into the potential benefits of ATDM strategies under incident occurrence.

In a summary, we try to cover all combinations of strategies and clusters for the analysis in Table 4-3. There are only two exceptional cases for Cluster C-4. As Cluster C-4 is for the weekend, and demand for weekend is very low. So we do not test it with dynamic shoulder lane and dynamic lane use control. As with Table 4-4, we do not include all combinations that we present in Table 4-3; Cluster B-0 and B-3 are not to be tested with weather-related strategies because no severe weather events exist in those clusters.

Table 4-2: Existing Operational Condition Candidates

Variables		All	Cluster B-0	Cluster B-3	Cluster B-4	Cluster C-4	Cluster B-5	Cluster B-6
Number of Records		321	67	5	3	4	13	1
Records (%)		100%	21%	2%	1%	1%	4%	1%
Cluster Description	AM Peak		High Demand	High Demand	Medium Demand	Low Demand	High Demand	Medium Demand
	PM Peak		High Demand	High Demand	High Demand	Medium	High Demand	High Demand
	Daily Weather		Clear / No Rain, No Snow	Moderate/ Heavy Rain Changing to Moderate Snow	Moderate Snow	Moderate Snow	Light Rain Changing to Moderate/ Heavy Rain	Moderate and Heavy Snow

Table 4-3: A Summary of Operational Conditions Considered in Phase 2 of the Analysis

	Cluster B-0	Cluster B-3	Cluster B-4	Cluster C-4	Cluster B-6
Dynamic Shoulder Lanes	x	x	x	-	x
Dynamic Lane Use Control	x	x	x	-	x
Dynamic Speed Limits	x	x	x	x	x
Adaptive Traffic Signal Control	x	x	x	x	x
Predictive Traveler Information	x	x	x	x	x
Dynamic Routing	x	x	x	x	x

Note: “X” means would be tested; “-“ means would not be tested.

Table 4-4: A Summary of Operational Conditions Considered in Phase 3 of the Analysis

	Cluster B-0	Cluster B-3	Cluster B-4	Cluster C-4	Cluster B-6
Dynamic Speed Limits	x	-	-	-	x
Predictive Traveler Information	x	-	-	-	x
Dynamic Routing	x	-	-	-	x
Snow Emergency Parking Management	-	-	x	-	x
Traffic Signal Preemption for Winter Maintenance Vehicles	-	-	x	-	x
Snowplow Routing	-	-	x	-	x
Anti-icing and Deicing operations	-	x	x	-	x
Speed Harmonization	x	x	x	x	x

Note: "X" means would be tested; "-" means would not be tested.

4.4 Analysis Scenarios

The Tables below provide a summary of the scenarios that are considered in each of the three phases described above. As shown in the tables, each scenario is described in terms of the combination of operational conditions and ATDM strategies to be modeled and the prediction attributes to be considered for each scenario. The list of research questions that each scenario contributes towards their answer is also given.

As illustrated in Table 4-5, which provides the list of scenarios to be conducted in phase 2, the first six scenarios are developed as base-case scenarios where the different operational conditions are modeled but no ATDM strategies are considered (i.e., do nothing scenarios). Scenarios 5 to 20 are devoted to quantifying the synergy and conflict among the different ATDM strategies and also quantifying these benefits for the different facilities and modes considering different operational conditions. For example, in scenario 7, the dynamic shoulder lane is modeled considering a high demand conditions. In scenario 12, the dynamic routing strategy is activated with the dynamic shoulder lane strategy. The results of these two scenarios would provide insight on the potential synergy/conflict between these two ATDM strategies. In the scenarios of phase 2, prediction attributes that involve predicting future congestion, examining prediction horizon sensitivity, and exploring the effect of travelers' response to information on the effectiveness of the ATDM strategies are considered. To capture the time horizon sensitivity, scenarios 7 - 11 will be repeated considering different values for the prediction horizon which is set at 20, 30 and 60 minutes, respectively. In addition, to capture the sensitivity of travelers' access and response to traveler information on the effectiveness on the dynamic routing strategies, scenarios 12, 14 and 17 are repeated considering three different values of the parameter that represents the travelers' access and compliance with information (e.g., 5%, 10% and 20%).

Table 4-5: A Summary of Modeled Scenarios in Phase 2

Scenario ID	Scenario Description: Operation Conditions and ATDM Strategies	Prediction Attributes	Research Questions addressed by the Scenario
1	**Cluster B-0 + Do-nothing**	**Predict Future Congestion**	**Base case**
2	**Cluster B-3 + Do-nothing**	**Predict Future Congestion**	**Base case**
3	**Cluster B-4 + Do-nothing**	**Predict Future Congestion**	**Base case**
4	**Cluster C-4 + Do-nothing**	**Predict Future Congestion**	**Base case**
5	**Cluster B-5 + Do-nothing**	**Predict Future Congestion**	**Base case**
6	**Cluster B-6 + Do-nothing**	**Predict Future Congestion**	**Base case**
7	**Cluster B-0** + Dynamic Shoulder Lane + (Dynamic Lane Use Control)	Predict Future Congestion Time Horizon Sensitivity	1,2,3,5,8,9, 10
8	**Cluster B-3**+ Dynamic Shoulder Lane + (Dynamic Lane Use Control)	Predict Future Congestion Time Horizon Sensitivity	1,2,3,5,8,9, 10
9	**Cluster B-4** + Dynamic Shoulder Lane + (Dynamic Lane Use Control)	Predict Future Congestion Time Horizon Sensitivity	1,2,3,5,8,9, 10
10	**Cluster B-5** + Dynamic Shoulder Lane + (Dynamic Lane Use Control)	Predict Future Congestion Time Horizon Sensitivity	1,2,3,5,8,9, 10
11	**Cluster B-6** + Dynamic Shoulder Lane + (Dynamic Lane Use Control)	Predict Future Congestion Time Horizon Sensitivity	1,2,3,5,8,9, 10
12	**Cluster B-0** + Dynamic Speed Limits + Adaptive Traffic Signal Control + Dynamic Routing + (Predictive Traveler Information)	Predict Future Congestion Time Horizon Sensitivity Traveler Response	1,2,3,5,8,9,10
13	**Cluster B-3** + Dynamic Speed Limits + Adaptive Traffic Signal Control + Dynamic Routing + (Predictive Traveler Information)	Predict Future Congestion Time Horizon Sensitivity Traveler Response	1,2,3,5,8,9,10
14	**Cluster B-4** + Dynamic Speed Limits + Adaptive Traffic Signal Control + Dynamic Routing+ (Predictive Traveler Information)	Predict Future Congestion Time Horizon Sensitivity	1,2,3,5,8,9,10

Scenario ID	Scenario Description: Operation Conditions and ATDM Strategies	Prediction Attributes	Research Questions addressed by the Scenario
		Traveler Response	
15	**Cluster C-4** + Dynamic Speed Limits + Adaptive Traffic Signal Control + Dynamic Routing+ (Predictive Traveler Information)	Predict Future Congestion Time Horizon Sensitivity Traveler Response	1,2,3,5,8,9,10
16	**Cluster B-6** + Dynamic Speed Limits + Adaptive Traffic Signal Control + Dynamic Routing+ (Predictive Traveler Information)	Predict Future Congestion Time Horizon Sensitivity Traveler Response	1,2,3,5,8,9,10

Note: strategies in parentheses mean optional strategies for testing

Table 4-6 provides a summary of scenarios that are modeled in phase 3. As shown in the table, these scenarios are devoted to a) capturing the effect of accurately predicting the future demand considering the impact of the ATDM strategies; b) examining the effect of the overall prediction accuracy on the effectiveness of the ATDM strategies; c) capturing the trade-off between prediction latency and coverage extent. Similar to the scenarios in phase 2, these scenarios also help in quantifying the synergy and conflict among the different ATDM strategies and also quantifying these benefits for the different facilities and modes considering different operational conditions. In these scenarios, only clear weather and heavy snow weather are to be tested, the prediction accuracy sensitivity will be modeled through introducing different levels of the travelers' access and compliance with information or connectivity level (e.g., 10%, 15% and 20%) (The details are shown in Section 9.2). This information level or connectivity is introduced to be able to examine the robustness of the ATDM strategies considering different levels of prediction accuracy.

Besides accuracy, latency and connectivity sensitivity analysis, another important task for phase 3 is to apply the snow maintenance strategies, i.e. the following four strategies: Snow Emergency Parking Management, Traffic Signal Preemption for Winter Maintenance Vehicles, Snowplow Routing, and Anti-icing and Deicing operations. The first three snow-related strategies are only to be tested under moderate snow or heavy snow, i.e. Cluster B-4 and B-6; and Anti-icing and deicing operations is to be tested for one more scenario Cluster B-3, which is the Moderate/Heavy Rain Changing to Moderate Snow. Two hypothetical scenarios are tested with incident interruptions.

Table 4-6: A Summary of Modeled Scenarios in Phase 3

Scenario ID	Scenario Description: Operation Conditions and ATDM Strategies	Prediction Attributes	Research Questions addressed by the Scenario
1	**Cluster B-0** + Dynamic Speed Limits+ Dynamic Routing+ (Predictive Traveler Information)	Predict Future Congestion Prediction Latency Sensitivity	1,2,3,6,7,11, 13,14
2	**Cluster B-6** + A Dynamic Speed Limits+ Dynamic Routing+ (Predictive Traveler Information)	Predict Future Congestion Prediction Latency Sensitivity	1,2,3,6,7,11, 13,14

Scenario ID	Scenario Description: Operation Conditions and ATDM Strategies	Prediction Attributes	Research Questions addressed by the Scenario
3	**Cluster B-0** + Dynamic Speed Limits+ Dynamic Routing+ (Predictive Traveler Information)	Predict Future Congestion Prediction Accuracy Sensitivity	1,2,3,4,11,12,14,17,18
4	**Cluster B-6** + Dynamic Speed Limits+ Dynamic Routing+ (Predictive Traveler Information)	Predict Future Congestion Prediction Accuracy Sensitivity	1,2,3,4,11,12,14,17,18
5	**Cluster B-0** + Speed Harmonization	Predict Future Congestion Prediction Accuracy Sensitivity	1,2,3,4,11,12,14,16,17,18
6	**Cluster B-6** + Speed Harmonization	Predict Future Congestion Prediction Accuracy Sensitivity	1,2,3,4,11,12,14,16,17,18
7	**Cluster B-4** + Snowplow Routing + Snow Emergency Parking Management, Traffic Signal Preemption for Winter Maintenance Vehicles	Predict Future Congestion Time Horizon Sensitivity Traveler Response	1,2,3,5,8,9,10
8	**Cluster B-6** + Snowplow Routing + Snow Emergency Parking Management, Traffic Signal Preemption for Winter Maintenance Vehicles	Predict Future Congestion Time Horizon Sensitivity Traveler Response	1,2,3,5,8,9,10
9	**Cluster B-3** + Anti-icing and Deicing operations	Predict Future Congestion Time Horizon Sensitivity Traveler Response	1,2,3,5,8,9,10
10	**Cluster B-4 + Incident (Cluster B-7)**	Predict Future Congestion Traveler Response	Hypothetical Operations

Note: strategies in parentheses mean optional strategies for testing

Chapter 5. Data Needs and Availability

This section delineates the data needs for the Testbed. This section will clearly detail data availability, and gaps. In addition, this section will provide a detailed plan for data collection and data mining to fill the identified gaps. If some of the gaps cannot be filled, the team will develop a plan to overcome issues pertaining to lack of data in order to ensure that the Testbed can be successfully built.

5.1 Data Needs

Modelling the weather-responsive ATDM strategies requires travelers' behavior, traffic, and weather data. As mentioned in previous chapters, the selected scenarios cover different traffic and weather conditions; therefore, time-dependent travel demand matrix should be adjusted according to different traffic and weather conditions. The data required for calibration includes weather data, freeway counts (flow). Note that the base travel demand matrix is obtained from Chicago Metropolitan Agency for Planning (CMAP) with the corresponding adjustment factors for different times of the day. This travel demand matrix is transformed into a time-dependent travel demand matrix based on freeway counts obtained from loop detector data.

In an ideal case, prior to adjusting the time-dependent demand table based on the traffic and weather data, the influence of external events (e.g. incidents, workzones, and planned special events) should be removed. However, incidents and workzones are very frequent in Chicago region and it is difficult to exclude these external events. Note that averaging over a long period of time can minimize the influence of these external events on the calibration of time-dependent demand table.

There are also some additional data requirement and needs for specific ATDM strategies, including Snowplow Routing and Snow Emergency Parking. Since different roadways have different priority for snow removal, identifying major roads is essential to perform an effective and efficient snow removal operation. Moreover, snow emergency parking information should be obtained from city officials.

5.2 Available Data

This section describes sources of the available data and a detailed data collection procedure for the entire Chicago regional network and Chicago Testbed network.

5.2.1 Weather Data

ASOS data with the 5 minute resolution will be used in conjunction with traffic detector data collected and aggregated over a 5-minute interval (see Section 5.2.2). ASOS 5-minute weather data are available on the NOAA National Climatic Data Center (NCDC) website (ftp://ftp.ncdc.noaa.gov/pub/data/asos-fivemin/). Table 5-1 and Figure 5-1 present the spatial distribution of ASOS stations for each respective network on the corresponding Google map, where circled areas represent a 10-mile radius of each station.

Table 5-1: Airports with ASOS Stations and Available Time Periods for Data (Chicago)

No	Airport	Location	ICAO code	ASOS data
1	Midway International Airport	Chicago, IL	KMDW	2005 - present
2	O'Hare International Airport	Chicago, IL	KORD	2000 - present
3	Dupage County Airport	Dupage, IL	KDPA	2005 - present
4	Chicago Executive Airport	Cook, IL	KPWK	2005 - present
5	Aurora Municipal Airport	Kane, IL	KARR	2005 - present

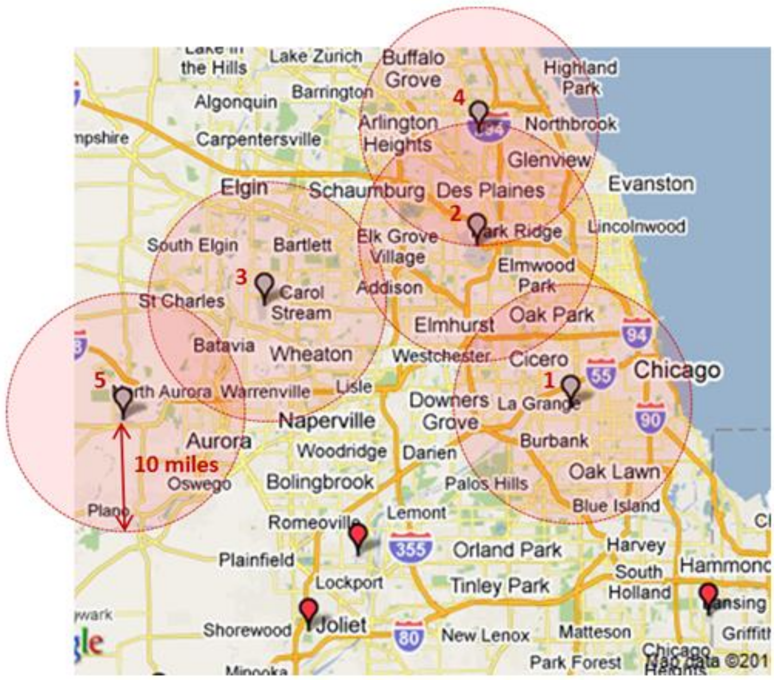

Figure 5-1: Chicago Study Area and Adjacent ASOS Stations
(Source: FAA, Surface Weather Observation Stations)

5.2.2 Traffic Data

The primary source of traffic data for supply-side parameter calibration is loop detectors installed on freeway lanes. Historical data with the 5-minute aggregation interval are used and the time periods for the data vary with the study site over the 2005-2011 period.

In selecting detector locations and collecting the data, the following criteria are mainly considered.

- Choose detectors as close as possible to ASOS stations.
- Remove the influence of other external events such as incidents/accidents, work zones and planned special events.

- Include various facility/lane types and calibrate separately for each type. For instance, types can be classified into mainlines, on-ramps, off-ramps, and HOV; and the number of lanes could be further distinguished.
- Find segments that experience a wide range of traffic regimes, i.e., free-flow, stop-and-go, and congested states.

Note that the process for removing the effect of external events is highly dependent on the availability of other event data. In case where there is difficulty obtaining detailed data for incidents, work zones, and special events, one could focus on traffic data and clean outliers in the dataset only. Since we are averaging measures over a long period of time, at least one year, the influence of other external events on traffic parameters is expected to be very small.

For the Chicago network, traffic data are obtained from Illinois Department of Transportation (IDOT). 5-minute aggregated data from 2009 are used. Figure 2-3 shows a map of the selected detector locations in Chicago. At each location, traffic data from north- or south-bound directions are obtained. Note that there is no HOV lane at any of the selected locations.

5.2.3 Accident Data

For the Chicago network, accident (crash) data are available from 2002 to 2012. Figure 2-8 shows a map of the selected accidents in Chicago. At each location, records for car crash times, route locations, weather and other conditions. However, the data does not include complete crash duration information and lane close effects.

5.3 Preliminary Data Collection Plan to Address Gaps

Besides weather data and traffic data, there are some additional data requirement and needs for Snowplow Routing and Snow Emergency Parking strategies. This section presents the data needs and sources for calibration and modeling Snowplow Routing and Snow Emergency Parking.

- Snowplow Routing

To have an effective and efficient snow removal operation, high priority roads should be identified. The current snowplow routing schedules for freeway and arterial roads is available from the City of Chicago Department of Transportation. These schedules should be compared to the traffic and weather data to identify the roads with high priority. In addition to the schedules, real-time information from snowplows is available through City of Chicago Plow Tracker website (http://www.cityofchicago.org/city/en/depts/mayor/iframe/plow_tracker.html).

- Snow Emergency Parking

In the Chicago region, Snow Emergency Parking is in effect when the snow accumulation is over two inches. During these instances, certain roads are closed to street parking. The list of these roads are available through the City of Chicago website (http://www.cityofchicago.org/city/en/depts/streets/provdrs/street/news/2014/nov/annual-winter-overnight-parking-ban-starts-3am-monday--december-.html) and City of Chicago Department of Transportation.

Chapter 6. Key Assumptions and Limitations

This section describes two main limitations that are anticipated for the proposed analysis: lack of adequate data and difficulty to achieve optimization.

The first limitation is related to the lack of adequate data and difficulty to collect Testbed-wide detailed data. Since it is difficult to collect all the data within the entire coverage of the Testbed network, some strategies will be only tested in selected community-wide sub-Testbed network, such as snowplow routing and snow emergency parking management; some vehicle to vehicle and vehicle to facility connection test will also be tested in selected areas; adaptive signal control test may be limited to a specific corridor or arterial segments. Besides the geographical coverage issue, we do not have adequate data that have long temporal coverage to predict the potential change in the travelers' short-term and long-term travel behavior in response to the deployed ATDM strategies. The method to address this limitation is to perform sensitivity analyses that extend to demand management with mode choices and departure time choices given different information level. Using calibrated choice models, a combination of earlier dissemination of information and school opening policy can affect the level of network performance positively under bad weather condition. But unknown to the decision maker is what percentage of travelers receive information, and how these travelers use the provided information.

The second limitation is related to determining the optimal combination of ATDM strategies with the most benefits. Most of the strategies are interdependent and correlated in terms of the resulting benefits, which may be conflicting (thus requiring trade-offs) or mutually-reinforcing under different situations. For example, the combination of snowplow routing, signal priority for snowplow vehicle, adaptive signal control and connected vehicles with signal information seems reasonable for traffic management. However, when we use time-dependent optimized signal control, frequent transitions may lead to instability; connected vehicles would provide information for signal plan optimization, which requires more computation to find global optimization strategies. To address this limitation, we propose performing sensitivity analyses that extend to different levels of vehicle to vehicle connectivity and market penetration rates. More detailed description related to sensitivity analyses is given in Chapter 9.

Chapter 7. Modeling Approach

This section details the modeling approach to test the hypotheses, and generate performance measure statistics to evaluate and compare alternatives. This section describes the analysis framework, application specific algorithms (existing ones and ones to be built), the tools needed for this analysis, and analysis phases or multi-tier approach to be used to conduct the overall modeling effort.

7.1 Analysis Framework

This section presents the overall analysis framework using Figure 7-1 as a guideline. Figure 7-1 illustrates the overall framework of the implemented traffic management system. The framework is designed to virtually emulate the decision making process in a typical traffic network management center and describes main processes detection, communications, and control/advisory information dissemination technologies; and system management decisions.

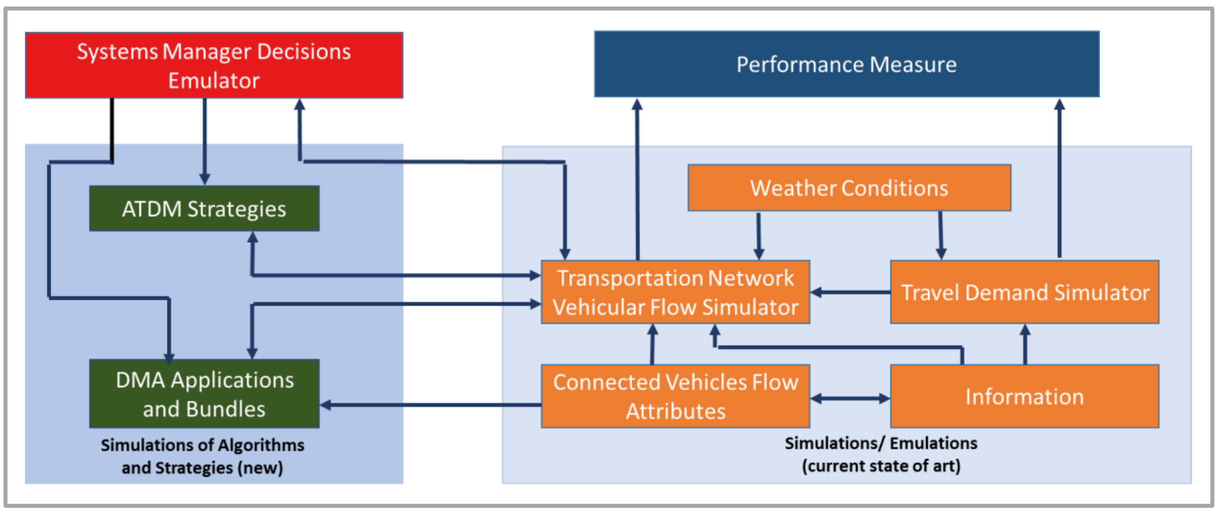

Figure 7-1: Preliminary Analysis Framework [Source: Booz Allen/NWU]

Weather-responsive operations introduce several potential strategies to be tested in the Chicago Testbed. During inclement weather events, traffic flow pattern and behaviors would change, and thus initial strategies and applications for normal weather should also be modified to mitigate weather impact on traffic. DYNASMART can be effectively used in this regard as it provides the estimation and prediction of traffic conditions under an anticipated weather and the environment to test and compare various alternative strategies on the network information and performance measurement. Figure 7-2 illustrates the overall architecture of the proposed strategy test and decision support system. The system supports operators' decision making in deploying alternative strategies given selected operational conditions described in Section 2.2 by integrating three components, namely DYNASMART, Scenario Manager and Scenario Library.

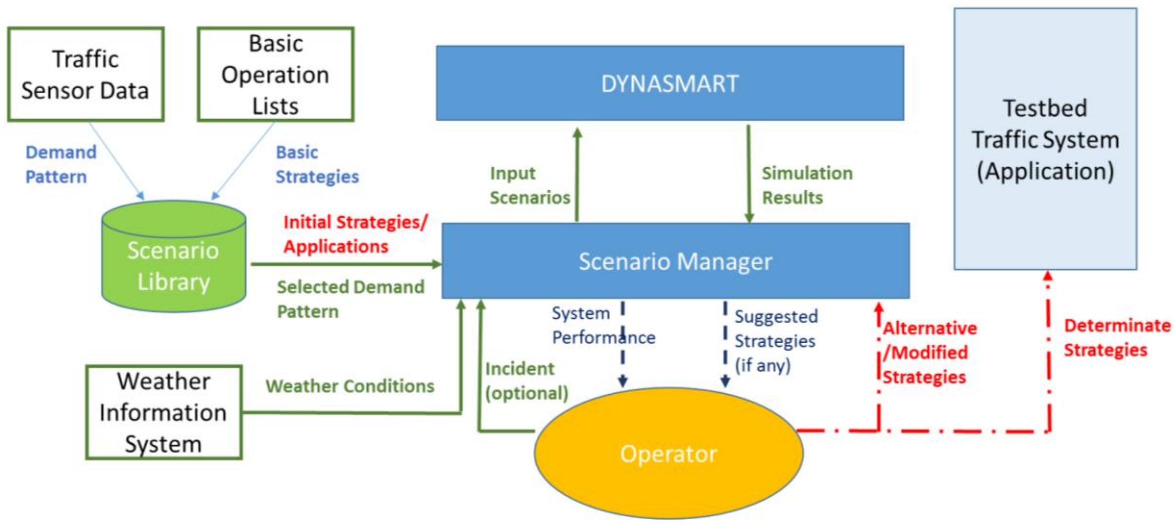

Figure 7-2: Framework Decision Support System for Scenario–based Strategies Application [Source: NWU]

7.2 Application-Specific Algorithm and Needed Tools

This section describes the algorithms and models that need to be used/ developed to satisfy the analysis approach. Table 7-1 presents a summary of the different strategies that will be modeled using the Chicago Testbed and an overview of how of these strategies are modeled.

Table 7-1: The DMA/ATDM Strategies Modeled using the Chicago Testbed

DMA/ATDM	Modeling Logic	
	Description	Logic

Dynamic Shoulder Lane	DYNASMART represents highway links at link level with a set of characteristics, including lane number and capacity. To model the dynamic lane shoulder strategy, the lane number or capacity of selected links could be increased. This shoulder lane would be configured to serve the traffic as long as the strategy is active (e.g., peak period, heavy snow, etc.). There is flag for selected links to tell whether the shoulder lane is active or not in order to keep the original link characteristics.	if (shoulder lane strategy starts){
		for (selected freeway links){
		- Increase the lane number (or capacity)
		- Keep the other characteristics the same
		- Turn the flag on
		}
		}
		if (shoulder lane strategy terminates){
		for (selected freeway links){
		- Decrease the lane number (or capacity)
		- Keep the other characteristics the same
		- Turn the flag off
		}
		}

DMA/ATDM	Modeling Logic	
	Description	Logic

Dynamic Lane Use Control	We define Dynamic Lane Use Control as Dynamic Reversible Express Lane.
	
	DYNASMART represents highway links at link level with a set of characteristics, including lane number and capacity. To model the Dynamic Reversible Express Lane, the lane number or capacity of selected reversible links could be increased. This reversible express lane would be configured to serve the traffic as long as the strategy is active (e.g., peak period, heavy snow, etc.). There is flag for selected links to tell whether the reversible lane is active.
	
	The reversible lane is only active when one direction is congested. Once reversible lane is needed to switch the direction when the other direction is congested, it has to be closed first until the density of selected link drops below the threshold, and then turn active on the other direction. The drop of density threshold is check vehicle dissipating on the reversible lane.
		if (reversible lane starts){
		for (selected freeway links){
		- Increase the lane number (or capacity)
		- Keep the other characteristics the same
		- Turn the flag on
		}
		}
		
		for (flag is on){
		if (reversible lane terminates){
		for (selected freeway links){
		- Decrease the lane number (or capacity)
		- Keep the other characteristics the same
		while (flag is on) {
		if (density of selected links is lower than threshold) {
		- Turn the flag off
		}
		}
		}
		}
		if (reversible lane swifts direction){
		- terminate the reversible lane
		- starts again on the other directions
		}
		}

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

DMA/ATDM	Modeling Logic	
	Description	Logic

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

Predictive Traveler Information	DYNASMART-X could implement a simulation-based short-term traffic network state prediction module, which runs in a rolling horizon framework. The prediction module provides information on the time-dependent link travel times for a pre-defined future horizon (e.g., 30 minutes). These predicted travel times could be used to develop different predictive traveler information strategies. The impact of the provided information on the travelers' route-mode choice decisions could be captured in the simulation.	- Conduct Prediction for a pre-defined horizon - Generate Predicted Travel Times for all links for the predicted horizon - Generate time-dependent shortest routes for all departure time intervals in the horizon. If a vehicle is equipped and the driver complies with the information, assign the vehicle to the new route.
Dynamic Routing	Travelers with access to en-route information are given the ability to switch to new routes in DYNASMART. These drivers compare their current routes with the new routes. Drivers are assumed to switch to the new route If the difference in the travel time is greater than a pre-defined threshold. The route diversion could be occurring at any junction along their routes including the DMS locations.	Assumptions: - The percentage of travelers with access to en-route information can be specified by user. Logic: - At each SP update interval, the shortest paths from all origin nodes to all destinations are generated. - For travelers with access to information, if the travel time (cost) of the new shortest path is better than the time of the current path by a pre-defined threshold, the traveler is assumed to switch to the new path.

DMA/ATDM	Modeling Logic	
	Description	**Logic**

Snow Emergency Parking Management	DYNASMART represents arterial links at link level with a set of characteristics, including lane number and capacity. To model the snow emergency parking management strategy, the capacity of selected links could be increased when the street parking is forbidden for snow route. The extra capacity would be configured to serve the traffic as long as the strategy is active (i.e. snow emergency route). There is flag for selected links to tell whether the snow emergency parking is active or not in order to keep the original link characteristics.	if (snow emergency parking starts){
		for (selected arterial links){
		- Increase the capacity
		- Keep the other characteristics the same
		- Turn the flag on
		}
		}
		if (snow emergency parking terminates){
		for (selected freeway links){
		- Decrease the capacity
		- Keep the other characteristics the same
		- Turn the flag off
		}
		}

Traffic Signal Preemption for Winter Maintenance Vehicles	Winter maintenance vehicles can be prioritized in a way that once such vehicle is detected, they are given the right to pass the signal. Vehicles are categorized with different types in DYNASMART. Once the winter maintenance vehicle is detected and identified coming from any arterial link, the traffic signal preemption will be activated and the signal green time for that direction will be extended until it passes the intersection. The preemption strategy will be deactivated with the maintenance vehicle passes the intersection.	if (traffic signal preemption starts){
		for (selected signal){
		-Keep in green
		}
		
		if (traffic signal preemption terminateds){
		for (selected signal){
		If (green time is shorter than designed green time)
		- Keep in green and turn red according to the designed plan
		Else
		- Turn red
		}

Snowplow Routing	An initial routing plan is determined prior to the departure of snow plow fleets. Then a dynamic traffic assignment and simulation model will emulates the actual traffic conditions to estimate the weather dependent traffic condition and level of service on each link. Based on these information the online re-routing planner will updated the routing plan.	- Generate initial routing plan based on basic network information and current weather condition. - Estimate and prediction dynamic service network information such as vehicle location and status, level of service, weather condition, and time dependent shortest paths. Re-routing planner will update the routing plan based on real time information
Anti-icing and Deicing Operations	This strategy might be modeled as link covering problems. The roads are assigned with priorities based on traffic volume and level of connectivity. The anti-icing and deicing operations will be designed to try to serve the roads with higher priorities first.	Assumption: the priority level of links will be determined exogenously to the simulation model.

DMA/ATDM	Modeling Logic	
	Description	**Logic**

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

7.2.1 Scenario Manager

As briefly introduced in Section 2.3 and shown in Figure 7-2, the Scenario Manager is a scenario generation and management tool that serves as an interface between the simulation tool, DYNASMART and a human decision maker, the operator. The role of Scenario Manager is to facilitate the process of developing and preparing input scenarios for simulation and the exchange of information between DYNASMART and traffic management operators. There are three different cases where Operator, Scenario Manager and DYNASMART interact with one another during the simulation implementation.

- Scenario Initialization: at the beginning of the implementation, the operator uses Scenario Manager to prepare an initial scenario set for the given day (e.g., weather scenario, traffic demand pattern, and initial strategies if any) and launch the DYNASMART model.
- Scenario Generation: during the implementation, Scenario Manager can access of on-running simulation results and provide the environment and measurement to compare the system performance in terms of speed or (link) travel time. The logic to suggest alternative strategies could be embedded in Scenario Manager and Scenario Library, and possible strategies would be selected and presented to the operator. For example, if DYNASMART-X predicts a noticeable decrease in corridor link speed due to a weather event, Scenario Manager could be able to provide suggestions for an alternative strategy, such as a new set of signal timing plan or new speed limits, which Scenario Manager retrieves from Scenario Library—a database of available weather-responsive signal timing plans, variable speed limits and other strategy setting. Operator creates necessary input files by Scenario Manager associated with some alternative strategy to initiate another branch of simulation to observe the alternative system performance under the new scenario. In other scenarios, if the strategies are not saved in Scenario Library, the operator can also include modified strategies in a new set of input files due to network measured system performance. The DYNASMART model can estimate and predict the network state under the new scenario (with alternative/modified strategies) in parallel with the network state under the original scenario (with initial strategies).

- Scenario Evaluation: once the DYNASMART-X completes the state prediction for the next prediction interval, Scenario Manager extracts various performance measures from the simulation output and presents to the operator a site-by-side comparison of network states under the new scenario and the original scenario. If the operator concludes that the expected benefit of switching strategies is significant, the new one is recommended to be deployed; if the expected benefit is not significant enough, another alternative scenario may be considered by going back to the Scenario Generation step.

The Scenario Generation and Scenario Evaluation procedures may be repeated whenever there is a need for considering an alternative strategy or switching back to the initial strategy due to changes in network conditions. With Scenario Manager and DYNASMART, the operator can specify and evaluate strategies for given operational conditions.

The Scenario Manager also provides the tools for system performance measurement. There have been many quantitative measures proposed for travel time variability in different contexts, but most frequently for one of two distinct purposes: either for overall assessment of the traffic performance, or for explaining individual preferences for choosing a route, trip departure time, or mode for a particular trip. All such measures can be derived from the travel time distribution to meet the needs of the particular analysis and hypotheses to be tested.

From the perspective of highway operations, making decisions about highway capacity expansion and traffic management strategies based on their impacts on system performance including travel time reliability of a certain facility has to be the focus of the analysis. Most of the actual data on travel time variability have been collected at the facility level. These data sources are valuable information for building certain analytical functions that relate reliability measures to the traffic volume and facility characteristics (number of lanes, length, cross-sectional design, access, traffic signals, etc.).

The reliability of travel is characterized and represented by the variability of travel times through the network's links and nodes along the travel paths followed by travelers, taking into account the correlation between link travel times. The travel time reliability analysis procedure incorporates two essential tools that provide the capability to produce reliability performance measures as output from operational planning and simulation models. The Scenario Manager, as an integral component of the overall analytical framework, captures external unreliable sources such as special events, adverse weather, and work zones, and generates appropriate files as input into simulation models. The other key analysis tool is a vehicle Trajectory Processor that calculates and visualizes travel time distributions and associated reliability indicators (such as 95th Percentile Travel Time, Buffer Time Index, Planning Time Index, Frequency that congestion exceeds some threshold, etc.) at the link, path, O-D and network levels. The detailed information for mobility and reliability as performance measures incorporated in operations and planning modeling could be found in (6).

7.2.2 DYNASMART

The Testbed is currently coded for 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. Offline model (DYNASMART-P) includes dynamic network analysis and evaluation, and online model (DYNASMART-X) adds short term and long term prediction to offline model.

DYNASMART-P 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 (both large and small) and is scalable, in terms of the geometric size of the network, with minimal degradation in performance. DYNASMART-P 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 in DYNASMART-P. 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.

The system is designed to run in a rolling horizon framework (7), with multiple asynchronous horizons for the various modules, as shown in Figure 7-3. The RT-DYNA module is executed every 30 seconds to continuously provide up-to-date estimates of the current state of the network. The P-DYNA module is executed less frequently, i.e. every 5 minutes, to project the current network state for a period (1 hour) in the future. The ODE and ODP modules provide the time-dependent OD desires in the network to be used in the simulation-assignment procedures of the state estimation and prediction. They also run periodically. The Consistency Checking modules (STCC and LTCC) interface periodically with the surveillance data collected from sensors and probes in the network, and correct some of the state estimation variables for discrepancies between the estimated values and the measured ones. The running periods of each module are all design parameters that can vary according to the particular network being modeled and the experimental setting.

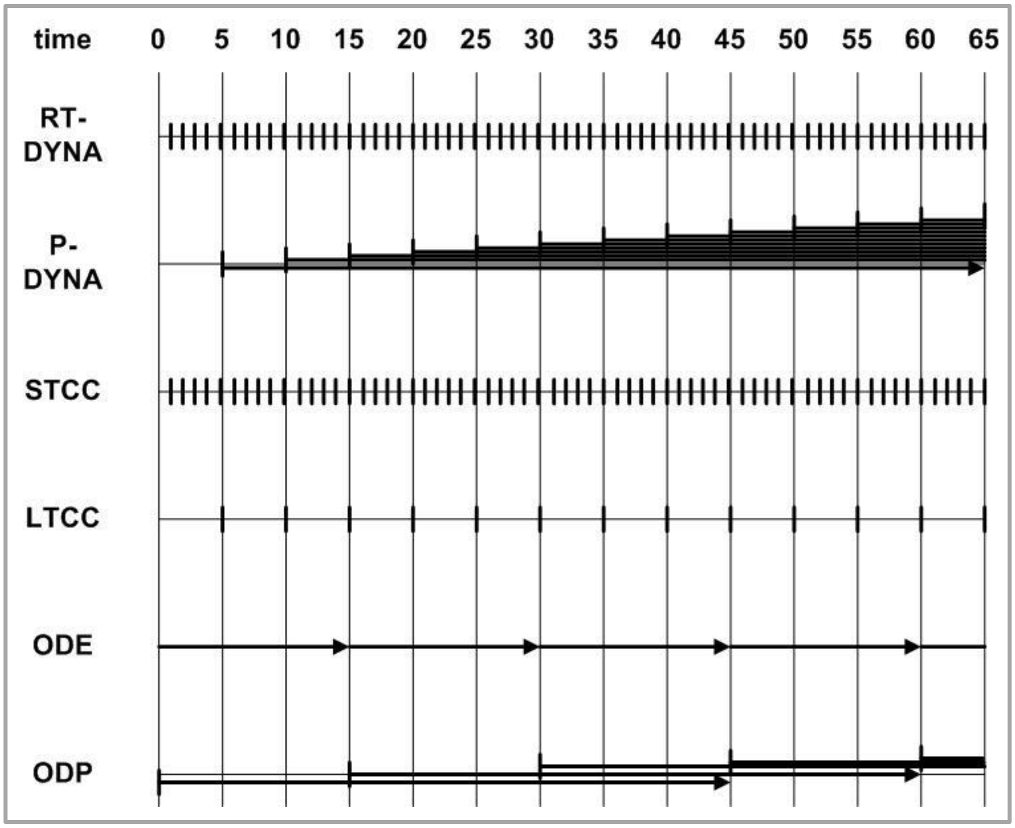

Figure 7-3: Rolling Horizon Framework of DYNASMART-X [Source: NWU]

7.3 Risks

For Chicago Testbed, the technical risk is controllable. The three-phase approach minimizes the technical risk as it enables incorporating the knowledge and lessons learned from each phase into the subsequent phases. In addition, developing a detailed analysis plan is expected to minimize any uncertainty regarding the settings of the modeled scenarios. Nonetheless, there is a risk associated with the schedule of the project and the allocated budget. For instance, every simulation run would require integration with demand adjustment/prediction, activation of the prediction module, activation of system management, etc. As such, more time for the preparation and quality assurance of these runs is expected. The risk associated with using a tight schedule increases in consideration of the limited amount of budgeted resources.

7.4 AMS Requirements

This section enumerates the AMS requirements that every Testbed attempts to satisfy. Table 7-2 shows the list of AMS requirements and the Testbed capability when it is fully developed classified into three levels:

1= The AMS requirement is **addressed** by the Testbed, 2= The AMS requirement is **partially addressed** by the Testbed or

3= The AMS requirement is **not addressed** by the Testbed.

Table 7-2: The AMS Requirements and the Capability of the Testbed

SNo	ID	Requirement	Chicago Testbed
1	SU-1	The AMS Testbed shall emulate and track each Traveler's time-referenced geographic location (position) as he/she plans, executes, and completes a trip within the transportation system.	1
2	SU-2	The AMS Testbed shall emulate and track each Travelers' time-referenced state and transition among various potential states (pre-trip, pedestrian, non-motorized traveler, light vehicle driver, light vehicle passenger, and transit rider) as they plan, exec	1
3	SU-3	The AMS Testbed shall emulate each Traveler's time-delimited tour planning, both in the pre-trip as well as en route states, subject to the nature and accuracy of available data on travel cost (parking fee, toll, fuel consumption, and transit fare),.	2
4	SU-4	The AMS Testbed shall emulate decision making by Pedestrians and Travelers in Non-motorized Modes of travel in the absence and presence of mobile devices, subject to the nature and accuracy of data available to support decision making.	3
5	SU-5	The AMS Testbed shall emulate decision making by Light Vehicle Drivers in the absence and presence of mobile devices, carry-in devices, integrated devices, and message signs subject to the nature and accuracy of data available to support decision making.	1
6	SU-6	The AMS Testbed shall emulate decision making by Light Vehicle Passengers in the absence and presence of mobile devices subject to the nature and accuracy of data available to support decision making.	1
7	SU-7	The AMS Testbed shall emulate decision making by Transit Riders in the absence and presence of mobile devices subject to the nature and accuracy of data available to support decision making.	3
8	SU-8	The AMS Testbed shall emulate tactical driving decisions made by Light Vehicle Drivers with respect to lane selection, lane changing, gap acceptance, following headway, speed, acceleration, deceleration, stopping, braking, hard braking, yielding, and merging subject to the nature and accuracy of data available to support decision making.	2
9	SU-9	The AMS Testbed shall emulate and track each Transit Driver and associated transit vehicle's time-referenced geographic location (position) within the transportation system.	3
10	SU-10	The AMS Testbed shall emulate tactical driving decisions made by Transit Drivers with respect to lane selection, lane changing, gap acceptance, following headway, speed, acceleration, deceleration, stopping, braking, hard braking, yielding, and merging su	3
11	SU-11	The AMS Testbed shall emulate fixed route/fixed schedule transit, flexible route bus, rail transit and paratransit.	2
12	SU-12	The AMS Testbed shall emulate a Transit Driver's adherence to dynamic transit dispatch plans (e.g., to counteract bus bunching) when received subject to the nature and accuracy of data available to support decision making.	3
13	SU-13	The AMS Testbed shall emulate decision making by Transit Drivers in the absence and presence of mobile devices, carry-in devices, integrated	3

SNo	ID	Requirement	Chicago Testbed
		devices, and message signs subject to the nature and accuracy of data available to support decision making.	
14	SU-14	The AMS Testbed shall emulate and track each Truck Driver and associated freight vehicle's time-referenced geographic location (position) within the transportation system.	3
15	SU-15	The AMS Testbed shall emulate tactical driving decisions made by Truck Drivers with respect to lane selection, lane changing, gap acceptance, following headway, speed, acceleration, deceleration, stopping, braking, hard braking, yielding, and merging subject to the nature and accuracy of data available to support decision making.	3
16	SU-16	The AMS Testbed shall emulate a Truck Driver's adherence to plans when received on dynamic routing, tours, and actions at waypoints subject to the nature and accuracy of data available to support decision making.	3
17	SU-17	The AMS Testbed shall emulate decision making by Truck Drivers in the absence and presence of mobile devices, carry-in devices, integrated devices, and message signs subject to the nature and accuracy of data available to support decision making.	3
18	SU-18	The AMS Testbed shall emulate and track each Public Safety Worker and public safety vehicle's time-referenced geographic location (position) within the transportation system, including in an active incident zone.	2
19	SU-19	The AMS Testbed shall emulate tactical driving decisions made by Public Safety Vehicle Drivers with respect to lane selection, lane changing, gap acceptance, following headway, speed, acceleration, deceleration, stopping, braking, hard braking, yielding,	3
20	SU-20	The AMS Testbed shall emulate a Public Safety Vehicle Driver's adherence to plans when received on dynamic routing, and response staging subject to the nature and accuracy of data available to support decision making.	3
21	SU-21	The AMS Testbed shall emulate the time-referenced geographic location of Public Safety Workers acting as emergency response personnel within an active incident zone in the absence and presence of Mobile Devices subject to the nature and accuracy of data available to support decision making	3
22	SU-22	The AMS Testbed shall emulate decision making by Public Safety Vehicle Drivers in the absence and presence of mobile devices, carry-in devices, integrated devices, and message signs subject to the nature and accuracy of data available to support decision	3
23	SU-23	The AMS Testbed shall emulate adherence by Drivers of light, transit, and freight vehicles with directions when received on presence of emergency response personnel subject to the nature and accuracy of data available to support decision making.	3
24	SU-24	The AMS Testbed shall emulate various compliance rates of System Users (drivers, pedestrians, bicyclists, light vehicle passengers, transit riders, transit drivers, truck drivers, and public safety vehicle driver) when presented with advisory and regulations.	1
25	CV-1	The AMS Testbed shall emulate Mobile Devices that are capable of transmitting messages via cellular or DSRC or both.	1
26	CV-2	The AMS Testbed shall emulate the time-referenced geographic location, operational status (ON, OFF, NOT FUNCTIONING), and power status of a	2

SNo	ID	Requirement	Chicago Testbed
		Mobile Device, and the state of the device (in use and connected to the vehicle, not in use but within a vehicle, o	
27	CV-3	The AMS Testbed shall emulate Carry-in Devices that are capable of transmitting messages via cellular or DSRC or both	2
28	CV-4	The AMS Testbed shall emulate the time-referenced geographic location, and operational status (ON, OFF, NOT FUNCTIONING) of Carry-In Devices.	2
29	CV-5	The AMS Testbed shall emulate Integrated Devices that are capable of Transmitting message via cellular or DSRC or both	2
30	CV-6	The AMS Testbed shall emulate the time-referenced geographic location, and operational status (ON, OFF, NOT FUNCTIONING) of Integrated Devices	2
31	CV-7	The AMS Testbed shall emulate coordinated or independent transmission of messages from Mobile Devices, Carry-in Devices and Integrated Devices when co-located in a vehicle (light, transit, freight, public safety) via cellular or DSRC or both.	1
32	CV-8	The AMS Testbed shall emulate the reception of messages by DSRC-capable Mobile Devices, Carry-in Devices and Integrated Devices from other local DSRC-capable mobile, carry-in, and Integrated Devices	3
33	CV-9	The AMS Testbed shall emulate the reliability of Mobile Devices, Carry-in Devices and Integrated Devices, specifically the reliability of a device to receive or send messages subject to local interference, device malfunction, or user error.	3
34	CV-10	The AMS Testbed shall track the time-referenced geographic- location and emulate the movement of Connected and Unconnected Vehicles within the transportation system, including time parked between trips made as a part of a multi-trip tour.	2
35	CV-11	The AMS Testbed shall reflect differences in vehicle size and weight among Light Vehicles, Transit Vehicles, Trucks and Public Safety Vehicles and associated differences in vehicle performance.	1
36	CS-1	The AMS Testbed shall emulate the geographic location (position), operational status (FUNCTIONING, NOT FUNCTIONING), and range of individual DSRC-capable Roadside Equipment (RSE) deployed as an element of a DSRC Roadside Device Network.	3
37	CS-2	The AMS Testbed shall emulate latency and reliability of messages passing through a DSRC Roadside Device Network, subject to the location and density of nearby roadside devices, relative position and capability of DSRC-capable devices (Mobile Devices,	3
38	CS-3	The AMS Testbed shall emulate latency and reliability of communications using a Wide-Area Wireless Network, subject to the location of capable devices, sources of interference, and overall communications load.	3
39	CS-4	The AMS Testbed shall emulate provision of roadside/local control by Traffic Control Systems through dynamic message signs, lane control signs, ramp meters, and traffic signals.	1
40	CS-5	The AMS Testbed shall emulate provision of advisory information by Traffic Control Systems through dynamic message signs and other forms of advisory information provision.	1
41	CS-6	The AMS Testbed shall emulate the capability of Traffic Control Systems to receive, process, and implement control setting changes from System	1

SNo	ID	Requirement	Chicago Testbed
		Managers, including the latency and reliability of response to System Manager direction.	
42	CS-7	The AMS Testbed shall emulate the provision of Traveler information via Broadcast Media, including television, radio and through the internet, including a differentiation of information delivered to System Users in pre-trip and en route states.	1
43	CS-8	The AMS Testbed shall emulate data capture from Traffic Detection Systems utilizing passive detection to estimate individual vehicle speed, location, and size or to estimate roadway segment occupancy, travel time, and aggregate vehicle flow where deployed	1
44	CS-9	The AMS Testbed shall emulate the accuracy, precision, latency and reliability of data aggregation and pre-processing actions within the Traffic Detection System prior to those data being made available to System Managers within an Operational Data Environment	1
45	OD-1	The AMS Testbed shall emulate Data Quality Control (QC) and Aggregation processes, including the nature and effectiveness of quality checks and data performed for different data types.	1
46	OD-2	The AMS Testbed shall emulate the processing time associated with performing Data Quality Control and Aggregation processes.	1
47	OD-3	The AMS Testbed shall emulate and differentiate between integrated and independent Data Quality Control and Aggregation processes in support of System Managers.	1
48	OD-4	The AMS Testbed shall emulate the capture and aggregation of data from Connected Vehicles, Mobile Devices, and Detection Systems into Private Sector Data Services.	2
49	OD-5	The AMS Testbed shall account for the processing time associated with performing Data Quality Control and Aggregation processes within Private Sector Data Services.	1
50	OD-6	The AMS Testbed shall emulate the provision of aggregated and quality controlled data products from Private Sector Data Services into Data QC and Aggregation processes supporting System Managers.	1
51	OD-7	The AMS Testbed shall emulate the use of Predictive Tools within an Operational Data Environment, dependent on the flow of data from Data QC and Aggregation processes.	1
52	OD-8	The AMS Testbed shall emulate and differentiate among alternative forms of Predictive Tools, including their prediction horizon, accuracy, scope, and processing time.	1
53	SM-1	The AMS Testbed shall emulate the duration and outcomes of decision-making by Freeway System and Tollway Managers, subject to the latency, accuracy, reliability and nature of Operational Data Environments available to support this decision-making.	1
54	SM-2	The AMS Testbed shall emulate the duration and outcomes of decision-making by Arterial System Managers, subject to the latency, accuracy, reliability and nature of Operational Data Environments available to support this decision-making.	1
55	SM-3	The AMS Testbed shall emulate the duration and outcomes of decision-making by Road-Weather System Managers, subject to the latency, accuracy, reliability and nature of Operational Data Environments available to support this decision-making.	1

SNo	ID	Requirement	Chicago Testbed
56	SM-4	The AMS Testbed shall emulate the duration and outcomes of decision-making by Transit System Managers, subject to the latency, accuracy, reliability and nature of Operational Data Environments available to support this decision-making.	3
57	SM-5	The AMS Testbed shall emulate the duration and outcomes of decision-making by Parking System Managers, subject to the latency, accuracy, reliability and nature of Operational Data Environments available to support this decision-making.	2
58	SM-6	The AMS Testbed shall emulate the duration and outcomes of decision-making by Freight System Managers, subject to the latency, accuracy, reliability and nature of Operational Data Environments available to support this decision-making.	3
59	SM-7	The AMS Testbed shall emulate the duration and outcomes of decision-making by Public Safety Managers, subject to the latency, accuracy, reliability and nature of Operational Data Environments available to support this decision-making.	2
60	SM-8	The AMS Testbed shall emulate the duration and outcomes of decision-making by Information Service Providers, subject to the latency, accuracy, reliability and nature of Operational Data Environments available to support this decision-making.	1
61	SM-9	The AMS Testbed shall emulate and differentiate the duration and outcomes of integrated versus independent decision-making among System Managers, including Freeway and Tollway System Managers, Signal System Mangers, Road-Weather System Managers, Parking S	1
62	SM-10	The AMS Testbed shall emulate the forms, scope and limitations of system control exerted by Freeway System and Tollway Managers, including messages passed through Broadcast Media, Traffic Control Systems, the DSRC Roadside Network or Wide-Area Wireless Networks	1
63	SM-11	The AMS Testbed shall emulate the forms, scope and limitations of system control exerted by Arterial System Managers, including messages passed through Traffic Control Systems, the DSRC Roadside Network or Wide-Area Wireless Networks to control or influence System User decision-making.	2
64	SM-12	The AMS Testbed shall emulate the forms, scope and limitations of system control exerted by Road-Weather System Managers, including messages passed through Broadcast Media, Traffic Control Systems, the DSRC Roadside Network or Wide-Area Wireless Networks	2
65	SM-13	The AMS Testbed shall emulate the forms, scope and limitations of system control exerted by Transit System Managers, including messages passed through Broadcast Media, Traffic Control Systems, the DSRC Roadside Network or Wide-Area Wireless Networks to control or influence System User decision-making.	3
66	SM-14	The AMS Testbed shall emulate the forms, scope and limitations of system control exerted by Parking System Managers, including messages passed through Broadcast Media, Traffic Control Systems, the DSRC Roadside Network or Wide-Area Wireless Networks to control or influence System User decision-making.	2
67	SM-15	The AMS Testbed shall emulate the forms, scope and limitations of system control exerted by Freight System Managers, including messages passed through Broadcast Media, Traffic Control Systems, the DSRC Roadside	2

SNo	ID	Requirement	Chicago Testbed
		Network or Wide-Area Wireless Networks to control or influence System User decision-making.	
68	SM-16	The AMS Testbed shall emulate the forms, scope and limitations of system control exerted by Public Safety Managers, including messages passed through Broadcast Media, Traffic Control Systems, the DSRC Roadside Network or Wide-Area Wireless Networks to control or influence System User decision-making.	2
69	SM-17	The AMS Testbed shall emulate the forms, scope and limitations of system control exerted by Information Service Providers, including messages passed through Broadcast Media, the DSRC Roadside Network or Wide-Area Wireless Networks to influence System User	2
70	SM-18	The AMS Testbed shall emulate the utilization of Automated Control by one or more System Managers who delegate specific forms of routine decision-making and control message generation.	1
71	DI-1	The AMS Testbed shall emulate the transmission and reception of Information and Data Flows between System Entities over a specific communications system, whether broadcast or point-to-point in nature, the interval at which the data flow occurs, and the co	1
72	DI-2	The AMS Testbed shall emulate the transmission and reception of Basic Safety Messages (BSM) among Connected Vehicles, Mobile Devices, and the DSRC Roadside Network.	3
73	DI-3	The AMS Testbed shall emulate the transmission of Basic Mobility Messages (BMM) from Connected Vehicles and Mobile Devices to the System Entity tasked with managing BMM messaging (either a Private Sector Data Services or a Data QC and Aggregation process)	3
74	DI-4	The AMS Testbed shall emulate the transmission of Signal, Phase and Timing (SPaT) Messages from the DSRC Roadside Device Network to DSRC-capable Connected Vehicles.	3
75	AP-1	The AMS Testbed shall emulate Dynamic Shoulder Lanes.	1
76	AP-2	The AMS Testbed shall emulate driver behaviors in Dynamic Shoulder Lanes that are distinct from behaviors on regular lanes.	1
77	AP-3	The AMS Testbed shall emulate restriction of access to Dynamic Shoulder Lanes by vehicle type (e.g., transit) and vehicle occupancy (e.g., HOV 2+, HOV 3+).	1
78	AP-4	The AMS Testbed shall emulate Dynamic Lane Use Control, including shoulder lanes.	1
79	AP-5	The AMS Testbed shall emulate Dynamic HOV/Managed Lanes.	2
80	AP-6	The AMS Testbed shall emulate detection of position, start time, duration, and length of queues on freeways and arterials in support of a Queue Warning DMA or Queue Warning strategy supporting System Manager decision-making.	2
81	AP-7	The AMS Testbed shall emulate altered driving behavior in response to Queue Warning messages generated by the Q-WARN DMA and delivered to Carry In or Integrated Devices within Connected Vehicles or through local signage within the Traffic Control System.	2
82	AP-8	The AMS Testbed shall emulate the estimation of dynamic target speed recommendations by roadway section and lane made by the SPD-HARM application or the Dynamic Speed Limits strategy deployed in support of System Managers.	1

SNo	ID	Requirement	Chicago Testbed
83	AP-9	The AMS Testbed shall emulate transmission of SPD-HARM enhanced target speed recommendations via message signs; or directly to Carry-In or Integrated Devices running the SPD-HARM application within a Connected Vehicle.	1
84	AP-10	The AMS Testbed shall emulate driver decision-making in response to target speed recommendations made by the SPD-HARM application running on a Carry-In or Integrated Device within a Connected Vehicle.	1
85	AP-11	The AMS Testbed shall emulate altered driving behavior in response to combined queue warning and target speed recommendations made by a combined Q-WARN/SPD-HARM application.	2
86	AP-12	The AMS Testbed shall emulate the creation, movement, and dispersion of a platoon of Connected Vehicles utilizing Coordinated Adaptive Cruise Control (CACC) application, traveling at the same speed and maintaining the same gap with their respective leader	3
87	AP-13	The AMS Testbed shall emulate the identification and implementation of altered signal control settings enhanced by the M-ISIG DMA bundle or the ATDM Adaptive Traffic Signal Control and Adaptive Ramp Metering strategies.	2
88	AP-14	The AMS Testbed shall emulate the identification and implementation of signal control settings optimized to allow for the rapid and safe movement of Public Safety Vehicles (PREEMPT), Trucks (FSIG), Transit Vehicles (TSP), and Pedestrians (PED-SIG).	2
89	AP-15	The AMS Testbed shall emulate the dynamic creation of high-occupancy vehicles through the DRIDE application running on Mobile Devices or through other Dynamic Ridesharing services supporting informal ridesharing.	3
90	AP-16	The AMS Testbed shall emulate multi-modal forms of Traveler information services that include cost, reliability and parking delivered pre-trip through Broadcast Media or pre-trip and en route through Mobile Devices, Carry-in Devices, and Integrated Device	2
91	AP-17	The AMS Testbed shall emulate Active Parking Management Strategies employed to support decision-making by Parking System Managers, including Dynamic Wayfinding, Dynamic Overflow Transit Parking, Dynamic Parking Reservation, and Dynamic Priced Parking	3
92	AP-18	The AMS Testbed shall emulate Dynamic HOV Lane Conversion, including dynamic alterations to access policy (e.g., HOV-2 to HOV-3) and price.	1
93	AP-19	The AMS Testbed shall emulate Intelligent Dynamic Transit Operations (IDTO), including transit connection protection and dynamic dispatch.	3
94	AP-20	The AMS Testbed shall emulate Incident Management practices, including the management of local incident zones, the staging of emergency response vehicles and personnel, and the closure of lanes and facilities required as a part of the incident response.	3
95	AP-21	The AMS Testbed shall emulate Dynamic Pricing and Dynamic Fare Reduction strategies, including dynamic changes to roadway tolls or transit fares.	1
96	AP-22	The AMS Testbed shall emulate the concurrent deployment of two or more DMAs or ATDM strategies, including synergies or conflicts arising from this interaction.	1
97	AP-23	The AMS Testbed shall emulate Dynamic Junction Control	1
98	AP-24	The AMS Testbed shall emulate Dynamic Merge Control	2

SNo	ID	Requirement	Chicago Testbed
99	AP-25	The AMS Testbed shall emulate Dynamic Lane Reversal or Contraflow lanes, including dynamically adjusting the lane directionality in response to real-time traffic conditions.	1
100	AP-26	The AMS Testbed shall emulate freight operations, including drayage optimization and freight Traveler information	3
101	OC-1	The AMS Testbed shall emulate a range of Operational Conditions, including variations in travel demand, weather, and incident patterns.	1
102	OC-2	The AMS Testbed shall be capable of calculating a consistent set of Performance Measures describing mobility, safety, and environmental impacts, over all Operational Conditions and subject to multiple alternative systems linking System Users and System Management	1
103	OC-3	The AMS Testbed shall be capable of being calibrated and validated using relevant Performance Measures against real-world conditions, both in terms of the representation of Operational Conditions and Alternative Systems, where such data are available from actual surface transportation systems.	1

Chapter 8. Model Calibration

8.1 Supply-side Parameter Calibration

The supply-side parameter calibration for this study includes two parts: calibrating parameters in the traffic flow model (i.e., modified Greenshields models) and estimating the weather adjustment factor (WAF). First, the traffic flow model is calibrated under different weather conditions based on pre-defined weather categories. The calibrated parameters for the normal weather are supplied to DYNASMART as the base case traffic flow model. The parameters under different weather conditions are used to obtain the weather adjustment factor (WAF), which is a reduction factor that reflects the weather impact on each traffic flow parameter. The detailed calibration procedure and the results are discussed in the following sections.

8.1.1 Calibration of Traffic Flow Model Parameters

8.1.1.1 Data Preparation

Traffic data used for the calibration are three major observations from loop detectors, i.e., including link volume (or flow rates), occupancy and speed. All traffic data have the aggregation interval of 5 minutes. The occupancy data are further converted into the density using the following relationship (8):

$$k = \frac{52.8}{L_v + L_s} \cdot occ \qquad (8\text{-}1)$$

where

k	=	density [veh/mi/lane]
L_v	=	average vehicle length [feet]
L_s	=	average sensor length [feet]
occ	=	occupancy [%]

L_v is assumed to be 5 meters (approximately 16.4 feet); and L_s is set to 2 meters (approximately 6.5 feet).Weather data are collected from nearby Automated Surface Observing System (ASOS) stations located at airports, which contain 5-minute aggregated information of visibility, rain intensity level and snow intensity level. Traffic data and weather data are then matched together according to the timestamps to classify each traffic observation into different weather categories.

8.1.1.2 Modified Greenshields Traffic Flow Model

Two types of modified Greenshields models are used in DYNASMART for traffic propagation. Type 1 is a dual-regime model in which constant free-flow speed is specified for the free-flow conditions (1st regime) and a modified Greenshields model is specified for congested-flow conditions (2nd regime) as shown in Figure 8-1.

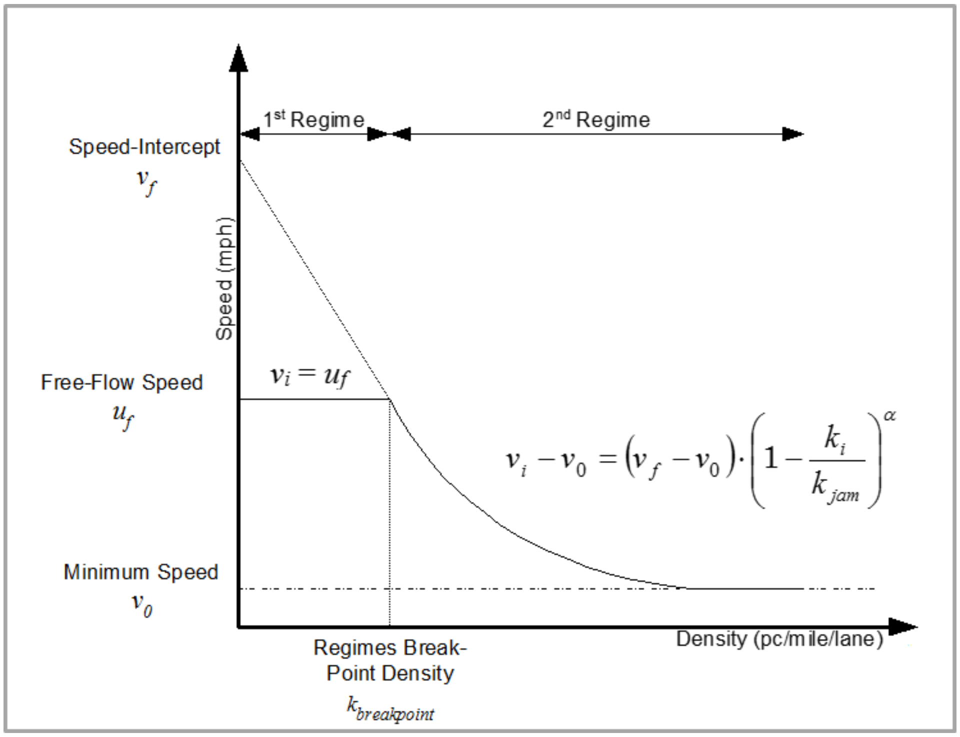

Figure 8-1: Type 1 Modified Greenshields Model (Dual-Regime Model) [Source: DYNASMART-P User's Guide, Accessed June, 2011]

In mathematical terms, the Type 1 modified Greenshields is expressed as follows:

$$v_i = \begin{cases} u_f & 0 < k_i < k_{breakpoint} \\ v_0 + (v_f - v_0)\left(1 - \dfrac{k_i}{k_{jam}}\right)^{\alpha} & k_{breakpoint} < k_i < k_{jam} \end{cases} \tag{8-2}$$

where

v_i	=	speed on link *i*
v_f	=	speed-intercept
u_f	=	free-flow speed on link *i*
v_0	=	minimum speed on link *i*
k_i	=	density on link *i*
k_{jam}	=	jam density on link *i*
α	=	power term
$k_{breakpoint}$	=	breakpoint density

Type 2 uses a single-regime to model traffic relations for both free- and congested-flow conditions as shown in Figure 8-2.

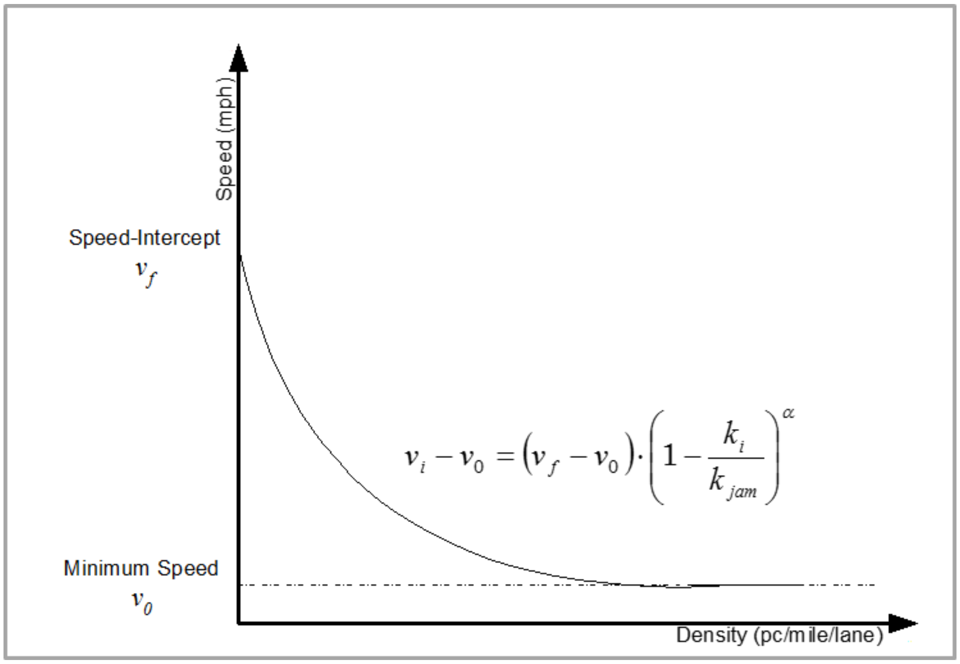

Figure 8-2: Type 2 Modified Greenshields Model (Single-Regime Model) [Source: DYNASMART-P User's Guide, Accessed June, 2011]

In mathematical terms, the type 2 modified Greenshields is expressed as follows:

$$v_i - v_0 = (v_f - v_0)\cdot\left(1-\frac{k_i}{k_{jam}}\right)^{\alpha} \tag{8-3}$$

Dual-regime models are generally applicable to freeways, whereas single-regime models apply to arterials. The reason why a two-regime model is applicable for freeways in particular is that freeways have typically more capacity than arterials, and can accommodate dense traffic (up to 2300 pc/hr/ln) at near free-flow speeds. On the other hand, arterials have signalized intersections, meaning that such a phenomenon may be short-lived, if present at all. Hence, a slight increase in traffic would elicit more deterioration in prevailing speeds than in the case of freeways. Therefore, arterial traffic relations are better explained using a single-regime model. All the traffic data used in this study come from loop detectors installed on highways. Therefore the dual-regime model is chosen to fit the collected historical data. For the dual regime model, the total six parameters are calibrated, namely, breakpoint density (k_{bp}), free flow speed (u_f), speed-intercept (v_f), minimum speed (v_0), jam density (k_{jam}), and the shape parameter (α). For the single regime model, only three parameters including speed-intercept (v_f), minimum speed (v_0), and the shape parameter (α) are used.

8.1.1.3 Weather Categorization

The weather categories were defined based on the precipitation type and the intensity. With a normal weather as the base case, in which no precipitation is observed, three levels of precipitation intensities (light, moderate and heavy) are used for both rain and snow. There are seven weather categories and the corresponding precipitation intensity ranges: normal (no precipitation), light rain (intensity less than 0.1 in./hr), moderate rain (0.1 to 0.3 in./hr), heavy rain (greater than 0.3 in./hr), light snow (less than 0.05

in./hr), moderate snow (0.05 to 0.1 in./hr), and heavy snow (greater than 0.1 in./hr). The values for the intensity range are based on the literature (9; 10).

8.1.1.4 Calibration Procedure and Results

After traffic data are categorized, parameters in the modified Greenshields model are calibrated for each weather condition using a nonlinear regression approach. The following steps describe the procedures for calibrating the dual-regime model, which is used in most cases when traffic data are collected from freeways.

Step 1. Plot the speed vs. density graph, and set initial values for all the parameters, i.e. breakpoint density (k_{bp}), speed-intercept (v_f), minimum speed (v_0), jam density (k_{jam}), and the shape parameter (α), based on observations.

Step 2. For each observed density (k_i), calculate the predicted speed value (v_i) using Eq. (2) and the parameters initialized in Step 1.

Step 3. Compute the squared difference between observed speed value (v_i) and predicted speed value (v_i), for each data point, and sum the squared error over the entire data set.

Step 4. Minimize the sum of squared error obtained in Step 3, by changing the values of model parameters.

Unlike the linear regression used in the previous research (4), which divides the data into two parts and estimates the two regimes separately, the nonlinear regression used in this study allows estimating the model as a whole, which gives a smooth joint point at the breakpoint density. Step 4 is implemented by Microsoft Excel Solver which uses the generalized reduced gradient algorithm to find the optimal solution. The goodness-of-fit of the nonlinear regression model can be measured by the root mean square error (RMSE) as shown in Equation (8-4), where $\hat{v}_i$ is the predicted/modeled value and v_i is the observed value for the i^{th} observation in the sample with the size of N. The smaller the RMSE is, the better the model represents the data.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(v_i - \hat{v}_i)^2} \tag{8-4}$$

Another measurement is the R-squared value, which is computed in the same way as in linear regression models. The expression is shown in Equation (8-5), where $\bar{v}$ represents the mean of the observed data. The R-squared value is the ratio of the regression sum of squares to the total sum of squares, which explains the proportion of variance accounted for in the dependent variable by the model (StatSoft, Inc., 2011). The closer R-squared value is to 1, the better the model fits the data.

$$R^2 = 1 - \frac{SSE}{SST} = 1 - \frac{\sum(v_i - \hat{v}_i)^2}{\sum(v_i - \bar{v})^2} \tag{8-5}$$

8.1.2 Calibration of Weather Adjustment Factor (WAF)

In DYNASMART, supply-side parameters that are expected to be affected by the weather condition are identified as presented in Table 8-1.The inclement weather impact on each of these parameters is represented by a corresponding weather adjustment factor (WAF) such that

$$f_i^{Weather\ Event} = F_i \cdot f_i^{Normal} \tag{8-6}$$

where $f_i^{Weather\ Event}$ denotes the value of parameter *i* under a certain weather event, f_i^{Normal} denotes the value of parameter *i* under the normal condition and F_i is the WAF for parameter *i*.

Table 8-1: Supply Side Properties Related with Weather Impact in DYNASMART

Category	*i*	Parameter Description
Traffic flow model[1]	1 2 3 4 5	Speed-intercept (mph)[1] Minimal speed (mph) Density break point (pcpmpl)[1] Jam density (pcpmpl) Shape term alpha
Link performance	6 7 8	Maximum service flow rate (pcphpl or vphpl) Saturation flow rate (vphpl) Posted speed limit adjustment margin(mph)
Left-turn capacity	9	g/c ratio
2-way stop sign capacity	10 11 12	Saturation flow rate for left-turn vehicles(vphpl) Saturation flow rate for through vehicles(vphpl) Saturation flow rate for right-turn vehicles(vphpl)
4-way stop sign capacity	13 14 15	Discharge rate for left-turn vehicles(vphpl) Discharge rate for through vehicles(vphpl) Discharge rate for right-turn vehicles(vphpl)
Yield sign capacity	16 17 18	Saturation flow rate for left-turn vehicles(vphpl) Saturation flow rate for through vehicles(vphpl) Saturation flow rate for right-turn vehicles(vphpl)

1) only available in dual-regime model
Source: Mahmassani et al. ,2009

The WAF is assumed to be a linear function of weather conditions, and is expressed in the following form

$$F_i = \beta_{i0} + \beta_{i1} \cdot v + \beta_{i2} \cdot r + \beta_{i3} \cdot s + \beta_{i4} \cdot v \cdot r + \beta_{i5} \cdot v \cdot s \tag{8-7}$$

where

F_i	weather adjustment factor for parameter *i*,
v	visibility (mile),
r	precipitation intensity of rain (inch/hr),
s	precipitation intensity of snow (inch/hr), and
$\beta_{i0}, \beta_{i1}, \beta_{i2}, \beta_{i3}, \beta_{i4}, \beta_{i5}$	coefficients to be estimated.

Thus, once the speed-density functions for different weather conditions (i.e., normal, light rain, moderate rain, etc.) are obtained for each network, a linear regression analysis is performed to obtain the WAF for each parameter based on observed rain intensities, snow intensities and visibility levels. A detailed description of the calibration procedure is provided below.

8.1.2.1 Calibration Procedure

The calibration of coefficients in Equation (8-7) includes the following steps.

Step 1. For each weather condition *c*, calculate the WAF for each parameter *i* such that $F_i = f_i^c / f_i^{Base}\ \forall c$, where Base denotes the normal (no precipitation) weather.

Step 2. Assign   to corresponding traffic-weather data such that each observation has a structure similar to the following: [time, traffic data (volume, speed, density), weather data(v, r, s), WAF($F_1,\cdots,F_i$)].

Step 3. For each parameter *i*, estimate $\beta_{i0}, \beta_{i1}, \beta_{i2}, \beta_{i3}, \beta_{i4}, \beta_{i5}$ coefficients by conducting the regression analysis using Equation (8-7) given as a dependent variable and weather data (v, r, s) for all observations as independent variables.

Note that not all of the parameters listed in Table 8-1 can be calibrated using the observation data. Some parameters could be inferred from other calibrated parameters.

(1) Traffic flow model related parameters, that is, speed-intercept (v_f), minimum speed(v_0), density break point(k_{bp}), jam density(k_{jam}), shape term alpha(α) and maximum service flow rate (q_{max}) can be calibrated from the traffic data. However, as minimum speed and jam density turn out to be insensitive to weather conditions from the calibration results, WAF for those parameters are assumed as 1, which indicates these are not affected by weather conditions. In addition, the shape parameter alpha is also fixed as 1 based on the observations that the both speed-intercept (v_f) and alpha(α) govern the shape of the curve and controlling for one variable results in a more consistent and meaningful pattern on the other allowing a better interpretation.

(2) Link characteristics: saturation flow rate, and posted speed limit adjustment could be inferred from the calibrated traffic flow model.

(3) Signal control: the adjustments in cycle length, offset, green, amber, maximum green, and minimum green could be inferred from the saturation flow rate.

(4) Left turn/stop sign/yield sign capacities could be calibrated using the traffic data, for example, maximum observed flow rate could be used as a surrogate of capacity

8.2 Demand-side Parameter Calibration

The demand-side parameter calibration for this study includes several considerations: the base-case OD matrix estimation, changes in dynamic OD trip patterns due to weather conditions, user responses to information and various advisory/control operations schemes, and so on. As an immediate task associated with the network building procedure, the base-case OD matrix estimation has been given priority in implementation plans for the demand-side parameter calibration. The base-case OD matrix here indicates a time-dependent OD matrix under the normal weather condition. As an effort to address the second consideration (demand pattern change under inclement weather conditions), the OD matrices for various adverse weather cases can also be estimated and investigated. The present document include the estimation procedure and results for both the base-case OD matrices and the OD matrices under adverse weather conditions for the study sites.

8.2.1 Estimating Base Case OD Matrix

8.2.1.1 Estimation Procedure

Time-dependent (or dynamic) origin-destination (TDOD) matrices are of crucial importance as an input for dynamic traffic assignment (DTA) models. Determining the scale and resolution of the network model is an essential step in planning applications, with important implications for specifying the associated time-dependent demand patterns. In order to capture the time-dependent pattern, a bi-level optimization method is used (11)

The inputs to this framework are:

- Static/historical OD matrix for the planning time horizon,
- Time-dependent traffic counts on selected observation links.

The output is:

- Time-dependent OD matrices over the time horizon with a chosen time interval (usually 5 or 15 minutes).

The resolution of the time intervals depends on the resolution of the link counts available. Although a higher resolution (smaller time intervals) are usually desirable, it must be noted that travelers are indifferent to very small intervals (e.g. 1 minute). Hence, it is safe to assume a uniform departure pattern within the specified time interval without losing much realism.

In the bi-level optimization approach, the upper-level problem is an ordinary least-squares (OLS) problem, which is to estimate the TDOD demand based on given link-flow proportions. The link-flow proportions are in turn generated from the dynamic traffic network loading problem at the lower level, which may be solved by a simulation-based DTA procedure (in this case we use the DYNASMART-P software) (12). The process is iterated until convergence in the reduction of root mean squared errors (RMSE) of the estimated link-flows is achieved.

The upper-level problem is a weighted multi-objective optimization problem. A mathematical programming platform AMPL is used with the solver KNITRO suited for large-scale non-linear problems (13). The solver KNITRO utilizes an interior point/conjugate graduate algorithm in order to converge to the optimum solution in a time-efficient manner (14). The first objective is to minimize the squared deviations between the simulated flows $M_{l,t}$ and the observed flows $O_{l,t}$ for all observation links $l \in L$ and simulation time intervals $t \in T$.

$$\min_{d_{i,j,h}} (1-w)\left(\sum_{l=1}^{L}\sum_{t=1}^{T}[M_{l,t}-O_{l,t}]^2\right)+(w)\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\left[\left\{\sum_{h=1}^{H}d_{i,j,h}\right\}-\delta_{i,j}\right]^2\right) \qquad (8\text{-}8)$$

$$subjectto\ \ d_{i,j,h}\geq 0, \quad \forall i,j,h$$

where

L : The set of observation links,
l : The index for observation links; *l*∈*L*,
T : The set of simulation time intervals,
t : The index for simulation time intervals; *t*∈*T*,
h : The set of departure time intervals,
H : The index for departure time intervals; *h*∈*H,*
I : The set of origins,
i : The index for origins; *i*∈*I*,
J : The set of destinations,
j : The index for destinations; *j*∈*J*,
$d_{i,j,h}$: Time-dependent OD flow from origin *i*∈*I* to destination *j*∈*J* at the time interval *h*∈*H*
$\delta_{i,j}$: The static OD flow from origin *i*∈*I* to destination *j*∈*J*
$p_{i,j,h,l,t}$: The proportion of demand for origin *i*, destination *j*, at departure time *h*, observed on link *l*, at simulation/observation time t.

The second objective is to minimize the squared deviations between the sums of the time-dependent OD flows $d_{i,j,h}$ over the departure time intervals and static OD flows $\delta_{i,j}$ for all OD pairs and . It must be noted that $d_{i,j,h}$'s are the decision variables of this problem and the outputs of our estimation problem.

The simulated flows $M_{l,t}$ are solved by the lower-level problem and are a function of the decision variables $d_{i,j,h}$ such that $M_{l,t}=\sum_{i,j,h}p_{i,j,h,l,t}d_{i,j,h}$. $p_{i,j,h,l,t}$ is the so-called link proportion, which describes the fraction of OD flow $d_{i,j,h}$ on the link flow $M_{l,t}$. The two stopping criteria used in this methodology are the root mean squared errors for demand and observations (15):

$$RMSE_{Demand}=\sqrt{\frac{\sum_{i=1}^{I}\sum_{j=1}^{J}\left[\left\{\sum_{h=1}^{H}d_{i,j,h}\right\}-\delta_{i,j}\right]^2}{IJH-1}} \qquad (8\text{-}9)$$

RMSE$_{Demand}$ is the measure of error for the deviation between the new time-dependent demand matrix and the original static demand matrix.

$$RMSE_{Flows}=\sqrt{\frac{\sum_{l=1}^{L}\sum_{t=1}^{T}[M_{l,t}-O_{l,t}]^2}{LT-1}} \qquad (8\text{-}10)$$

RMSE$_{Flow}$ is the measure of error for the deviation between the simulated and the observed link flows.

Figure 8-3 illustrates the conceptual relationship between two criteria used in the optimization process. Since the original static OD matrix (left circle in Figure 8-3) typically does not agree well with the actual observations (right circle), our goal is to find a new time-dependent matrix (middle circle) whose resulting traffic flows are well matched with the observed traffic flows, but at the same time not deviating too much from the original static matrix, which was used as a seed for the new matrix. The final new time-dependent OD matrix is therefore obtained by minimizing both $RMSE_{Flows}$ and $RMSE_{Demand}$.

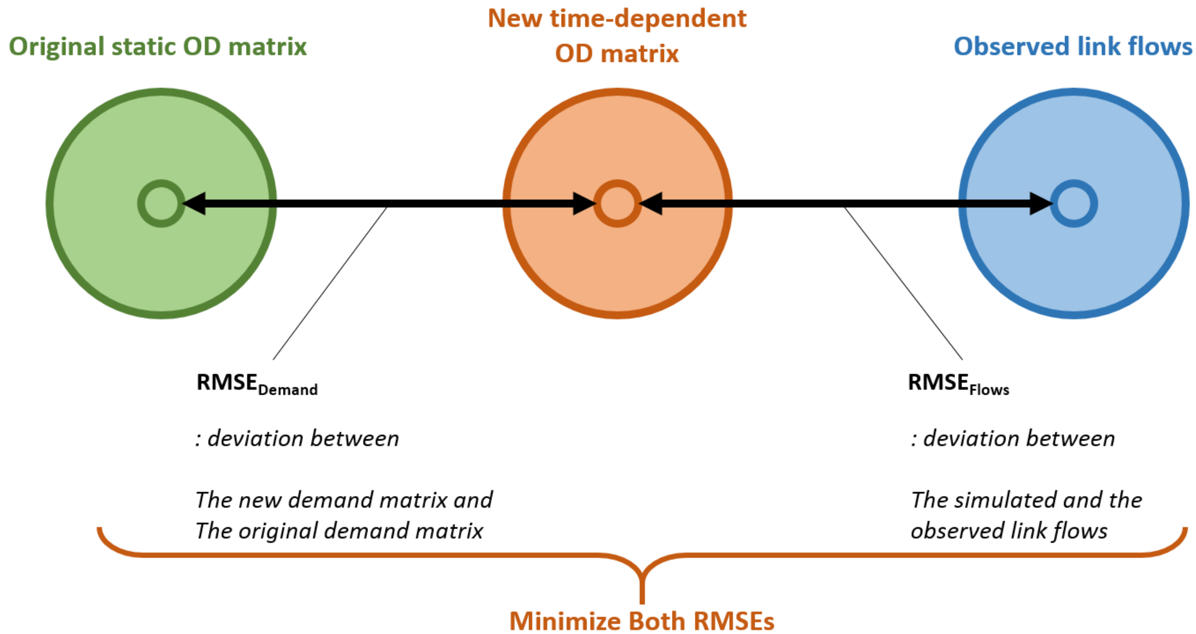

Figure 8-3: Two Criteria in the Optimization Process [Source: NWU]

8.2.2 Estimating OD Matrix under Unclear Weather Conditions

The clustering procedure described in the Section 2.2 provides a good starting point for preparing a historical OD matrix (reflecting day-to-day variation) for the planning time horizon under consideration. Based on the results of joint clustering, a characteristic scenario from each cluster or a specific scenario related to a particular operational condition is chosen and the extended model can be expressed as Equation (8-11).

$$\begin{pmatrix} (1-\omega)C_1 \\ \vdots \\ (1-\omega)C_k \\ \omega C_1 \\ \vdots \\ \omega C_k \end{pmatrix} = \begin{pmatrix} (1-\omega)P_1 & \cdots & 0 \\ \vdots & \ddots & 0 \\ 0 & 0 & (1-\omega)P_k \\ \omega A & \cdots & 0 \\ \vdots & \ddots & 0 \\ 0 & \cdots & \omega A \end{pmatrix} \times \begin{pmatrix} D_1 \\ \vdots \\ D_k \end{pmatrix} + \begin{pmatrix} (1-\omega)E_1 \\ \vdots \\ (1-\omega)E_k \\ \omega \Pi_1 \\ \vdots \\ \omega \Pi_k \end{pmatrix} \tag{8-11}$$

where,

C_k = vector of measured flows related to each cluster or the day under a specific operational condition on the links, whose elements are $c_{(l,h),k}$, which is measured clustered traffic volume on link l , during observation interval h, on day k.

P_k = matrix of link-flow proportions related to each cluster or the day under a specific operational condition, whose elements are $p_{(l,h),(t,I,j),k}$.

D_k= vector of OD demand flows related to a characteristic scenario in each cluster or a specific operational condition, whose elements are $d_{(t,I,j),k}$ on day k.

E_k = vector of error terms, whose elements are ϵ for link flow based on each cluster or a specific operational condition.

Π_k = vector of combined error terms, whose elements are $\pi_{(I,j),k}$, k for total traffic demand during target period.

ω is a positive weight.

Equation (8-11) has a similar form to the multiple linear regression model shown in Equation (8-12). The vector Y represents dependent variables, $(X_1,\cdots, X_k)$ are independent variables, $(D_1,\cdots, D_k)T$ are coefficients to be estimated, and ε is a vector of error terms.

$$Y = (X_1, \cdots, X_k) \times \begin{pmatrix} D_1 \\ \vdots \\ D_k \end{pmatrix} + \varepsilon \tag{8-12}$$

For different clusters, the OD demand matrices D_m are different. Accordingly, link-flow proportions X_k's in Equation (8-12) would have different values. The OD estimation based on cluster results can be accomplished by solving the mathematical program with the objective function shown in Equation (8-13) and constraints in Equation (8-14).

$$\min Z = \sum_k \left\{ (1-\omega) \sum_{l,h} \left[\sum_{t,i,j} \hat{p}_{(l,h),(t,i,j),k} \times d_{(t,i,j),k} - c_{(l,h),k} \right]^2 + w \sum_{t,j} \left[\sum_t d_{(t,i,j),k} - g_{(i,j)} \right]^2 \right\} \tag{8-13}$$

$D_{(t,I,j)}$>=0, $\hat{p}_{(l,h),(t,i,j),k}$ = assignment $d_{(t,I,j),k}$ from DTA, $\forall, l, h, t, j, k$. (8-14)

where, g(I,j)= target demand, which is the total traffic demand during period of interest for each OD pair (i,j).

Chapter 9. Evaluation Approach

This section presents the system evaluation plan to address the DMA and ATDM research questions based on the analysis conducted and the approach to conducting sensitivity analysis.

9.1 Evaluation Plan to Answer DMA and ATDM Questions Based on Analysis Conducted

The different analysis scenarios described Chapter 4 have the goal to answer the research questions from Chapter 3. In this Chapter the different analysis scenarios are mapped to the research questions.

Synergies, Conflicts, and Benefits under various Operational Conditions, Modes and, Facility Types:

The different scenarios from Chapter 4 are designed to be able to test the different strategies alone as well as together under different demand scenarios. This has the purpose to be able to provide insights on synergy or potential conflicts between the different strategies. As each of the strategies is tested alone and together in various combinations, this provides a possibility to define packages of strategies with maximum benefit. Strategies can be applied jointly or alone and with different levels. By testing different levels of strategies alone and jointly, the result will show effectiveness relationships of the strategies as well as their synergies/conflicts.

Prediction Accuracy:

The prediction accuracy will be handled in some scenarios of phase 2 and 3 (see Section 4.4). As the simulation models and their predictability are not handled in a statistical sense with distributions, their accuracy is tested with samples if the strategy is in place in the Chicago Testbed. The scenarios to be tested are forecasting level of services under conditions that are not used for calibration and can therefore measure the accuracy.

Active Management or Latency:

The main goals of these strategies are proactive and reactive deployments to mitigate congestion and avoid flow breakdown in the network. Scenarios are tested, where strategies are deployed proactive - before a breakdown happens - and reactive, after delays are already observed. The difference in effectiveness of these two different scenarios can then be used to measure the influence of active management and its latency.

9.2 Sensitivity Analyses

Sensitivity analysis will be conducted to account for limitation related to lack data for some of the model parameters and/or assumptions that are used in developing the simulation logic for the different strategies. This is true for demand management strategies and their impact, as data for proper model calibration in the Chicago case is often missing. To address these limitations, we propose conducting a sensitivity analysis that covers the possible ranges of these unknown parameters. For example, most strategies will affect the level of service on the network. As the level of service affects travelers' behavior such as departure time or mode choice, these demand changes can be integrated by sensitivity analysis within a reasonable range of changing demand. Although, calibrated demand models are available, there is still a lot of uncertainty for example about how many travelers would access information about level of service changes and therefore reconsider their choices. The sensitivity analysis plan is extended in the following sections.

Demand Scenarios for Sensitivity Analysis

Several demand scenarios are intended to be simulated for the sensitivity analysis. One for the benchmark case, which is 100% of the demand under the normal weather condition (i.e., no snow); and the other seven scenarios with different demand levels under different bad weather condition. For the generation scenarios, we start with the full demand (100%) and reduce the total demand with different Demand Management Strategies. As the number of users given information about new travel times, and thus re-considering their choices, is unknown, different demand reduction scenarios are introduced from 5% to 10% and 20%.

Sensitivity Analysis for Connectivity

As the market penetration for connectivity is crucial for determining its effectiveness, sensitivity for connectivity is also conducted. Continuing advances in wireless technology and processing power provide the opportunity to create an internet of cars where individual vehicles are connected to each other and to the Traffic Management Center (TMC) through a wireless network. The flow of information in this network creates safer driving environment, improves mobility, makes online monitoring and management possible, and provides essential data for offline planning. Connected Vehicles technology is expected to reduce crashes by improving drivers' situational awareness, while reducing/eliminating congestion, decreasing energy consumption, and improving negative environmental impacts of driving (e.g., by reducing emissions and greenhouse gases).

This scenarios for the Chicago Testbed incorporates two main types of communications, vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I). V2V communications transmit information between individual vehicles while V2I communications transmit information between individual vehicles and TMC. Consequently, all aspects of drivers' decision making, from strategic to operational decisions, will improve. The amount of these improvements, however, depends of the market penetration rate of connected vehicles. At low market penetration rates of connected vehicles, minor improvements are expected, while major improvements are expected at high market penetration rates. Therefore, three levels of market penetration rates will be considered in the sensitivity analysis: 10%, 50%, and 90%. 10% market penetration rate represents the early stages of adopting this technology where only early adopters choose the connected vehicles technologies. 50% market penetration rate represents the early stages of this technology's popularity. Finally, 90% market penetration rate represents the near full penetration of Connected Vehicles technologies.

Figure 9-1 shows a simulation sensitivity analysis for speed harmonization compliance rate, where the compliance is modeled from 0% (a,d), 10% (b,e) and 90% (c,f).

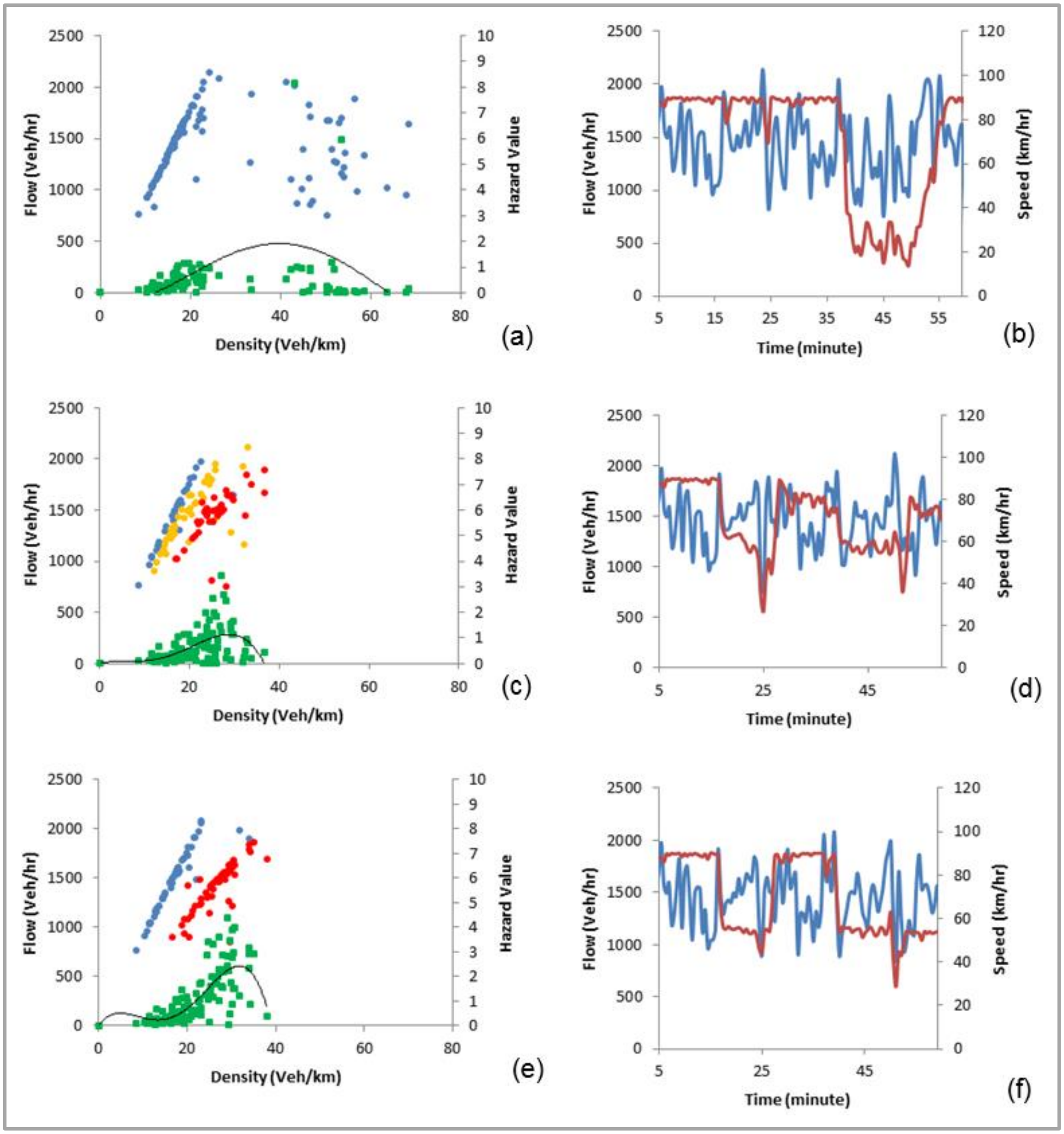

Figure 9-1: (a) Fundamental Diagram (Blue for 25m/s speed limit) and Hazard Value (Green) for Simulation with Active Speed Harmonization and 0% Compliance; (b) Fundamental Diagram (Blue, Orange and Red for 25, 20 and 15 m/s Speed Limit Respectively) and Hazard Value (Green) for Simulation with Active Speed Harmonization and 10% Compliance; (c) Fundamental Diagram (Blue, Orange and Red for 25, 20 and 15 m/s Speed Limit Respectively) and Hazard Value (Green) for Simulation with Active Speed Harmonization and 90% Compliance; (d) Flow (Blue) and Speed (Red) Evolution over Time for Simulation with Active Speed Harmonization and 0% Compliance; (e) Flow (Blue) and Speed (Red) Evolution over Time for Simulation with Active Speed Harmonization and 10% Compliance; (f) Flow (Blue) and Speed (Red) Evolution over Time for Simulation with Active Speed Harmonization and 90% Compliance. [Source: NWU]

9.3 Anticipated Implementation Cost

The AMS Team will estimate the implementation costs of the ATDM and DMA applications by assessing similar implementation efforts and reviewing cost databases (e.g., IDAS Database).

Chapter 10. Execution Plan

This section presents the execution plan including a detailed schedule, budget and key roles of staff.

10.1 Schedule

This section summarizes the process shown in Figure 10-1 used to conduct the analysis for Chicago Testbed. The analysis scenarios for this Testbed will span three analysis phases to demonstrate and evaluate the ATDM strategies applications capabilities:

- Phase 1: represents about 20% of the total project effort.
- Phase 2: represents about 40% of the total project effort.
- Phase 3: represents about 40% of the total project effort.

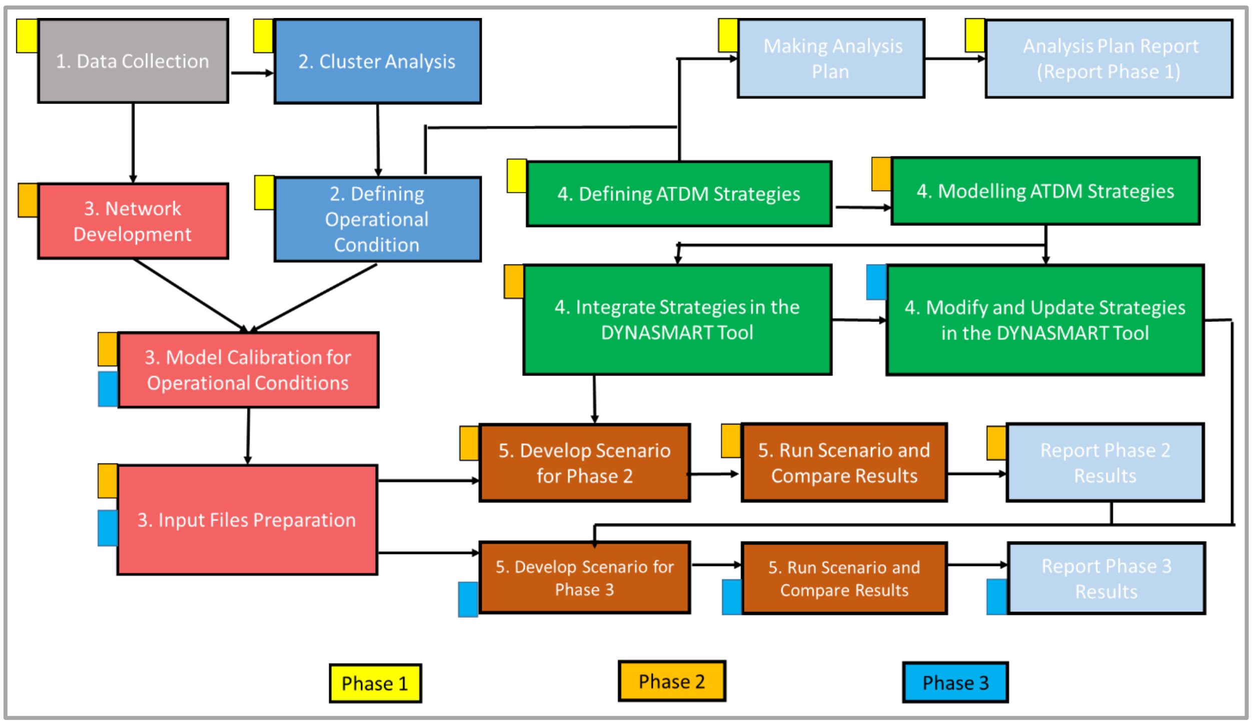

Figure 10-1: Execution Steps and Overview of Project Tasks [Source: Booz Allen]

The team will follow 5 steps for the three-Phase approach to completing the analysis:

- Data Collection (see Section 5.3).
- Operational Condition Definition (see Section 2.2 and Appendix).
- Network Model Calibration (see Chapter 8).
- Application-Specific Algorithm and Needed Tools (see Section 7.1 and 7.2).
- Analysis Scenarios (see Section 4.3).

Appendix

Note that portions of the appendix are contained in the body of the analysis plan.

Clustering Data Description

Traffic Flow Data

The primary source of traffic data is loop detectors installed on freeway lanes. Historical data with the 5-minute interval is obtained from the Illinois DOT in 2009, where the daily 24-hour traffic flow demand profile is described in a vector, which includes 288 5-minute intervals of flow volume. Figure 2-3 shows a map of the 13 selected detector locations in Chicago. The clustering data is aggregated from these 13 detector datasets. At each location, traffic data from north- or southbound directions are obtained. Before the clustering procedure is executed, the dataset is filtered according to the percentage of observations and those days with less than 90% valid observations are excluded from the dataset. The total of 321 days' aggregated daily traffic flow data labeled from 1 to 321 comprise the test dataset.

Weather Time-Series Data

In order to keep time consistence with traffic data, ASOS data with the 5 minute resolution will be used in conjunction with traffic detector data collected and aggregated over a 5-minute interval. ASOS 5-minute weather data are available on the NOAA National Climatic Data Center (NCDC) website (ftp://ftp.ncdc.noaa.gov/pub/data/asos-fivemin). In this cluster analysis study, we are using the ASOS data obtained from O'Hare International Airport (KORD), Chicago, IL in 2009.

With the same data structure of traffic data, the daily 24-hour weather condition is described in a vector, which includes 288 5-minute intervals. The data contain information on various weather parameters such as visibility, precipitation type and intensity, temperature, wind speed and direction (3). Among these, precipitation type and intensity are used as the main attributes to represent a different weather condition in each interval. The following seven categories are identified based on the combination of these attribute values in Table A - 1: Clear, Light Rain, Moderate Rain, Heavy Rain, Light Snow, Moderate Snow and Heavy Snow(4). The main focus of the index definition is on capturing a relative order of precipitation intensity within the same precipitation type (e.g., Light, Moderate and Heavy). Given the fact that other weather parameters are typically highly correlated with these two attributes (e.g., visibility decreases as precipitation intensity increases), we assume that the proposed seven weather categories can cover the majority of weather conditions that commonly occur in daily driving situations. These categories are those adopted in previous FHWA projects for incorporating the effect of weather in traffic modeling tools (4; 5).

Table A - 1: Weather Condition Index

Weather condition	Condition Index	Precipitation Type	Precipitation Intensity (in/hr)
Clear	0	None	0
Light Rain	1	Rain	(0,0.1]
Moderate Rain	2	Rain	(0.1,0.3)

Weather condition	Condition Index	Precipitation Type	Precipitation Intensity (in/hr)
Heavy Rain	3	Rain	>= 0.3
Light Snow	4	Snow	(0,0.05]
Moderate Snow	5	Snow	(0.05,0.1)
Heavy Snow	6	Snow	>=0.1

Consider M weather time series, and one time series data is recognized as daily record consisting of T data points. In this study, we have 288 time intervals in 5-minute observation interval every day and 365 time series in 2009. Each data point is assigned one of the seven weather categories index according to their precipitation type and intensity. Given this categorization, the variables will be used in the cluster analysis using a numerical index, denoted by Im(t), which represents a weather condition at time interval t of the mth time series shown as Table A - 2. The clustering is performed based on this M×T matrix of Im(t), i.e., a 365 × 288 matrix, to represent yearly weather condition in 5-minute observation records; M rows are partitioned into K groups by viewing M time series as M entities to be clustered and each entity (a time series with T intervals) as a T-dimensional point.

Table A - 2: Data Matrix of Weather Condition Index

	$t=1$	$t=2$	$t=3$	$\cdots$	$t=T$
$m=1$	$I_1(1)$	$I_1(2)$	$I_1(3)$	$\cdots$	$I_1(T)$
$m=2$	$I_2(1)$	$I_2(2)$	$I_2(3)$	$\cdots$	$I_2(T)$
$m=3$	$I_3(1)$	$I_3(2)$	$I_3(3)$	$\cdots$	$I_3(T)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$		$\vdots$
m=M	$I_M(1)$	$I_M(2)$	$I_M(3)$	$\cdots$	$I_M(T)$

It is noted that the order or magnitude of the index values may not reflect the actual impacts of the associated weather conditions on the network traffic performance. For instance, the impact of Heavy Rain (I=3) on traffic could be more similar to that of Moderate Snow (I=5) than that of Light Snow (I=4) while the squared Euclidean distance between I=3 and I=5 is greater than that of I=3 and I=4. Because the clustering is performed based on the comparison of the entire index sequences (e.g., Im(1),·· Im(T),vs. In(1),·· In(T),), rather than based on a point-to-point comparison (e.g., Im(T) vs. In(T)), and the combination of such indices generally contains sufficient information to permit the distinction of daily pattern. Another important aspect of the proposed weather condition index is its simplicity. We intended to use a clustering variable that is as simple as possible and can be constructed purely based on the weather parameter attributes. This is to investigate the value of scenario clustering in a more general and practical setting.

Datasets

We are using data obtained from 13 detectors 321 days in 2009, the original dataset is too huge to show. Table A - 3, Table A - 4, and Table A - 5 give three samples of our dataset, and Table A - 6 and Table A - 7 show the look-up table for filtered traffic data and weather data.

Table A - 3: Traffic Data from Detector Edens 1021S and Weather Data from KORD on Oct 29, 2009

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2009/10/29	0:00	0:05	249	5.7570	43.2517	CLEAR
2009/10/29	0:05	0:10	117	3.6613	31.9563	CLEAR
2009/10/29	0:10	0:15	126	3.8331	32.8718	CLEAR
2009/10/29	0:15	0:20	129	4.6180	27.9342	CLEAR
2009/10/29	0:20	0:25	114	3.1317	36.4015	CLEAR
2009/10/29	0:25	0:30	93	3.8811	23.9622	CLEAR
2009/10/29	0:30	0:35	120	4.5251	26.5186	CLEAR
2009/10/29	0:35	0:40	111	3.5375	31.3782	CLEAR
2009/10/29	0:40	0:45	111	3.5310	31.4361	CLEAR
2009/10/29	0:45	0:50	69	2.2353	30.8682	CLEAR
2009/10/29	0:50	0:55	81	3.0781	26.3148	CLEAR
2009/10/29	0:55	1:00	78	2.8505	27.3640	CLEAR
2009/10/29	1:00	1:05	87	3.7880	22.9672	CLEAR
2009/10/29	1:05	1:10	87	3.8492	22.6024	CLEAR
2009/10/29	1:10	1:15	102	3.1183	32.7104	CLEAR
2009/10/29	1:15	1:20	78	2.8293	27.5683	CLEAR
2009/10/29	1:20	1:25	NA	NA	NA	CLEAR
2009/10/29	1:25	1:30	NA	NA	NA	CLEAR
2009/10/29	1:30	1:35	0	1.9387	0.0000	CLEAR
2009/10/29	1:35	1:40	NA	NA	NA	CLEAR
2009/10/29	1:40	1:45	75	2.7914	26.8684	CLEAR
2009/10/29	1:45	1:50	63	2.0012	31.4808	CLEAR
2009/10/29	1:50	1:55	66	3.0673	21.5171	CLEAR
2009/10/29	1:55	2:00	84	3.5357	23.7575	CLEAR
2009/10/29	2:00	2:05	42	1.3062	32.1554	CLEAR
2009/10/29	2:05	2:10	69	2.6742	25.8018	CLEAR
2009/10/29	2:10	2:15	39	1.4468	26.9568	CLEAR
2009/10/29	2:15	2:20	39	1.4083	27.6920	CLEAR
2009/10/29	2:20	2:25	42	2.0590	20.3986	CLEAR
2009/10/29	2:25	2:30	81	2.6478	30.5911	CLEAR
2009/10/29	2:30	2:35	66	2.4773	26.6422	CLEAR
2009/10/29	2:35	2:40	30	0.8231	36.4474	CLEAR
2009/10/29	2:40	2:45	63	2.1902	28.7647	CLEAR
2009/10/29	2:45	2:50	27	0.5838	46.2448	CLEAR
2009/10/29	2:50	2:55	60	2.3696	25.3209	CLEAR
2009/10/29	2:55	3:00	27	1.3738	19.6534	CLEAR
2009/10/29	3:00	3:05	57	2.1821	26.1216	CLEAR

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2009/10/29	3:05	3:10	48	1.9460	24.6659	CLEAR
2009/10/29	3:10	3:15	60	2.4931	24.0667	CLEAR
2009/10/29	3:15	3:20	63	2.0946	30.0768	CLEAR
2009/10/29	3:20	3:25	51	1.7274	29.5233	CLEAR
2009/10/29	3:25	3:30	57	2.7790	20.5110	CLEAR
2009/10/29	3:30	3:35	51	1.8780	27.1565	CLEAR
2009/10/29	3:35	3:40	42	1.8073	23.2393	CLEAR
2009/10/29	3:40	3:45	60	2.8375	21.1457	CLEAR
2009/10/29	3:45	3:50	36	1.3946	25.8140	CLEAR
2009/10/29	3:50	3:55	54	1.4639	36.8870	CLEAR
2009/10/29	3:55	4:00	45	1.3131	34.2697	CLEAR
2009/10/29	4:00	4:05	42	1.6662	25.2071	CLEAR
2009/10/29	4:05	4:10	75	2.7161	27.6128	CLEAR
2009/10/29	4:10	4:15	69	2.6317	26.2186	CLEAR
2009/10/29	4:15	4:20	84	3.2939	25.5019	CLEAR
2009/10/29	4:20	4:25	75	2.9634	25.3091	CLEAR
2009/10/29	4:25	4:30	81	2.9182	27.7568	CLEAR
2009/10/29	4:30	4:35	102	4.1612	24.5124	CLEAR
2009/10/29	4:35	4:40	75	2.0088	37.3358	CLEAR
2009/10/29	4:40	4:45	93	2.8479	32.6561	CLEAR
2009/10/29	4:45	4:50	123	3.7848	32.4986	CLEAR
2009/10/29	4:50	4:55	117	3.8312	30.5389	CLEAR
2009/10/29	4:55	5:00	108	2.7990	38.5849	CLEAR
2009/10/29	5:00	5:05	102	3.3605	30.3525	CLEAR
2009/10/29	5:05	5:10	150	4.6384	32.3389	CLEAR
2009/10/29	5:10	5:15	138	3.9157	35.2424	CLEAR
2009/10/29	5:15	5:20	198	6.1254	32.3242	CLEAR
2009/10/29	5:20	5:25	174	5.1390	33.8587	CLEAR
2009/10/29	5:25	5:30	180	5.8791	30.6170	CLEAR
2009/10/29	5:30	5:35	201	5.0846	39.5312	CLEAR
2009/10/29	5:35	5:40	234	6.0978	38.3744	CLEAR
2009/10/29	5:40	5:45	255	7.9501	32.0751	CLEAR
2009/10/29	5:45	5:50	267	7.6163	35.0564	CLEAR
2009/10/29	5:50	5:55	342	10.5565	32.3972	CLEAR
2009/10/29	5:55	6:00	315	8.6593	36.3770	CLEAR
2009/10/29	6:00	6:05	318	9.6862	32.8302	CLEAR
2009/10/29	6:05	6:10	450	11.8589	37.9462	CLEAR
2009/10/29	6:10	6:15	405	11.8515	34.1729	CLEAR

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2009/10/29	6:15	6:20	534	15.1253	35.3052	CLEAR
2009/10/29	6:20	6:25	492	20.7625	23.6965	CLEAR
2009/10/29	6:25	6:30	474	17.8135	26.6090	CLEAR
2009/10/29	6:30	6:35	486	27.2272	17.8498	CLEAR
2009/10/29	6:35	6:40	471	20.3830	23.1075	CLEAR
2009/10/29	6:40	6:45	372	25.4547	14.6142	CLEAR
2009/10/29	6:45	6:50	453	18.6354	24.3086	CLEAR
2009/10/29	6:50	6:55	438	18.8674	23.2146	CLEAR
2009/10/29	6:55	7:00	453	19.1807	23.6174	CLEAR
2009/10/29	7:00	7:05	105	81.8176	1.2833	CLEAR
2009/10/29	7:05	7:10	NA	NA	NA	CLEAR
2009/10/29	7:10	7:15	NA	NA	NA	CLEAR
2009/10/29	7:15	7:20	165	57.7593	2.8567	CLEAR
2009/10/29	7:20	7:25	321	32.9452	9.7434	CLEAR
2009/10/29	7:25	7:30	363	26.6111	13.6409	CLEAR
2009/10/29	7:30	7:35	240	41.0529	5.8461	CLEAR
2009/10/29	7:35	7:40	213	50.1227	4.2496	CLEAR
2009/10/29	7:40	7:45	210	37.9751	5.5299	CLEAR
2009/10/29	7:45	7:50	384	22.3379	17.1905	CLEAR
2009/10/29	7:50	7:55	345	28.2907	12.1948	CLEAR
2009/10/29	7:55	8:00	339	26.4086	12.8367	CLEAR
2009/10/29	8:00	8:05	252	43.9591	5.7326	CLEAR
2009/10/29	8:05	8:10	282	30.0825	9.3742	CLEAR
2009/10/29	8:10	8:15	270	38.1954	7.0689	CLEAR
2009/10/29	8:15	8:20	375	18.9814	19.7562	CLEAR
2009/10/29	8:20	8:25	363	17.9730	20.1970	CLEAR
2009/10/29	8:25	8:30	303	11.4856	26.3808	CLEAR
2009/10/29	8:30	8:35	345	10.9590	31.4811	CLEAR
2009/10/29	8:35	8:40	333	8.7256	38.1637	CLEAR
2009/10/29	8:40	8:45	297	7.1946	41.2810	CLEAR
2009/10/29	8:45	8:50	327	7.6304	42.8549	CLEAR
2009/10/29	8:50	8:55	333	8.7578	38.0232	CLEAR
2009/10/29	8:55	9:00	306	8.3319	36.7262	CLEAR
2009/10/29	9:00	9:05	306	7.3869	41.4246	CLEAR
2009/10/29	9:05	9:10	366	9.6675	37.8589	CLEAR
2009/10/29	9:10	9:15	387	9.4446	40.9756	CLEAR
2009/10/29	9:15	9:20	372	10.4624	35.5557	CLEAR
2009/10/29	9:20	9:25	423	11.0503	38.2794	CLEAR

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2009/10/29	9:25	9:30	312	8.6215	36.1887	CLEAR
2009/10/29	9:30	9:35	363	10.9106	33.2703	CLEAR
2009/10/29	9:35	9:40	390	12.9925	30.0173	CLEAR
2009/10/29	9:40	9:45	435	13.6044	31.9749	CLEAR
2009/10/29	9:45	9:50	417	13.1239	31.7742	CLEAR
2009/10/29	9:50	9:55	411	12.7112	32.3338	CLEAR
2009/10/29	9:55	10:00	387	10.5551	36.6648	CLEAR
2009/10/29	10:00	10:05	378	10.0165	37.7376	CLEAR
2009/10/29	10:05	10:10	393	10.5713	37.1762	CLEAR
2009/10/29	10:10	10:15	396	10.2733	38.5467	CLEAR
2009/10/29	10:15	10:20	366	11.6534	31.4072	CLEAR
2009/10/29	10:20	10:25	357	11.0438	32.3260	CLEAR
2009/10/29	10:25	10:30	408	12.4981	32.6449	CLEAR
2009/10/29	10:30	10:35	390	11.3708	34.2985	CLEAR
2009/10/29	10:35	10:40	366	10.5937	34.5487	CLEAR
2009/10/29	10:40	10:45	393	12.3351	31.8604	CLEAR
2009/10/29	10:45	10:50	396	12.0563	32.8459	CLEAR
2009/10/29	10:50	10:55	354	10.4507	33.8733	CLEAR
2009/10/29	10:55	11:00	363	11.5268	31.4918	CLEAR
2009/10/29	11:00	11:05	369	10.3694	35.5854	CLEAR
2009/10/29	11:05	11:10	357	13.6409	26.1713	CLEAR
2009/10/29	11:10	11:15	453	17.4010	26.0330	CLEAR
2009/10/29	11:15	11:20	378	12.8590	29.3959	CLEAR
2009/10/29	11:20	11:25	414	11.4923	36.0242	CLEAR
2009/10/29	11:25	11:30	393	12.4071	31.6754	CLEAR
2009/10/29	11:30	11:35	438	13.0105	33.6652	CLEAR
2009/10/29	11:35	11:40	393	13.4281	29.2669	CLEAR
2009/10/29	11:40	11:45	411	12.2658	33.5079	CLEAR
2009/10/29	11:45	11:50	378	11.4894	32.9000	CLEAR
2009/10/29	11:50	11:55	357	11.0789	32.2235	CLEAR
2009/10/29	11:55	12:00	345	10.7442	32.1103	CLEAR
2009/10/29	12:00	12:05	387	11.5323	33.5580	CLEAR
2009/10/29	12:05	12:10	372	12.6284	29.4574	CLEAR
2009/10/29	12:10	12:15	354	11.9086	29.7264	CLEAR
2009/10/29	12:15	12:20	396	11.3872	34.7758	CLEAR
2009/10/29	12:20	12:25	360	11.4037	31.5688	CLEAR
2009/10/29	12:25	12:30	348	9.3932	37.0482	CLEAR
2009/10/29	12:30	12:35	432	13.0336	33.1451	CLEAR

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2009/10/29	12:35	12:40	327	9.6452	33.9030	CLEAR
2009/10/29	12:40	12:45	318	9.1199	34.8687	CLEAR
2009/10/29	12:45	12:50	345	10.9645	31.4652	CLEAR
2009/10/29	12:50	12:55	348	10.9410	31.8069	CLEAR
2009/10/29	12:55	13:00	354	10.5932	33.4178	CLEAR
2009/10/29	13:00	13:05	336	10.9343	30.7289	CLEAR
2009/10/29	13:05	13:10	345	10.3336	33.3862	CLEAR
2009/10/29	13:10	13:15	303	9.8454	30.7757	CLEAR
2009/10/29	13:15	13:20	339	9.2505	36.6468	CLEAR
2009/10/29	13:20	13:25	348	10.2062	34.0968	CLEAR
2009/10/29	13:25	13:30	351	10.0033	35.0883	CLEAR
2009/10/29	13:30	13:35	381	10.4277	36.5373	CLEAR
2009/10/29	13:35	13:40	363	10.9208	33.2394	CLEAR
2009/10/29	13:40	13:45	390	12.5179	31.1555	CLEAR
2009/10/29	13:45	13:50	342	10.0417	34.0579	CLEAR
2009/10/29	13:50	13:55	342	10.4475	32.7352	CLEAR
2009/10/29	13:55	14:00	390	11.4249	34.1359	CLEAR
2009/10/29	14:00	14:05	333	10.2231	32.5732	CLEAR
2009/10/29	14:05	14:10	381	11.2257	33.9401	CLEAR
2009/10/29	14:10	14:15	369	10.1409	36.3872	CLEAR
2009/10/29	14:15	14:20	405	11.9716	33.8299	CLEAR
2009/10/29	14:20	14:25	360	10.2501	35.1215	CLEAR
2009/10/29	14:25	14:30	384	11.1056	34.5771	CLEAR
2009/10/29	14:30	14:35	378	11.6517	32.4417	CLEAR
2009/10/29	14:35	14:40	399	12.3650	32.2684	CLEAR
2009/10/29	14:40	14:45	381	11.0952	34.3393	CLEAR
2009/10/29	14:45	14:50	408	11.8526	34.4228	CLEAR
2009/10/29	14:50	14:55	369	14.7290	25.0525	CLEAR
2009/10/29	14:55	15:00	264	30.3415	8.7009	CLEAR
2009/10/29	15:00	15:05	384	16.3596	23.4724	CLEAR
2009/10/29	15:05	15:10	282	25.0126	11.2743	CLEAR
2009/10/29	15:10	15:15	318	24.6627	12.8940	CLEAR
2009/10/29	15:15	15:20	258	46.1238	5.5936	CLEAR
2009/10/29	15:20	15:25	267	31.7714	8.4038	CLEAR
2009/10/29	15:25	15:30	330	28.9589	11.3955	CLEAR
2009/10/29	15:30	15:35	318	33.7074	9.4341	CLEAR
2009/10/29	15:35	15:40	324	24.6695	13.1336	CLEAR
2009/10/29	15:40	15:45	327	19.1320	17.0918	CLEAR

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2009/10/29	15:45	15:50	315	36.6125	8.6036	LIGHT RAIN
2009/10/29	15:50	15:55	267	40.9202	6.5249	LIGHT RAIN
2009/10/29	15:55	16:00	315	36.6569	8.5932	LIGHT RAIN
2009/10/29	16:00	16:05	342	15.9176	21.4857	LIGHT RAIN
2009/10/29	16:05	16:10	294	31.4225	9.3563	LIGHT RAIN
2009/10/29	16:10	16:15	363	24.2370	14.9771	LIGHT RAIN
2009/10/29	16:15	16:20	336	30.9086	10.8708	LIGHT RAIN
2009/10/29	16:20	16:25	366	28.4160	12.8801	LIGHT RAIN
2009/10/29	16:25	16:30	336	34.3362	9.7856	LIGHT RAIN
2009/10/29	16:30	16:35	405	22.1001	18.3257	LIGHT RAIN
2009/10/29	16:35	16:40	294	31.5971	9.3046	LIGHT RAIN
2009/10/29	16:40	16:45	327	31.4078	10.4114	CLEAR
2009/10/29	16:45	16:50	393	21.3984	18.3659	CLEAR
2009/10/29	16:50	16:55	375	20.9169	17.9281	CLEAR
2009/10/29	16:55	17:00	342	24.9184	13.7248	LIGHT RAIN
2009/10/29	17:00	17:05	339	22.4292	15.1142	LIGHT RAIN
2009/10/29	17:05	17:10	360	22.5348	15.9753	LIGHT RAIN
2009/10/29	17:10	17:15	333	25.5996	13.0080	CLEAR
2009/10/29	17:15	17:20	339	37.4054	9.0629	CLEAR
2009/10/29	17:20	17:25	258	40.0658	6.4394	CLEAR
2009/10/29	17:25	17:30	285	35.3904	8.0530	CLEAR
2009/10/29	17:30	17:35	279	35.6066	7.8356	CLEAR
2009/10/29	17:35	17:40	276	37.9284	7.2769	CLEAR
2009/10/29	17:40	17:45	288	33.5735	8.5782	CLEAR
2009/10/29	17:45	17:50	312	20.9342	14.9039	CLEAR
2009/10/29	17:50	17:55	258	33.8087	7.6312	CLEAR
2009/10/29	17:55	18:00	270	37.4067	7.2180	CLEAR
2009/10/29	18:00	18:05	288	35.0131	8.2255	CLEAR
2009/10/29	18:05	18:10	216	41.3610	5.2223	CLEAR
2009/10/29	18:10	18:15	288	35.0691	8.2123	CLEAR
2009/10/29	18:15	18:20	279	35.5373	7.8509	CLEAR
2009/10/29	18:20	18:25	261	36.7493	7.1022	CLEAR
2009/10/29	18:25	18:30	321	25.2840	12.6958	CLEAR
2009/10/29	18:30	18:35	294	34.5939	8.4986	CLEAR
2009/10/29	18:35	18:40	315	32.2431	9.7695	CLEAR
2009/10/29	18:40	18:45	327	35.5564	9.1967	CLEAR
2009/10/29	18:45	18:50	285	33.1472	8.5980	CLEAR
2009/10/29	18:50	18:55	309	30.2409	10.2179	LIGHT RAIN

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2009/10/29	18:55	19:00	282	27.5887	10.2216	CLEAR
2009/10/29	19:00	19:05	303	29.2043	10.3752	CLEAR
2009/10/29	19:05	19:10	321	34.1332	9.4043	CLEAR
2009/10/29	19:10	19:15	297	32.4927	9.1405	CLEAR
2009/10/29	19:15	19:20	294	28.7969	10.2094	LIGHT RAIN
2009/10/29	19:20	19:25	270	32.2639	8.3685	LIGHT RAIN
2009/10/29	19:25	19:30	294	31.6957	9.2757	LIGHT RAIN
2009/10/29	19:30	19:35	321	35.2822	9.0981	LIGHT RAIN
2009/10/29	19:35	19:40	303	30.9067	9.8037	LIGHT RAIN
2009/10/29	19:40	19:45	300	27.9897	10.7182	LIGHT RAIN
2009/10/29	19:45	19:50	243	36.8346	6.5971	LIGHT RAIN
2009/10/29	19:50	19:55	276	25.7542	10.7167	LIGHT RAIN
2009/10/29	19:55	20:00	333	25.1137	13.2597	LIGHT RAIN
2009/10/29	20:00	20:05	408	19.4015	21.0293	LIGHT RAIN
2009/10/29	20:05	20:10	291	32.8617	8.8553	LIGHT RAIN
2009/10/29	20:10	20:15	354	25.0708	14.1200	RAIN
2009/10/29	20:15	20:20	351	22.9391	15.3014	RAIN
2009/10/29	20:20	20:25	360	17.7646	20.2651	+RA
2009/10/29	20:25	20:30	360	18.0811	19.9103	RAIN
2009/10/29	20:30	20:35	345	12.0932	28.5285	RAIN
2009/10/29	20:35	20:40	342	10.0608	33.9934	LIGHT RAIN
2009/10/29	20:40	20:45	288	8.6714	33.2125	LIGHT RAIN
2009/10/29	20:45	20:50	384	12.2274	31.4049	LIGHT RAIN
2009/10/29	20:50	20:55	294	9.7960	30.0124	LIGHT RAIN
2009/10/29	20:55	21:00	285	9.2791	30.7141	LIGHT RAIN
2009/10/29	21:00	21:05	303	8.9986	33.6720	LIGHT RAIN
2009/10/29	21:05	21:10	294	10.4660	28.0911	RAIN
2009/10/29	21:10	21:15	330	10.5517	31.2747	LIGHT RAIN
2009/10/29	21:15	21:20	339	11.3557	29.8529	LIGHT RAIN
2009/10/29	21:20	21:25	306	9.3764	32.6352	LIGHT RAIN
2009/10/29	21:25	21:30	285	9.3308	30.5439	LIGHT RAIN
2009/10/29	21:30	21:35	309	8.7873	35.1645	LIGHT RAIN
2009/10/29	21:35	21:40	291	8.7146	33.3921	LIGHT RAIN
2009/10/29	21:40	21:45	303	10.4166	29.0883	LIGHT RAIN
2009/10/29	21:45	21:50	306	9.3714	32.6526	LIGHT RAIN
2009/10/29	21:50	21:55	261	9.6917	26.9304	LIGHT RAIN
2009/10/29	21:55	22:00	258	8.4876	30.3973	LIGHT RAIN
2009/10/29	22:00	22:05	261	8.0616	32.3757	LIGHT RAIN

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2009/10/29	22:05	22:10	255	7.7493	32.9062	LIGHT RAIN
2009/10/29	22:10	22:15	255	8.2617	30.8652	LIGHT RAIN
2009/10/29	22:15	22:20	264	8.8508	29.8279	LIGHT RAIN
2009/10/29	22:20	22:25	264	8.1934	32.2212	LIGHT RAIN
2009/10/29	22:25	22:30	213	7.1190	29.9201	LIGHT RAIN
2009/10/29	22:30	22:35	231	8.6336	26.7561	LIGHT RAIN
2009/10/29	22:35	22:40	249	7.4903	33.2428	LIGHT RAIN
2009/10/29	22:40	22:45	237	7.5710	31.3038	LIGHT RAIN
2009/10/29	22:45	22:50	222	6.5728	33.7756	LIGHT RAIN
2009/10/29	22:50	22:55	243	7.4565	32.5891	RAIN
2009/10/29	22:55	23:00	210	7.4636	28.1364	LIGHT RAIN
2009/10/29	23:00	23:05	192	5.5761	34.4330	RAIN
2009/10/29	23:05	23:10	177	6.4699	27.3575	RAIN
2009/10/29	23:10	23:15	171	5.2658	32.4739	RAIN
2009/10/29	23:15	23:20	216	5.9573	36.2580	RAIN
2009/10/29	23:20	23:25	225	6.4186	35.0544	RAIN
2009/10/29	23:25	23:30	165	4.4446	37.1240	RAIN
2009/10/29	23:30	23:35	153	4.7395	32.2821	RAIN
2009/10/29	23:35	23:40	183	5.9648	30.6799	RAIN
2009/10/29	23:40	23:45	177	5.0790	34.8493	LIGHT RAIN
2009/10/29	23:45	23:50	153	5.1040	29.9762	RAIN
2009/10/29	23:50	23:55	135	4.2118	32.0529	LIGHT RAIN
2009/10/29	23:55	0:00	141	5.3892	26.2182	RAIN

Table A - 4: Traffic Data from Detector Edens 1021S and Weather Data from KORD on Dec 04, 2009

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2009/12/4	0:00	0:05	144	5.0349	47.6671	CLEAR
2009/12/4	0:05	0:10	189	6.2238	50.6120	CLEAR
2009/12/4	0:10	0:15	111	4.1346	44.7447	CLEAR
2009/12/4	0:15	0:20	105	3.5071	49.8990	CLEAR
2009/12/4	0:20	0:25	150	5.3013	47.1582	CLEAR
2009/12/4	0:25	0:30	90	2.6392	56.8351	CLEAR
2009/12/4	0:30	0:35	99	3.0038	54.9308	CLEAR
2009/12/4	0:35	0:40	108	3.7997	47.3722	CLEAR
2009/12/4	0:40	0:45	96	2.9737	53.8047	CLEAR
2009/12/4	0:45	0:50	99	3.9251	42.0370	CLEAR
2009/12/4	0:50	0:55	93	2.8100	55.1605	CLEAR

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2009/12/4	0:55	1:00	93	6.5598	23.6289	CLEAR
2009/12/4	1:00	1:05	84	3.0590	45.7669	LIGHT SNOW
2009/12/4	1:05	1:10	66	2.1874	50.2876	LIGHT SNOW
2009/12/4	1:10	1:15	99	4.3142	38.2454	LIGHT SNOW
2009/12/4	1:15	1:20	90	2.6530	56.5393	LIGHT SNOW
2009/12/4	1:20	1:25	NA	NA	NA	LIGHT SNOW
2009/12/4	1:25	1:30	NA	NA	NA	LIGHT SNOW
2009/12/4	1:30	1:35	0	2.3889	0.0000	LIGHT SNOW
2009/12/4	1:35	1:40	93	2.6947	57.5203	LIGHT SNOW
2009/12/4	1:40	1:45	75	2.6807	46.6289	CLEAR
2009/12/4	1:45	1:50	57	2.5961	36.5929	CLEAR
2009/12/4	1:50	1:55	60	1.9120	52.3014	CLEAR
2009/12/4	1:55	2:00	60	2.1399	46.7305	CLEAR
2009/12/4	2:00	2:05	66	2.2308	49.3098	CLEAR
2009/12/4	2:05	2:10	48	1.8638	42.9232	CLEAR
2009/12/4	2:10	2:15	45	2.0497	36.5914	CLEAR
2009/12/4	2:15	2:20	39	1.1419	56.9250	CLEAR
2009/12/4	2:20	2:25	48	1.6681	47.9574	CLEAR
2009/12/4	2:25	2:30	69	2.2730	50.5949	CLEAR
2009/12/4	2:30	2:35	75	2.1968	56.9022	CLEAR
2009/12/4	2:35	2:40	54	1.6815	53.5241	CLEAR
2009/12/4	2:40	2:45	63	1.9388	54.1567	CLEAR
2009/12/4	2:45	2:50	60	3.0870	32.3940	CLEAR
2009/12/4	2:50	2:55	48	2.1435	37.3226	CLEAR
2009/12/4	2:55	3:00	42	1.8486	37.8665	CLEAR
2009/12/4	3:00	3:05	57	2.4287	39.1153	CLEAR
2009/12/4	3:05	3:10	57	2.1913	43.3529	CLEAR
2009/12/4	3:10	3:15	51	2.1371	39.7736	LIGHT SNOW
2009/12/4	3:15	3:20	51	2.2188	38.3089	LIGHT SNOW
2009/12/4	3:20	3:25	42	1.8261	38.3324	LIGHT SNOW
2009/12/4	3:25	3:30	72	2.5701	46.6910	LIGHT SNOW
2009/12/4	3:30	3:35	51	2.1325	39.8589	LIGHT SNOW
2009/12/4	3:35	3:40	57	2.0007	47.4829	LIGHT SNOW
2009/12/4	3:40	3:45	63	2.2666	46.3249	LIGHT SNOW
2009/12/4	3:45	3:50	66	2.5320	43.4432	LIGHT SNOW
2009/12/4	3:50	3:55	60	2.3619	42.3394	LIGHT SNOW
2009/12/4	3:55	4:00	42	1.7274	40.5245	LIGHT SNOW
2009/12/4	4:00	4:05	54	2.3340	38.5599	LIGHT SNOW

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2009/12/4	4:05	4:10	63	2.1179	49.5773	LIGHT SNOW
2009/12/4	4:10	4:15	72	2.1285	56.3778	LIGHT SNOW
2009/12/4	4:15	4:20	75	3.2352	38.6376	LIGHT SNOW
2009/12/4	4:20	4:25	81	2.5941	52.0409	LIGHT SNOW
2009/12/4	4:25	4:30	96	3.2573	49.1197	LIGHT SNOW
2009/12/4	4:30	4:35	81	3.3578	40.2052	LIGHT SNOW
2009/12/4	4:35	4:40	84	2.8902	48.4401	LIGHT SNOW
2009/12/4	4:40	4:45	105	4.1565	42.1028	LIGHT SNOW
2009/12/4	4:45	4:50	132	4.1347	53.2086	LIGHT SNOW
2009/12/4	4:50	4:55	111	3.1259	59.1831	LIGHT SNOW
2009/12/4	4:55	5:00	126	3.4415	61.0208	LIGHT SNOW
2009/12/4	5:00	5:05	111	3.3423	55.3515	LIGHT SNOW
2009/12/4	5:05	5:10	108	3.3183	54.2452	LIGHT SNOW
2009/12/4	5:10	5:15	126	3.5996	58.3392	LIGHT SNOW
2009/12/4	5:15	5:20	159	5.1143	51.8159	CLEAR
2009/12/4	5:20	5:25	165	4.4099	62.3590	CLEAR
2009/12/4	5:25	5:30	159	4.4921	58.9927	CLEAR
2009/12/4	5:30	5:35	222	8.1623	45.3303	CLEAR
2009/12/4	5:35	5:40	210	5.3824	65.0262	CLEAR
2009/12/4	5:40	5:45	243	6.7501	59.9989	CLEAR
2009/12/4	5:45	5:50	216	6.0353	59.6494	CLEAR
2009/12/4	5:50	5:55	264	7.3845	59.5839	CLEAR
2009/12/4	5:55	6:00	294	7.8070	62.7646	CLEAR
2009/12/4	6:00	6:05	309	8.8783	58.0068	CLEAR
2009/12/4	6:05	6:10	378	10.8904	57.8490	CLEAR
2009/12/4	6:10	6:15	405	10.1378	66.5824	CLEAR
2009/12/4	6:15	6:20	441	11.4059	64.4403	CLEAR
2009/12/4	6:20	6:25	459	13.9827	54.7105	CLEAR
2009/12/4	6:25	6:30	480	13.1145	61.0012	CLEAR
2009/12/4	6:30	6:35	468	13.0235	59.8918	CLEAR
2009/12/4	6:35	6:40	450	12.1336	61.8120	CLEAR
2009/12/4	6:40	6:45	441	13.3804	54.9311	CLEAR
2009/12/4	6:45	6:50	378	10.7536	58.5848	CLEAR
2009/12/4	6:50	6:55	399	12.1895	54.5553	CLEAR
2009/12/4	6:55	7:00	402	12.0263	55.7114	CLEAR
2009/12/4	7:00	7:05	399	9.8125	67.7706	CLEAR
2009/12/4	7:05	7:10	360	10.3868	57.7658	CLEAR
2009/12/4	7:10	7:15	390	10.5731	61.4770	CLEAR

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2009/12/4	7:15	7:20	396	10.7997	61.1128	CLEAR
2009/12/4	7:20	7:25	429	11.6271	61.4945	CLEAR
2009/12/4	7:25	7:30	450	14.5024	51.7157	CLEAR
2009/12/4	7:30	7:35	435	15.2390	47.5754	CLEAR
2009/12/4	7:35	7:40	441	11.3275	64.8866	CLEAR
2009/12/4	7:40	7:45	330	7.3894	74.4311	CLEAR
2009/12/4	7:45	7:50	324	7.8273	68.9896	CLEAR
2009/12/4	7:50	7:55	345	8.0126	71.7619	CLEAR
2009/12/4	7:55	8:00	339	11.1869	50.5055	CLEAR
2009/12/4	8:00	8:05	351	7.5668	77.3116	CLEAR
2009/12/4	8:05	8:10	357	8.2944	71.7349	CLEAR
2009/12/4	8:10	8:15	360	8.4427	71.0670	CLEAR
2009/12/4	8:15	8:20	351	9.5082	61.5261	CLEAR
2009/12/4	8:20	8:25	351	7.9899	73.2171	CLEAR
2009/12/4	8:25	8:30	NA	NA	NA	CLEAR
2009/12/4	8:30	8:35	363	8.5849	70.4729	CLEAR
2009/12/4	8:35	8:40	342	8.6931	65.5689	CLEAR
2009/12/4	8:40	8:45	324	7.9689	67.7632	CLEAR
2009/12/4	8:45	8:50	360	9.0902	66.0053	CLEAR
2009/12/4	8:50	8:55	354	8.2317	71.6738	CLEAR
2009/12/4	8:55	9:00	333	11.0333	50.3023	CLEAR
2009/12/4	9:00	9:05	345	8.1258	70.7622	CLEAR
2009/12/4	9:05	9:10	348	8.7857	66.0166	CLEAR
2009/12/4	9:10	9:15	354	8.6380	68.3030	CLEAR
2009/12/4	9:15	9:20	363	8.9879	67.3128	CLEAR
2009/12/4	9:20	9:25	387	11.5041	56.0669	CLEAR
2009/12/4	9:25	9:30	402	11.8143	56.7109	CLEAR
2009/12/4	9:30	9:35	402	10.3108	64.9802	CLEAR
2009/12/4	9:35	9:40	387	11.0790	58.2182	CLEAR
2009/12/4	9:40	9:45	363	10.7148	56.4637	CLEAR
2009/12/4	9:45	9:50	333	9.2053	60.2911	CLEAR
2009/12/4	9:50	9:55	390	12.0023	54.1563	CLEAR
2009/12/4	9:55	10:00	363	11.3331	53.3834	CLEAR
2009/12/4	10:00	10:05	333	9.8819	56.1634	CLEAR
2009/12/4	10:05	10:10	414	11.9682	57.6529	CLEAR
2009/12/4	10:10	10:15	408	13.0610	52.0636	CLEAR
2009/12/4	10:15	10:20	351	10.1747	57.4956	CLEAR
2009/12/4	10:20	10:25	417	12.4091	56.0073	CLEAR

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2009/12/4	10:25	10:30	390	11.0789	58.6700	CLEAR
2009/12/4	10:30	10:35	375	12.2999	50.8134	CLEAR
2009/12/4	10:35	10:40	450	13.0127	57.6360	CLEAR
2009/12/4	10:40	10:45	414	11.3223	60.9418	CLEAR
2009/12/4	10:45	10:50	387	11.2022	57.5782	CLEAR
2009/12/4	10:50	10:55	375	10.8360	57.6779	CLEAR
2009/12/4	10:55	11:00	333	9.6333	57.6125	CLEAR
2009/12/4	11:00	11:05	393	11.2186	58.3850	CLEAR
2009/12/4	11:05	11:10	393	12.0775	54.2332	CLEAR
2009/12/4	11:10	11:15	375	11.5912	53.9204	CLEAR
2009/12/4	11:15	11:20	366	10.5383	57.8842	CLEAR
2009/12/4	11:20	11:25	417	13.1488	52.8565	CLEAR
2009/12/4	11:25	11:30	348	10.3967	55.7867	CLEAR
2009/12/4	11:30	11:35	375	12.6847	49.2721	CLEAR
2009/12/4	11:35	11:40	345	9.3870	61.2549	CLEAR
2009/12/4	11:40	11:45	405	12.0749	55.9011	CLEAR
2009/12/4	11:45	11:50	399	11.8626	56.0587	CLEAR
2009/12/4	11:50	11:55	369	10.8288	56.7928	CLEAR
2009/12/4	11:55	12:00	390	11.3791	57.1223	CLEAR
2009/12/4	12:00	12:05	378	11.8360	53.2275	CLEAR
2009/12/4	12:05	12:10	384	11.6772	54.8076	CLEAR
2009/12/4	12:10	12:15	333	10.5017	52.8487	CLEAR
2009/12/4	12:15	12:20	384	10.9288	58.5611	CLEAR
2009/12/4	12:20	12:25	423	12.4867	56.4599	CLEAR
2009/12/4	12:25	12:30	381	11.0777	57.3223	CLEAR
2009/12/4	12:30	12:35	363	10.8555	55.7320	CLEAR
2009/12/4	12:35	12:40	393	11.0224	59.4245	CLEAR
2009/12/4	12:40	12:45	378	10.5587	59.6665	CLEAR
2009/12/4	12:45	12:50	354	10.1575	58.0849	CLEAR
2009/12/4	12:50	12:55	384	11.8223	54.1349	CLEAR
2009/12/4	12:55	13:00	342	10.2079	55.8391	CLEAR
2009/12/4	13:00	13:05	384	12.5772	50.8856	CLEAR
2009/12/4	13:05	13:10	351	10.3510	56.5163	CLEAR
2009/12/4	13:10	13:15	366	9.8259	62.0811	CLEAR
2009/12/4	13:15	13:20	369	10.3728	59.2896	CLEAR
2009/12/4	13:20	13:25	360	10.1740	58.9736	CLEAR
2009/12/4	13:25	13:30	366	12.3650	49.3327	CLEAR
2009/12/4	13:30	13:35	408	12.1895	55.7856	CLEAR

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2009/12/4	13:35	13:40	408	12.1895	55.7856	CLEAR
2009/12/4	13:40	13:45	351	9.7954	59.7222	CLEAR
2009/12/4	13:45	13:50	348	9.7916	59.2346	CLEAR
2009/12/4	13:50	13:55	387	12.2190	52.7868	CLEAR
2009/12/4	13:55	14:00	318	9.5620	55.4275	CLEAR
2009/12/4	14:00	14:05	402	10.5721	63.3741	CLEAR
2009/12/4	14:05	14:10	366	11.0164	55.3720	CLEAR
2009/12/4	14:10	14:15	369	9.8188	62.6350	CLEAR
2009/12/4	14:15	14:20	381	10.0736	63.0358	CLEAR
2009/12/4	14:20	14:25	381	12.8000	49.6093	CLEAR
2009/12/4	14:25	14:30	402	20.2867	33.0265	CLEAR
2009/12/4	14:30	14:35	354	21.6665	27.2310	CLEAR
2009/12/4	14:35	14:40	381	16.6543	38.1283	CLEAR
2009/12/4	14:40	14:45	291	20.6477	23.4893	CLEAR
2009/12/4	14:45	14:50	429	15.1134	47.3091	CLEAR
2009/12/4	14:50	14:55	312	24.8899	20.8920	CLEAR
2009/12/4	14:55	15:00	339	20.8769	27.0634	CLEAR
2009/12/4	15:00	15:05	348	17.5361	33.0747	CLEAR
2009/12/4	15:05	15:10	390	18.6842	34.7888	CLEAR
2009/12/4	15:10	15:15	336	27.4140	20.4276	CLEAR
2009/12/4	15:15	15:20	291	34.4870	14.0633	CLEAR
2009/12/4	15:20	15:25	309	20.5812	25.0228	CLEAR
2009/12/4	15:25	15:30	339	24.5549	23.0097	CLEAR
2009/12/4	15:30	15:35	351	21.9496	26.6520	CLEAR
2009/12/4	15:35	15:40	297	26.2581	18.8513	CLEAR
2009/12/4	15:40	15:45	279	39.8309	11.6744	CLEAR
2009/12/4	15:45	15:50	306	29.1901	17.4717	CLEAR
2009/12/4	15:50	15:55	324	29.2502	18.4614	CLEAR
2009/12/4	15:55	16:00	303	33.8260	14.9293	CLEAR
2009/12/4	16:00	16:05	375	23.4530	26.6490	CLEAR
2009/12/4	16:05	16:10	291	36.8397	13.1652	CLEAR
2009/12/4	16:10	16:15	330	24.5048	22.4446	CLEAR
2009/12/4	16:15	16:20	300	33.9729	14.7176	CLEAR
2009/12/4	16:20	16:25	330	31.0311	17.7241	CLEAR
2009/12/4	16:25	16:30	351	24.1713	24.2022	CLEAR
2009/12/4	16:30	16:35	333	30.2641	18.3386	CLEAR
2009/12/4	16:35	16:40	321	23.2131	23.0473	CLEAR
2009/12/4	16:40	16:45	315	27.2841	19.2420	CLEAR

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2009/12/4	16:45	16:50	303	37.3352	13.5261	LIGHT SNOW
2009/12/4	16:50	16:55	276	29.9518	15.3580	LIGHT SNOW
2009/12/4	16:55	17:00	267	39.9655	11.1346	LIGHT SNOW
2009/12/4	17:00	17:05	273	37.7224	12.0618	LIGHT SNOW
2009/12/4	17:05	17:10	375	18.5115	33.7628	LIGHT SNOW
2009/12/4	17:10	17:15	414	22.2283	31.0415	LIGHT SNOW
2009/12/4	17:15	17:20	321	30.2941	17.6602	LIGHT SNOW
2009/12/4	17:20	17:25	270	41.6196	10.8122	LIGHT SNOW
2009/12/4	17:25	17:30	351	28.4756	20.5439	CLEAR
2009/12/4	17:30	17:35	372	25.6850	24.1386	CLEAR
2009/12/4	17:35	17:40	297	37.5344	13.1879	CLEAR
2009/12/4	17:40	17:45	306	38.8563	13.1253	CLEAR
2009/12/4	17:45	17:50	354	30.6770	19.2327	CLEAR
2009/12/4	17:50	17:55	336	30.9122	18.1159	CLEAR
2009/12/4	17:55	18:00	390	21.4358	30.3231	CLEAR
2009/12/4	18:00	18:05	312	24.1187	21.5601	CLEAR
2009/12/4	18:05	18:10	291	35.9535	13.4897	CLEAR
2009/12/4	18:10	18:15	345	28.0777	20.4789	CLEAR
2009/12/4	18:15	18:20	318	31.1995	16.9874	CLEAR
2009/12/4	18:20	18:25	267	37.3130	11.9262	CLEAR
2009/12/4	18:25	18:30	339	27.7936	20.3284	CLEAR
2009/12/4	18:30	18:35	282	36.0001	13.0555	CLEAR
2009/12/4	18:35	18:40	288	29.4327	16.3084	CLEAR
2009/12/4	18:40	18:45	345	28.6404	20.0766	LIGHT SNOW
2009/12/4	18:45	18:50	273	39.0852	11.6412	LIGHT SNOW
2009/12/4	18:50	18:55	318	31.0452	17.0719	LIGHT SNOW
2009/12/4	18:55	19:00	252	38.4171	10.9326	LIGHT SNOW
2009/12/4	19:00	19:05	246	35.9453	11.4062	LIGHT SNOW
2009/12/4	19:05	19:10	273	35.1544	12.9429	LIGHT SNOW
2009/12/4	19:10	19:15	294	31.8234	15.3975	LIGHT SNOW
2009/12/4	19:15	19:20	351	21.7800	26.8595	LIGHT SNOW
2009/12/4	19:20	19:25	297	35.2539	14.0410	LIGHT SNOW
2009/12/4	19:25	19:30	294	30.1167	16.2700	LIGHT SNOW
2009/12/4	19:30	19:35	333	26.7471	20.7499	LIGHT SNOW
2009/12/4	19:35	19:40	330	31.7928	17.2995	LIGHT SNOW
2009/12/4	19:40	19:45	369	25.9693	23.6818	LIGHT SNOW
2009/12/4	19:45	19:50	291	33.0276	14.6847	LIGHT SNOW
2009/12/4	19:50	19:55	321	24.5062	21.8312	LIGHT SNOW

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2009/12/4	19:55	20:00	336	20.8080	26.9128	LIGHT SNOW
2009/12/4	20:00	20:05	336	23.4782	23.8519	LIGHT SNOW
2009/12/4	20:05	20:10	375	14.6302	42.7199	LIGHT SNOW
2009/12/4	20:10	20:15	285	8.7522	54.2721	LIGHT SNOW
2009/12/4	20:15	20:20	300	7.7861	64.2173	LIGHT SNOW
2009/12/4	20:20	20:25	309	7.7689	66.2897	LIGHT SNOW
2009/12/4	20:25	20:30	324	7.9980	67.5165	LIGHT SNOW
2009/12/4	20:30	20:35	330	10.0623	54.6593	CLEAR
2009/12/4	20:35	20:40	279	8.0006	58.1209	LIGHT SNOW
2009/12/4	20:40	20:45	312	8.4162	61.7855	LIGHT SNOW
2009/12/4	20:45	20:50	258	7.4301	57.8726	LIGHT SNOW
2009/12/4	20:50	20:55	303	7.9723	63.3440	LIGHT SNOW
2009/12/4	20:55	21:00	273	6.7440	67.4674	LIGHT SNOW
2009/12/4	21:00	21:05	333	8.7138	63.6918	LIGHT SNOW
2009/12/4	21:05	21:10	267	6.8693	64.7809	LIGHT SNOW
2009/12/4	21:10	21:15	291	7.3211	66.2471	LIGHT SNOW
2009/12/4	21:15	21:20	306	8.6683	58.8350	LIGHT SNOW
2009/12/4	21:20	21:25	288	8.2197	58.3960	LIGHT SNOW
2009/12/4	21:25	21:30	327	7.8297	69.6065	LIGHT SNOW
2009/12/4	21:30	21:35	309	7.9677	64.6363	LIGHT SNOW
2009/12/4	21:35	21:40	324	7.6162	70.9014	LIGHT SNOW
2009/12/4	21:40	21:45	285	7.6627	61.9888	LIGHT SNOW
2009/12/4	21:45	21:50	312	9.2238	56.3760	LIGHT SNOW
2009/12/4	21:50	21:55	288	7.5809	63.3169	CLEAR
2009/12/4	21:55	22:00	270	7.1549	62.8943	CLEAR
2009/12/4	22:00	22:05	312	8.1410	63.8741	CLEAR
2009/12/4	22:05	22:10	279	7.0666	65.8028	CLEAR
2009/12/4	22:10	22:15	333	8.5179	65.1571	CLEAR
2009/12/4	22:15	22:20	294	7.3112	67.0201	CLEAR
2009/12/4	22:20	22:25	351	10.6159	55.1059	CLEAR
2009/12/4	22:25	22:30	279	7.6129	61.0809	CLEAR
2009/12/4	22:30	22:35	303	8.2563	61.1657	CLEAR
2009/12/4	22:35	22:40	297	7.9126	62.5587	CLEAR
2009/12/4	22:40	22:45	267	7.5627	58.8415	CLEAR
2009/12/4	22:45	22:50	309	8.5473	60.2526	CLEAR
2009/12/4	22:50	22:55	303	7.3922	68.3149	CLEAR
2009/12/4	22:55	23:00	231	6.2371	61.7278	CLEAR
2009/12/4	23:00	23:05	225	6.9583	53.8928	CLEAR

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2009/12/4	23:05	23:10	243	6.7008	60.4404	CLEAR
2009/12/4	23:10	23:15	246	7.4468	55.0570	CLEAR
2009/12/4	23:15	23:20	297	6.8086	72.7021	CLEAR
2009/12/4	23:20	23:25	234	6.0724	64.2253	CLEAR
2009/12/4	23:25	23:30	243	6.4730	62.5673	CLEAR
2009/12/4	23:30	23:35	201	5.8610	57.1579	LIGHT SNOW
2009/12/4	23:35	23:40	228	5.5747	68.1648	LIGHT SNOW
2009/12/4	23:40	23:45	216	5.0684	71.0276	LIGHT SNOW
2009/12/4	23:45	23:50	228	5.2670	72.1470	LIGHT SNOW
2009/12/4	23:50	23:55	198	5.4406	60.6549	LIGHT SNOW
2009/12/4	23:55	0:00	186	4.9396	62.7584	LIGHT SNOW

Table A - 5: Traffic Data from Detector Edens 1021S and Weather Data from KORD on Feb 18, 2009

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2/18/2009	0:00	0:05	54	4.35656	62.04	LIGHT RAIN
2/18/2009	0:05	0:10	81	4.77412	72.0095	LIGHT RAIN
2/18/2009	0:10	0:15	84	6.56055	58.8342	LIGHT RAIN
2/18/2009	0:15	0:20	75	4.45168	72.4335	LIGHT RAIN
2/18/2009	0:20	0:25	66	3.52392	77.0607	LIGHT RAIN
2/18/2009	0:25	0:30	66	4.90901	61.0553	LIGHT RAIN
2/18/2009	0:30	0:35	69	4.67719	65.0659	LIGHT RAIN
2/18/2009	0:35	0:40	48	3.81435	53.7006	LIGHT RAIN
2/18/2009	0:40	0:45	48	3.63405	61.6468	LIGHT RAIN
2/18/2009	0:45	0:50	36	2.63563	60.1348	LIGHT RAIN
2/18/2009	0:50	0:55	48	3.87919	56.9245	LIGHT RAIN
2/18/2009	0:55	1:00	42	2.77882	69.815	LIGHT RAIN
2/18/2009	1:00	1:05	57	3.73944	63.4013	LIGHT RAIN
2/18/2009	1:05	1:10	42	3.99532	48.9712	LIGHT RAIN
2/18/2009	1:10	1:15	45	3.2393	62.8065	LIGHT RAIN
2/18/2009	1:15	1:20	54	3.50605	63.0873	LIGHT RAIN
2/18/2009	1:20	1:25	60	4.39353	55.9884	LIGHT RAIN
2/18/2009	1:25	1:30	24	1.56279	75.9525	LIGHT RAIN
2/18/2009	1:30	1:35	18	1.23776	69.4245	LIGHT RAIN
2/18/2009	1:35	1:40	39	2.48105	72.7334	LIGHT RAIN
2/18/2009	1:40	1:45	39	3.30463	51.5525	LIGHT RAIN

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2/18/2009	1:45	1:50	51	3.69756	61.4393	LIGHT RAIN
2/18/2009	1:50	1:55	33	2.29187	65.8766	LIGHT RAIN
2/18/2009	1:55	2:00	21	1.48832	61.7271	LIGHT RAIN
2/18/2009	2:00	2:05	33	2.14352	67.0743	LIGHT RAIN
2/18/2009	2:05	2:10	63	3.52323	71.9165	LIGHT RAIN
2/18/2009	2:10	2:15	18	1.03152	77.7564	LIGHT RAIN
2/18/2009	2:15	2:20	0	2.8476	65.0285	LIGHT RAIN
2/18/2009	2:20	2:25	30	2.93543	46.7373	LIGHT RAIN
2/18/2009	2:25	2:30	33	2.81417	59.1237	LIGHT RAIN
2/18/2009	2:30	2:35	24	2.63877	39.714	LIGHT RAIN
2/18/2009	2:35	2:40	27	2.22724	63.6574	LIGHT RAIN
2/18/2009	2:40	2:45	42	4.65373	46.8339	LIGHT RAIN
2/18/2009	2:45	2:50	39	3.48714	50.7073	LIGHT RAIN
2/18/2009	2:50	2:55	24	2.33582	46.7487	LIGHT RAIN
2/18/2009	2:55	3:00	21	1.68572	53.2512	LIGHT RAIN
2/18/2009	3:00	3:05	45	2.74159	63.66	CLEAR
2/18/2009	3:05	3:10	39	3.24647	52.5153	CLEAR
2/18/2009	3:10	3:15	33	2.00731	74.6127	CLEAR
2/18/2009	3:15	3:20	33	3.57415	40.9262	CLEAR
2/18/2009	3:20	3:25	27	3.84331	24.4607	CLEAR
2/18/2009	3:25	3:30	42	4.37966	44.8403	CLEAR
2/18/2009	3:30	3:35	30	2.79981	45.9632	CLEAR
2/18/2009	3:35	3:40	54	4.17747	59.3477	CLEAR
2/18/2009	3:40	3:45	39	3.64613	65.3596	CLEAR
2/18/2009	3:45	3:50	48	3.61704	60.3479	CLEAR
2/18/2009	3:50	3:55	42	3.53169	53.933	CLEAR
2/18/2009	3:55	4:00	30	2.39985	55.5432	CLEAR
2/18/2009	4:00	4:05	45	4.04502	47.6368	LIGHT RAIN
2/18/2009	4:05	4:10	57	4.39899	61.2091	LIGHT RAIN
2/18/2009	4:10	4:15	51	4.07306	55.8675	LIGHT RAIN
2/18/2009	4:15	4:20	69	5.13149	66.0057	LIGHT RAIN
2/18/2009	4:20	4:25	57	3.20952	73.445	LIGHT RAIN
2/18/2009	4:25	4:30	90	5.45185	71.5896	LIGHT RAIN
2/18/2009	4:30	4:35	96	4.40321	79.9633	LIGHT RAIN
2/18/2009	4:35	4:40	96	6.86609	61.6037	LIGHT RAIN

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2/18/2009	4:40	4:45	96	5.2772	72.5897	LIGHT RAIN
2/18/2009	4:45	4:50	114	6.44999	74.792	LIGHT RAIN
2/18/2009	4:50	4:55	150	7.8338	71.5891	LIGHT RAIN
2/18/2009	4:55	5:00	120	6.74941	70.6785	LIGHT RAIN
2/18/2009	5:00	5:05	147	8.13932	69.7562	LIGHT RAIN
2/18/2009	5:05	5:10	171	10.5736	63.2711	LIGHT RAIN
2/18/2009	5:10	5:15	213	9.23797	82.3994	LIGHT RAIN
2/18/2009	5:15	5:20	210	11.7762	65.6231	LIGHT RAIN
2/18/2009	5:20	5:25	219	11.3332	71.4994	LIGHT RAIN
2/18/2009	5:25	5:30	225	11.6712	68.5418	LIGHT RAIN
2/18/2009	5:30	5:35	228	9.7631	80.326	LIGHT RAIN
2/18/2009	5:35	5:40	270	11.4529	81.746	LIGHT RAIN
2/18/2009	5:40	5:45	276	12.9674	75.2466	LIGHT RAIN
2/18/2009	5:45	5:50	276	14.0833	69.7958	LIGHT RAIN
2/18/2009	5:50	5:55	339	15.7429	73.3375	LIGHT RAIN
2/18/2009	5:55	6:00	324	16.4938	67.9999	LIGHT RAIN
2/18/2009	6:00	6:05	381	19.3557	69.51	LIGHT RAIN
2/18/2009	6:05	6:10	393	19.4583	71.6159	LIGHT RAIN
2/18/2009	6:10	6:15	387	17.8592	73.4906	LIGHT RAIN
2/18/2009	6:15	6:20	426	21.5331	67.4434	LIGHT RAIN
2/18/2009	6:20	6:25	393	20.7487	65.3896	LIGHT RAIN
2/18/2009	6:25	6:30	429	21.649	67.9318	LIGHT RAIN
2/18/2009	6:30	6:35	342	17.0521	68.8255	LIGHT RAIN
2/18/2009	6:35	6:40	387	19.9817	65.8776	LIGHT RAIN
2/18/2009	6:40	6:45	324	14.8459	73.8896	LIGHT RAIN
2/18/2009	6:45	6:50	408	19.9116	69.6737	LIGHT RAIN
2/18/2009	6:50	6:55	426	23.0565	62.4852	LIGHT RAIN
2/18/2009	6:55	7:00	411	19.9599	70.8564	LIGHT RAIN
2/18/2009	7:00	7:05	414	19.7922	71.2051	LIGHT RAIN
2/18/2009	7:05	7:10	402	19.8735	68.3886	LIGHT RAIN
2/18/2009	7:10	7:15	411	19.3649	71.3401	LIGHT RAIN
2/18/2009	7:15	7:20	396	19.2913	68.9751	LIGHT RAIN
2/18/2009	7:20	7:25	405	20.8529	66.7633	LIGHT RAIN
2/18/2009	7:25	7:30	408	20.0115	68.8875	LIGHT RAIN
2/18/2009	7:30	7:35	432	21.562	67.5474	LIGHT RAIN

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2/18/2009	7:35	7:40	384	17.1454	74.8566	LIGHT RAIN
2/18/2009	7:40	7:45	405	20.5486	66.8959	LIGHT RAIN
2/18/2009	7:45	7:50	372	17.8225	71.9894	LIGHT RAIN
2/18/2009	7:50	7:55	381	16.3521	77.7793	LIGHT RAIN
2/18/2009	7:55	8:00	354	16.5273	73.2891	LIGHT RAIN
2/18/2009	8:00	8:05	420	19.7083	71.9441	LIGHT RAIN
2/18/2009	8:05	8:10	366	18.1065	69.9271	LIGHT RAIN
2/18/2009	8:10	8:15	357	15.6045	76.4688	LIGHT RAIN
2/18/2009	8:15	8:20	363	19.7059	65.6703	LIGHT RAIN
2/18/2009	8:20	8:25	363	17.8976	69.7262	LIGHT RAIN
2/18/2009	8:25	8:30	369	17.7441	72.3671	CLEAR
2/18/2009	8:30	8:35	399	20.0327	68.1392	CLEAR
2/18/2009	8:35	8:40	372	15.8795	78.5585	CLEAR
2/18/2009	8:40	8:45	381	21.306	62.7863	CLEAR
2/18/2009	8:45	8:50	387	19.8486	67.7699	CLEAR
2/18/2009	8:50	8:55	378	20.4911	64.9687	CLEAR
2/18/2009	8:55	9:00	366	19.8319	63.9953	CLEAR
2/18/2009	9:00	9:05	336	17.8151	66.2458	CLEAR
2/18/2009	9:05	9:10	351	18.9266	65.423	CLEAR
2/18/2009	9:10	9:15	348	17.5931	67.9067	CLEAR
2/18/2009	9:15	9:20	357	18.0058	69.5324	CLEAR
2/18/2009	9:20	9:25	366	17.2443	73.7982	CLEAR
2/18/2009	9:25	9:30	357	19.4783	64.1462	CLEAR
2/18/2009	9:30	9:35	351	18.5875	66.1881	CLEAR
2/18/2009	9:35	9:40	366	18.6475	70.0231	CLEAR
2/18/2009	9:40	9:45	360	18.8569	66.8439	CLEAR
2/18/2009	9:45	9:50	306	15.9856	66.9363	CLEAR
2/18/2009	9:50	9:55	342	16.9846	71.7428	CLEAR
2/18/2009	9:55	10:00	297	15.9132	66.1292	CLEAR
2/18/2009	10:00	10:05	294	19.4037	54.1559	CLEAR
2/18/2009	10:05	10:10	312	17.0164	68.3496	CLEAR
2/18/2009	10:10	10:15	321	14.8786	74.1548	CLEAR
2/18/2009	10:15	10:20	312	15.1881	74.518	CLEAR
2/18/2009	10:20	10:25	336	19.4431	67.2002	CLEAR
2/18/2009	10:25	10:30	351	19.8402	61.971	CLEAR

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2/18/2009	10:30	10:35	318	15.1122	74.5715	CLEAR
2/18/2009	10:35	10:40	288	19.2953	56.242	CLEAR
2/18/2009	10:40	10:45	345	18.5978	66.693	CLEAR
2/18/2009	10:45	10:50	312	15.3067	74.2663	CLEAR
2/18/2009	10:50	10:55	303	15.9371	65.9731	CLEAR
2/18/2009	10:55	11:00	303	17.3374	67.3835	CLEAR
2/18/2009	11:00	11:05	354	20.6505	62.1319	CLEAR
2/18/2009	11:05	11:10	282	14.5309	69.3472	CLEAR
2/18/2009	11:10	11:15	282	18.0809	58.2057	CLEAR
2/18/2009	11:15	11:20	297	14.1778	73.2403	CLEAR
2/18/2009	11:20	11:25	330	15.9134	73.6953	CLEAR
2/18/2009	11:25	11:30	330	17.5912	70.9343	CLEAR
2/18/2009	11:30	11:35	333	15.1715	76.2701	CLEAR
2/18/2009	11:35	11:40	327	16.6275	70.6126	CLEAR
2/18/2009	11:40	11:45	270	15.2712	64.6425	CLEAR
2/18/2009	11:45	11:50	318	18.9477	61.776	CLEAR
2/18/2009	11:50	11:55	291	15.0447	71.1958	CLEAR
2/18/2009	11:55	12:00	345	21.0587	59.398	CLEAR
2/18/2009	12:00	12:05	321	17.7912	65.7129	CLEAR
2/18/2009	12:05	12:10	300	18.4573	60.6581	CLEAR
2/18/2009	12:10	12:15	300	18.4573	60.6581	CLEAR
2/18/2009	12:15	12:20	300	15.3016	70.2017	CLEAR
2/18/2009	12:20	12:25	288	15.8562	67.3857	CLEAR
2/18/2009	12:25	12:30	330	16.1592	71.1426	CLEAR
2/18/2009	12:30	12:35	321	20.2001	56.7192	CLEAR
2/18/2009	12:35	12:40	330	15.4348	75.165	CLEAR
2/18/2009	12:40	12:45	324	19.1686	60.7797	CLEAR
2/18/2009	12:45	12:50	300	16.9975	65.1945	CLEAR
2/18/2009	12:50	12:55	279	14.2346	71.0588	CLEAR
2/18/2009	12:55	13:00	312	19.3613	57.7657	CLEAR
2/18/2009	13:00	13:05	324	15.7962	70.848	CLEAR
2/18/2009	13:05	13:10	351	19.5344	68.1607	CLEAR
2/18/2009	13:10	13:15	318	15.4861	72.0442	CLEAR
2/18/2009	13:15	13:20	279	15.6743	64.4784	CLEAR
2/18/2009	13:20	13:25	309	15.7749	73.0008	CLEAR

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2/18/2009	13:25	13:30	312	15.8364	70.3577	CLEAR
2/18/2009	13:30	13:35	378	22.6751	64.4691	CLEAR
2/18/2009	13:35	13:40	309	15.2861	70.286	CLEAR
2/18/2009	13:40	13:45	354	17.9204	70.233	CLEAR
2/18/2009	13:45	13:50	303	16.9375	65.4841	CLEAR
2/18/2009	13:50	13:55	327	19.1835	60.869	CLEAR
2/18/2009	13:55	14:00	345	17.6627	70.0058	CLEAR
2/18/2009	14:00	14:05	339	21.0205	59.3154	CLEAR
2/18/2009	14:05	14:10	330	17.8375	67.9451	CLEAR
2/18/2009	14:10	14:15	369	22.3644	61.059	CLEAR
2/18/2009	14:15	14:20	318	16.3203	68.6499	CLEAR
2/18/2009	14:20	14:25	393	19.5237	72.5103	CLEAR
2/18/2009	14:25	14:30	384	18.7419	72.9269	CLEAR
2/18/2009	14:30	14:35	348	18.5175	67.4753	CLEAR
2/18/2009	14:35	14:40	441	26.3257	60.1235	CLEAR
2/18/2009	14:40	14:45	420	20.8449	71.8254	CLEAR
2/18/2009	14:45	14:50	414	21.6546	67.4124	LIGHT SNOW
2/18/2009	14:50	14:55	465	23.3152	68.9429	LIGHT SNOW
2/18/2009	14:55	15:00	408	22.0423	65.1489	LIGHT SNOW
2/18/2009	15:00	15:05	483	25.2306	66.7472	LIGHT SNOW
2/18/2009	15:05	15:10	417	20.6584	70.0218	LIGHT SNOW
2/18/2009	15:10	15:15	489	25.0537	68.0639	LIGHT SNOW
2/18/2009	15:15	15:20	465	22.0603	71.2374	LIGHT SNOW
2/18/2009	15:20	15:25	519	22.4105	77.9736	LIGHT SNOW
2/18/2009	15:25	15:30	420	18.952	74.695	LIGHT SNOW
2/18/2009	15:30	15:35	441	21.4118	70.7297	LIGHT SNOW
2/18/2009	15:35	15:40	531	30.2814	61.6775	LIGHT SNOW
2/18/2009	15:40	15:45	441	20.1435	74.412	LIGHT SNOW
2/18/2009	15:45	15:50	471	24.084	66.8532	LIGHT SNOW
2/18/2009	15:50	15:55	399	19.66	69.5219	LIGHT SNOW
2/18/2009	15:55	16:00	438	20.9208	72.0584	LIGHT SNOW
2/18/2009	16:00	16:05	441	20.8998	71.6657	LIGHT SNOW
2/18/2009	16:05	16:10	411	18.5503	75.083	LIGHT SNOW
2/18/2009	16:10	16:15	381	19.3463	68.6494	LIGHT SNOW
2/18/2009	16:15	16:20	426	21.4207	68.4358	LIGHT SNOW

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2/18/2009	16:20	16:25	411	19.1266	72.6324	LIGHT SNOW
2/18/2009	16:25	16:30	444	22.331	68.4752	LIGHT SNOW
2/18/2009	16:30	16:35	432	24.7701	60.8039	LIGHT SNOW
2/18/2009	16:35	16:40	459	23.385	67.5741	LIGHT SNOW
2/18/2009	16:40	16:45	378	19.0132	68.3242	LIGHT SNOW
2/18/2009	16:45	16:50	438	20.5998	71.5768	LIGHT SNOW
2/18/2009	16:50	16:55	372	18.2899	69.4975	LIGHT SNOW
2/18/2009	16:55	17:00	342	39.2676	39.7316	LIGHT SNOW
2/18/2009	17:00	17:05	303	62.0824	17.4581	LIGHT SNOW
2/18/2009	17:05	17:10	402	50.417	27.2492	LIGHT SNOW
2/18/2009	17:10	17:15	387	42.0078	32.4018	LIGHT SNOW
2/18/2009	17:15	17:20	384	44.9819	30.2599	LIGHT SNOW
2/18/2009	17:20	17:25	387	27.0823	53.168	LIGHT SNOW
2/18/2009	17:25	17:30	390	21.648	61.0791	LIGHT SNOW
2/18/2009	17:30	17:35	312	15.7333	68.2642	LIGHT SNOW
2/18/2009	17:35	17:40	327	18.2013	62.7593	LIGHT SNOW
2/18/2009	17:40	17:45	363	19.8687	63.4206	LIGHT SNOW
2/18/2009	17:45	17:50	354	19.3168	62.2019	LIGHT SNOW
2/18/2009	17:50	17:55	324	20.7656	54.5516	LIGHT SNOW
2/18/2009	17:55	18:00	321	18.3667	59.3829	LIGHT SNOW
2/18/2009	18:00	18:05	324	19.4315	58.0594	LIGHT SNOW
2/18/2009	18:05	18:10	297	20.3822	50.681	LIGHT SNOW
2/18/2009	18:10	18:15	297	22.3789	46.8779	LIGHT SNOW
2/18/2009	18:15	18:20	270	21.2113	44.9662	LIGHT SNOW
2/18/2009	18:20	18:25	297	26.5085	39.585	LIGHT SNOW
2/18/2009	18:25	18:30	255	18.4394	50.0994	LIGHT SNOW
2/18/2009	18:30	18:35	285	18.6851	52.8519	LIGHT SNOW
2/18/2009	18:35	18:40	285	20.4566	49.807	LIGHT SNOW
2/18/2009	18:40	18:45	270	21.343	45.8341	LIGHT SNOW
2/18/2009	18:45	18:50	294	21.1675	48.3858	LIGHT SNOW
2/18/2009	18:50	18:55	285	18.9102	52.6787	LIGHT SNOW
2/18/2009	18:55	19:00	273	19.6768	49.9999	LIGHT SNOW
2/18/2009	19:00	19:05	252	18.1963	50.0912	LIGHT SNOW
2/18/2009	19:05	19:10	243	17.0586	51.9376	LIGHT SNOW
2/18/2009	19:10	19:15	219	14.1733	53.1793	LIGHT SNOW

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2/18/2009	19:15	19:20	282	20.2317	50.4639	LIGHT SNOW
2/18/2009	19:20	19:25	189	13.6381	51.4115	LIGHT SNOW
2/18/2009	19:25	19:30	249	21.0231	44.5097	LIGHT SNOW
2/18/2009	19:30	19:35	237	17.872	49.3073	LIGHT SNOW
2/18/2009	19:35	19:40	228	17.0263	48.6336	LIGHT SNOW
2/18/2009	19:40	19:45	234	15.0136	55.0226	LIGHT SNOW
2/18/2009	19:45	19:50	240	18.4158	49.0005	LIGHT SNOW
2/18/2009	19:50	19:55	258	22.5177	42.9958	LIGHT SNOW
2/18/2009	19:55	20:00	198	15.724	48.0146	LIGHT SNOW
2/18/2009	20:00	20:05	189	13.5689	53.1092	LIGHT SNOW
2/18/2009	20:05	20:10	195	14.8683	48.7331	LIGHT SNOW
2/18/2009	20:10	20:15	240	15.6049	55.5893	LIGHT SNOW
2/18/2009	20:15	20:20	219	18.7539	44.1447	LIGHT SNOW
2/18/2009	20:20	20:25	216	17.9025	46.2154	LIGHT SNOW
2/18/2009	20:25	20:30	207	11.9152	61.9297	LIGHT SNOW
2/18/2009	20:30	20:35	234	14.6808	61.9111	LIGHT SNOW
2/18/2009	20:35	20:40	258	23.4856	45.0118	LIGHT SNOW
2/18/2009	20:40	20:45	258	16.3086	56.9305	LIGHT SNOW
2/18/2009	20:45	20:50	180	12.306	52.9406	LIGHT SNOW
2/18/2009	20:50	20:55	198	15.2138	49.3431	LIGHT SNOW
2/18/2009	20:55	21:00	243	16.8243	54.108	LIGHT SNOW
2/18/2009	21:00	21:05	195	9.739	67.9954	LIGHT SNOW
2/18/2009	21:05	21:10	192	11.918	62.435	LIGHT SNOW
2/18/2009	21:10	21:15	246	13.4141	64.5298	LIGHT SNOW
2/18/2009	21:15	21:20	192	13.5062	54.5379	LIGHT SNOW
2/18/2009	21:20	21:25	195	13.8371	53.2868	LIGHT SNOW
2/18/2009	21:25	21:30	222	14.5397	56.8641	LIGHT SNOW
2/18/2009	21:30	21:35	168	12.3215	52.1841	LIGHT SNOW
2/18/2009	21:35	21:40	207	15.9121	47.0371	LIGHT SNOW
2/18/2009	21:40	21:45	207	13.7059	55.7645	LIGHT SNOW
2/18/2009	21:45	21:50	171	10.2178	62.6062	LIGHT SNOW
2/18/2009	21:50	21:55	216	13.9855	57.5585	LIGHT SNOW
2/18/2009	21:55	22:00	162	13.3913	51.6873	LIGHT SNOW
2/18/2009	22:00	22:05	180	11.393	59.2586	LIGHT SNOW
2/18/2009	22:05	22:10	171	9.84978	65.9215	LIGHT SNOW

	Start Time	End Time	Volume	Occupancy	Speed	Weather Conditions
2/18/2009	22:10	22:15	129	8.08511	60.5734	LIGHT SNOW
2/18/2009	22:15	22:20	165	11.7782	56.4696	LIGHT SNOW
2/18/2009	22:20	22:25	135	11.1893	50.0433	LIGHT SNOW
2/18/2009	22:25	22:30	132	8.63171	66.0279	LIGHT SNOW
2/18/2009	22:30	22:35	165	9.51303	64.2792	LIGHT SNOW
2/18/2009	22:35	22:40	174	12.5924	52.5027	LIGHT SNOW
2/18/2009	22:40	22:45	141	9.99288	56.7888	LIGHT SNOW
2/18/2009	22:45	22:50	135	9.98188	58.8824	LIGHT SNOW
2/18/2009	22:50	22:55	102	5.20334	73.4024	LIGHT SNOW
2/18/2009	22:55	23:00	111	7.08875	64.6991	LIGHT SNOW
2/18/2009	23:00	23:05	117	8.48777	53.7175	LIGHT SNOW
2/18/2009	23:05	23:10	111	7.49688	63.8183	LIGHT SNOW
2/18/2009	23:10	23:15	105	5.84012	70.0639	LIGHT SNOW
2/18/2009	23:15	23:20	105	6.59214	61.0901	LIGHT SNOW
2/18/2009	23:20	23:25	125	6.4186	35.0544	LIGHT SNOW
2/18/2009	23:25	23:30	165	4.4446	37.124	LIGHT SNOW
2/18/2009	23:30	23:35	153	4.7395	32.2821	LIGHT SNOW
2/18/2009	23:35	23:40	183	5.9648	30.6799	LIGHT SNOW
2/18/2009	23:40	23:45	177	5.079	34.8493	LIGHT SNOW
2/18/2009	23:45	23:50	153	5.104	29.9762	LIGHT SNOW
2/18/2009	23:50	23:55	135	4.2118	32.0529	LIGHT SNOW
2/18/2009	23:55	0:00	141	5.3892	26.2182	LIGHT SNOW

Table A - 6: Scenario Look-up Table for Filtered Traffic Data

Date	ID	Date	ID	Date	ID	Date	ID
2009/1/1	1	2009/2/1	32	2009/3/1	57	2009/4/1	84
2009/1/2	2	2009/2/2	33	2009/3/2	58	2009/4/2	85
2009/1/3	3	2009/2/3	34	2009/3/3	59	2009/4/3	86
2009/1/4	4	2009/2/6	35	2009/3/4	60	2009/4/4	87
2009/1/5	5	2009/2/7	36	2009/3/5	61	2009/4/5	88
2009/1/6	6	2009/2/8	37	2009/3/6	62	2009/4/6	89
2009/1/7	7	2009/2/9	38	2009/3/7	63	2009/4/7	90
2009/1/8	8	2009/2/10	39	2009/3/8	64	2009/4/9	91
2009/1/9	9	2009/2/11	40	2009/3/9	65	2009/4/10	92
2009/1/10	10	2009/2/12	41	2009/3/10	66	2009/4/11	93
2009/1/11	11	2009/2/13	42	2009/3/11	67	2009/4/12	94

Date	ID	Date	ID	Date	ID	Date	ID
2009/1/12	12	2009/2/14	43	2009/3/12	68	2009/4/13	95
2009/1/13	13	2009/2/15	44	2009/3/13	69	2009/4/14	96
2009/1/14	14	2009/2/16	45	2009/3/14	70	2009/4/15	97
2009/1/15	15	2009/2/17	46	2009/3/15	71	2009/4/16	98
2009/1/16	16	2009/2/18	47	2009/3/16	72	2009/4/17	99
2009/1/17	17	2009/2/19	48	2009/3/17	73	2009/4/18	100
2009/1/18	18	2009/2/20	49	2009/3/18	74	2009/4/19	101
2009/1/19	19	2009/2/22	50	2009/3/20	75	2009/4/20	102
2009/1/20	20	2009/2/23	51	2009/3/21	76	2009/4/21	103
2009/1/21	21	2009/2/24	52	2009/3/22	77	2009/4/22	104
2009/1/22	22	2009/2/25	53	2009/3/23	78	2009/4/23	105
2009/1/23	23	2009/2/26	54	2009/3/24	79	2009/4/24	106
2009/1/24	24	2009/2/27	55	2009/3/28	80	2009/4/25	107
2009/1/25	25	2009/2/28	56	2009/3/29	81	2009/4/26	108
2009/1/26	26			2009/3/30	82	2009/4/27	109
2009/1/27	27			2009/3/31	83	2009/4/28	110
2009/1/28	28					2009/4/29	111
2009/1/29	29					2009/4/30	112
2009/1/30	30						
2009/1/31	31						
2009/5/1	113	2009/6/1	139	2009/7/1	165	2009/8/1	189
2009/5/2	114	2009/6/2	140	2009/7/3	166	2009/8/2	190
2009/5/3	115	2009/6/3	141	2009/7/4	167	2009/8/3	191
2009/5/4	116	2009/6/4	142	2009/7/6	168	2009/8/4	192
2009/5/5	117	2009/6/5	143	2009/7/9	169	2009/8/5	193
2009/5/6	118	2009/6/6	144	2009/7/11	170	2009/8/6	194
2009/5/7	119	2009/6/8	145	2009/7/12	171	2009/8/7	195
2009/5/8	120	2009/6/9	146	2009/7/13	172	2009/8/11	196
2009/5/9	121	2009/6/10	147	2009/7/15	173	2009/8/12	197
2009/5/10	122	2009/6/11	148	2009/7/16	174	2009/8/13	198
2009/5/11	123	2009/6/12	149	2009/7/17	175	2009/8/15	199
2009/5/12	124	2009/6/13	150	2009/7/18	176	2009/8/16	200
2009/5/13	125	2009/6/14	151	2009/7/19	177	2009/8/17	201
2009/5/14	126	2009/6/15	152	2009/7/20	178	2009/8/18	202
2009/5/15	127	2009/6/16	153	2009/7/22	179	2009/8/20	203
2009/5/16	128	2009/6/17	154	2009/7/23	180	2009/8/22	204
2009/5/17	129	2009/6/18	155	2009/7/24	181	2009/8/23	205

Date	ID	Date	ID	Date	ID	Date	ID
2009/5/18	130	2009/6/22	156	2009/7/25	182	2009/8/24	206
2009/5/19	131	2009/6/23	157	2009/7/26	183	2009/8/25	207
2009/5/20	132	2009/6/24	158	2009/7/27	184	2009/8/26	208
2009/5/21	133	2009/6/25	159	2009/7/28	185	2009/8/27	209
2009/5/27	134	2009/6/26	160	2009/7/29	186	2009/8/28	210
2009/5/28	135	2009/6/27	161	2009/7/30	187	2009/8/29	211
2009/5/29	136	2009/6/28	162	2009/7/31	188	2009/8/30	212
2009/5/30	137	2009/6/29	163			2009/8/31	213
2009/5/31	138	2009/6/30	164				
2009/9/1	214	2009/10/1	239	2009/11/1	265	2009/12/2	292
2009/9/2	215	2009/10/2	240	2009/11/2	266	2009/12/3	293
2009/9/3	216	2009/10/3	241	2009/11/3	267	2009/12/4	294
2009/9/4	217	2009/10/5	242	2009/11/4	268	2009/12/5	295
2009/9/6	218	2009/10/6	243	2009/11/5	269	2009/12/6	296
2009/9/7	219	2009/10/7	244	2009/11/6	270	2009/12/7	297
2009/9/8	220	2009/10/8	245	2009/11/7	271	2009/12/8	298
2009/9/9	221	2009/10/9	246	2009/11/8	272	2009/12/9	299
2009/9/10	222	2009/10/10	247	2009/11/9	273	2009/12/10	300
2009/9/11	223	2009/10/11	248	2009/11/10	274	2009/12/11	301
2009/9/12	224	2009/10/12	249	2009/11/11	275	2009/12/12	302
2009/9/13	225	2009/10/13	250	2009/11/12	276	2009/12/13	303
2009/9/14	226	2009/10/14	251	2009/11/13	277	2009/12/14	304
2009/9/15	227	2009/10/15	252	2009/11/14	278	2009/12/15	305
2009/9/16	228	2009/10/16	253	2009/11/15	279	2009/12/16	306
2009/9/17	229	2009/10/17	254	2009/11/16	280	2009/12/17	307
2009/9/21	230	2009/10/19	255	2009/11/17	281	2009/12/18	308
2009/9/22	231	2009/10/20	256	2009/11/18	282	2009/12/19	309
2009/9/23	232	2009/10/23	257	2009/11/19	283	2009/12/20	310
2009/9/24	233	2009/10/24	258	2009/11/20	284	2009/12/21	311
2009/9/25	234	2009/10/26	259	2009/11/21	285	2009/12/22	312
2009/9/26	235	2009/10/27	260	2009/11/22	286	2009/12/23	313
2009/9/27	236	2009/10/28	261	2009/11/24	287	2009/12/24	314
2009/9/29	237	2009/10/29	262	2009/11/26	288	2009/12/25	315
2009/9/30	238	2009/10/30	263	2009/11/28	289	2009/12/26	316
		2009/10/31	264	2009/11/29	290	2009/12/27	317
				2009/11/30	291	2009/12/28	318
						2009/12/29	319

Date	ID	Date	ID	Date	ID	Date	ID
						2009/12/30	320
						2009/12/31	321

Table A - 7: Scenario Look-up Table for Filtered Unclear Weather Data

Date	ID	Date	ID	Date	ID	Date	ID
2009/1/3	1	2009/4/2	47	2009/7/1	94	2009/10/16	140
2009/1/4	2	2009/4/3	48	2009/7/4	95	2009/10/17	141
2009/1/6	3	2009/4/5	49	2009/7/5	96	2009/10/20	142
2009/1/7	4	2009/4/6	50	2009/7/7	97	2009/10/21	143
2009/1/8	5	2009/4/13	51	2009/7/8	98	2009/10/22	144
2009/1/9	6	2009/4/14	52	2009/7/10	99	2009/10/23	145
2009/1/10	7	2009/4/18	53	2009/7/11	100	2009/10/24	146
2009/1/11	8	2009/4/19	54	2009/7/15	101	2009/10/25	147
2009/1/12	9	2009/4/20	55	2009/7/16	102	2009/10/26	148
2009/1/13	10	2009/4/21	56	2009/7/21	103	2009/10/27	149
2009/1/14	11	2009/4/23	57	2009/7/22	104	2009/10/29	150
2009/1/17	12	2009/4/24	58	2009/7/24	105	2009/10/30	151
2009/1/18	13	2009/4/25	59	2009/7/26	106	2009/10/31	152
2009/1/20	14	2009/4/26	60	2009/7/27	107	2009/11/2	153
2009/1/27	15	2009/4/27	61	2009/7/28	108	2009/11/14	154
2009/1/28	16	2009/4/28	62	2009/7/30	109	2009/11/15	155
2009/1/29	17	2009/4/29	63	2009/8/1	110	2009/11/16	156
2009/2/3	18	2009/4/30	64	2009/8/7	111	2009/11/17	157
2009/2/9	19	2009/5/1	65	2009/8/8	112	2009/11/18	158
2009/2/11	20	2009/5/6	66	2009/8/9	113	2009/11/19	159
2009/2/13	21	2009/5/7	67	2009/8/16	114	2009/11/20	160
2009/2/14	22	2009/5/8	68	2009/8/17	115	2009/11/24	161
2009/2/15	23	2009/5/9	69	2009/8/19	116	2009/11/25	162
2009/2/17	24	2009/5/13	70	2009/8/20	117	2009/11/26	163
2009/2/18	25	2009/5/15	71	2009/8/21	118	2009/11/29	164
2009/2/19	26	2009/5/16	72	2009/8/26	119	2009/12/2	165
2009/2/21	27	2009/5/18	73	2009/8/27	120	2009/12/3	166
2009/2/22	28	2009/5/25	74	2009/8/28	121	2009/12/4	167
2009/2/25	29	2009/5/26	75	2009/8/29	122	2009/12/5	168
2009/2/26	30	2009/5/27	76	2009/9/6	123	2009/12/7	169
2009/2/27	31	2009/5/29	77	2009/9/20	124	2009/12/8	170
2009/2/28	32	2009/5/30	78	2009/9/21	125	2009/12/9	171
2009/3/1	33	2009/6/1	79	2009/9/22	126	2009/12/10	172

Date	ID	Date	ID	Date	ID	Date	ID
2009/3/2	34	2009/6/2	80	2009/9/25	127	2009/12/12	173
2009/3/3	35	2009/6/8	81	2009/9/27	128	2009/12/13	174
2009/3/7	36	2009/6/9	82	2009/9/28	129	2009/12/14	175
2009/3/8	37	2009/6/10	83	2009/10/1	130	2009/12/18	176
2009/3/9	38	2009/6/11	84	2009/10/2	131	2009/12/19	177
2009/3/10	39	2009/6/12	85	2009/10/3	132	2009/12/20	178
2009/3/11	40	2009/6/13	86	2009/10/4	133	2009/12/21	179
2009/3/23	41	2009/6/16	87	2009/10/6	134	2009/12/22	180
2009/3/24	42	2009/6/18	88	2009/10/8	135	2009/12/23	181
2009/3/26	43	2009/6/19	89	2009/10/9	136	2009/12/24	182
2009/3/28	44	2009/6/21	90	2009/10/12	137	2009/12/25	183
2009/3/29	45	2009/6/22	91	2009/10/14	138	2009/12/26	184
2009/3/31	46	2009/6/24	92	2009/10/15	139	2009/12/27	185
				2009/12/30	186	2009/12/31	187

Cluster Analysis

Overview of Operational Condition Selection Procedures

First we provide an overview of operational condition selection procedures using a two-step joint clustering approach, as illustrated in Figure A - 1. The two-step joint clustering approach is defined as following:

- Step 1: We first conduct weather condition recognition to identify significant weather patterns. We use K-means algorithm with historical weather index data, which represent different weather categories (see Table A - 1) to classify K different weather patterns identified as cluster 1 to cluster K.
- Step 2: Conditional upon each given weather cluster j, j=1...k (from Step 1), we then use the K-means algorithm on the corresponding historical traffic flow data for that cluster to generate traffic flow (sub)patterns under each identified weather condition. The traffic flow (sub)patterns are described as pattern M-j, where M=A,B… represents the traffic flow pattern, and j=1,…,k to represents the weather condition pattern. The M-j patterns are the joint clusters we seek to identify.

Note that it is possible to do a single step clustering, but an effective method or algorithm is required to evaluate the influence of weather on traffic in order to decide the weight of weather data, the weight of traffic data, and the weight for their combination. The selection of weights will be very critical to the results. The two-step joint model avoids this problem. Furthermore, weather is independent from traffic, but weather affects traffic. The interaction between weather and traffic is kind of hierarchical relationship. Therefore, the two-step joint approach, which is based on the logic of hierarchical clustering, is more suitable than single step approach. With the two-step joint clustering results, we calculate the frequency of each joint cluster, check the consistency between clustered operational conditions and the corresponding system performance with speed data, and select the high frequency and/or significant effecting one under identified weather conditions as our recommended operational conditions for the Chicago Testbed.

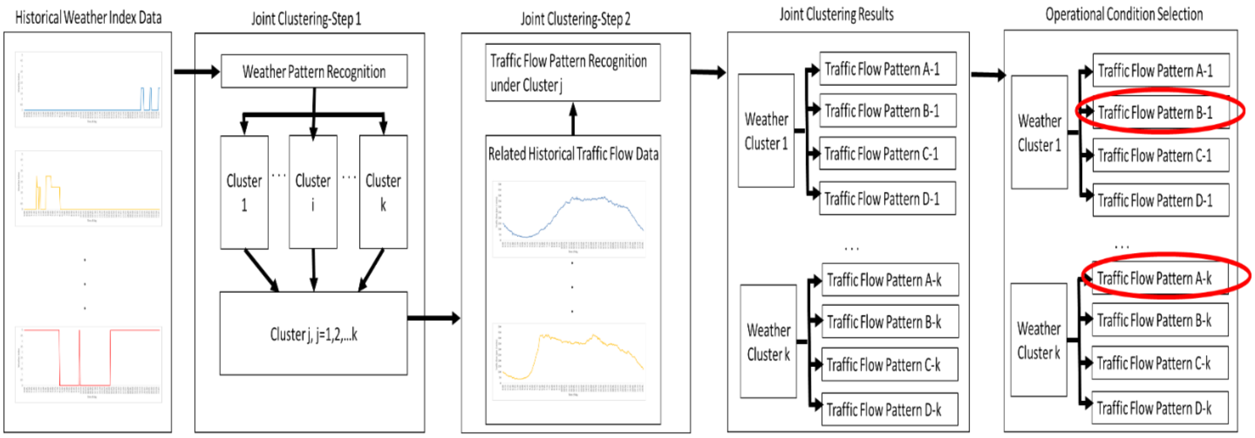

Figure A - 1: Operational Condition Selection with Joint Clustering Approach [Source: NWU]

The remainder of this document is organized as follows. Section 2 presents the detailed K-mean clustering algorithm and steps. Section 3 describes the weather time-series data and traffic flow data used for the joint clustering procedures. Section 4 presents the joint clustering results and identifies the recommended clusters. Section 5 concludes the cluster analysis with the recommended operational conditions for the Chicago Testbed.

K-Means Clustering Algorithm

Given a large scale dataset, it is difficult to discriminate between useful data set and ineffectual items. Some datasets may include redundant information or attributes, while others may hold unique information. Although it is possible to analyze each data element or subset one by one, such a task would be very time consuming and inefficient. Hence, clustering techniques (1)are widely used to determine the intrinsic grouping or structure in an unlabeled data set by classifying data into homogeneous groups where the within-group-object similarity is maximized and the between-group-object similarity is minimized. The K-means algorithm is a widely used procedure for this purpose.

However, the pure version of the K-means algorithm has some limitations in use, particularly with regard to the number of clusters K. The parameter K is known to be difficult to determine since it is sensitive to the initial partition's selection. If the number of clusters chosen is not appropriate for a given data set, poor clusters may result. Therefore, a criterion for choosing a reasonable K is adopted (Eq. (1)) (2) by examining final within-cluster sum of squares (WCSS) values J(K) (Eq. (2)).

$$R = \frac{J(K) - J(K+1)}{J(K)} \times 100\,\% \qquad (1)$$

where,

R = rate of change (decrease) in value of minimal WCSS as the number of clusters K increases (in percentage)

$$J(K) = \min_{S} \sum_{i=1}^{K} D(S_i) = \min_{S} \sum_{i=1}^{K} \sum_{X_n \in S_i} \left\| X_n - \mu_i \right\|^2 \tag{2}$$

where,

K = number of clusters in the data set,

X_n=nth observation vector,

μ_i= the mean of points in S_i,

S_i= the cluster i,

$D(S_i)$ = the within-cluster sum of squares of cluster i,

$J(K)$ = the minimal within-cluster sum of squares.

Since $J(K)$ decreases monotonically with increasing number of clusters K, the procedure starts with a small value of K (e.g., K=1) and checks the rate of decrease R by incrementally increasing K (by +1). The process continues until the rate of decrease R falls below a certain threshold, suggesting that adding clusters would not meaningfully improve the objective function. The steps of the K-means clustering procedure used in this project are listed below:

S1. Initialization:

Randomly assign an initial set of means $\mu_1^{(t)},\ldots,\mu_K^{(t)}$, iter = 0, *t*=1 and $J(K)=\infty$.

S2. Searching optimal allocation and centroid for K clusters:

S2.1.Checking iteration condition: if iter < 10, then go to **S2.2**; otherwise, **S3**

S2.2. Allocating samples to clusters:

If t=1, $\mu_1^{(t)},\ldots,\mu_K^{(t)} = \mu_1^{(1)},\ldots,\mu_K^{(1)}$; otherwise, $u_i^t = \frac{1}{\left|S_i^{(t-1)}\right|}\sum_{X_j \in S_i^{t-1}} X_j$

For each $\boldsymbol{X}$, if $\left\|X_j - \mu_i^{(t)}\right\| \leq \left\|X_j - \mu_l^{(t)}\right\| \ \forall 1 \leq l \leq K$, then assign $\boldsymbol{X_j}$ into cluster $S_i^{(t)}$. Go to **S2.3.**

S2.3. Checking convergence:

If $S_i^{(t)} = S_i^{(t-1)}$ for all *i*, then calculate $J(K)\_new$ and go to **S2.4**; otherwise, t=t+1, go back to **S2.2**.

S2.4. Checking optimization:

If$J(K)_{new} < J(K)$, then $J(K) = J(K)\_new$ and results are $S_i^{(t)}$; otherwise, iter = iter + 1, go back to **S2.1.**

S3. Checking threshold:

If $R \leq 5\%$, K is selected as a desirable number of clusters and $S_i^{(t)}$ is accepted, the procedure stops; otherwise, $K=K+1$ and go to **S1**.

After the two-step joint clustering process is completed, a traffic flow and weather condition library reflecting the cluster results will be built, and will serve as the reference for creating associated demand files and weather condition files used as input scenarios for the traffic simulation model and/or as initial matrix in an online implementation.

Joint Clustering Results

Weather Pattern Identification

After filtering clear days, that is the days without any precipitation of either rain or snow identified as cluster 0, a total of 187 weather scenarios labeled from 1 to 187 is created according to historical weather data. Figure A - 2 presents a plot of the minimized objective function value from historical weather data, J(K), as a function of K. It can be calculated that the rate becomes lower than the 5% when K=5. Therefore, K=5 is selected as the number of clusters.

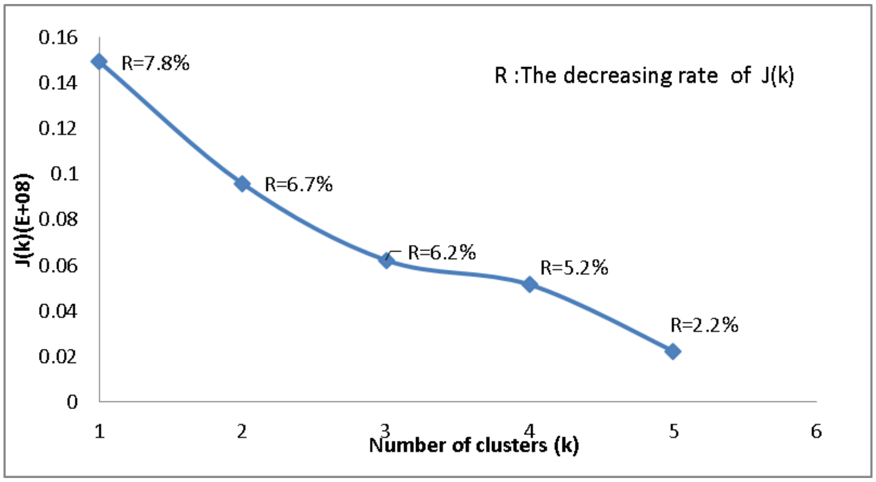

Figure A - 2: Minimized within-cluster Sum of Squares (WCSS) Value with Respect to the Number of Clusters. [Source: NWU]

The weather condition cluster results are presented in Table A - 8, where the number of scenarios in each cluster varies widely across clusters. For instance, Cluster 1 contains 107 scenarios whereas Cluster 3 contains only 12 scenarios. The relative sizes of clusters indicate the relative likelihoods of weather conditions represented by the associated clusters; Cluster 3 represents relatively rare weather conditions while Cluster 1 represents the most common weather conditions in the given data set.

Table A - 8: The Weather Cluster Results

Cluster 1	1	2	17	18	19	26	29	37	38	40
	41	43	46	48	50	52	53	57	58	59
	60	62	63	64	65	67	68	69	71	72
	73	74	76	77	78	79	80	81	82	83
	84	85	86	88	89	90	91	92	93	94
	95	96	97	98	99	100	101	102	103	104
	105	106	107	108	109	110	111	112	113	114
	115	116	117	118	121	122	123	125	126	127
	128	129	133	134	137	140	141	142	143	146
	147	148	152	153	154	155	156	157	158	159
	160	164	165	172	173	174	175			
Cluster 2	5	10	14	16	22	28	32	34	35	39
	45	54	55	56	70	119	120	136	145	151
	163	168	169	179	187					
Cluster 3	3	4	9	12	15	20	25	31	49	176
	183	186								
Cluster 4	6	7	11	27	170	171	177	180	184	185
Cluster 5	8	13	21	23	24	30	33	36	42	44
	47	51	61	66	75	87	124	130	131	132
	135	138	139	144	149	150	161	162	166	167
	178	181	182							

For the purpose of investigating between group dissimilarities across clusters, the cluster centers of the obtained five clusters are depicted in Figure A - 3, which plots the centroid value (i.e., mean) of the weather condition indices (i.e., $I_m(t)$) of the members of each cluster under weather clustering. One can observe distinct characteristics of five weather scenario clusters, where Clusters 1 represent light rainy days, Cluster 2 shows the days with moderate and/or heavy rain changing to light rain, Cluster 3 presents the days with gradual changing process from (moderate) rain to moderate snow, Clusters 4 represents mostly moderate snow days which might end with snow or rain, and Cluster 5 displays the days starting with light rain and changing into moderate or heavy rain in the evening. The five identified weather patterns are used for weather effected traffic flow pattern recognition in section 4.2 as Step 2 of joint clustering approach.

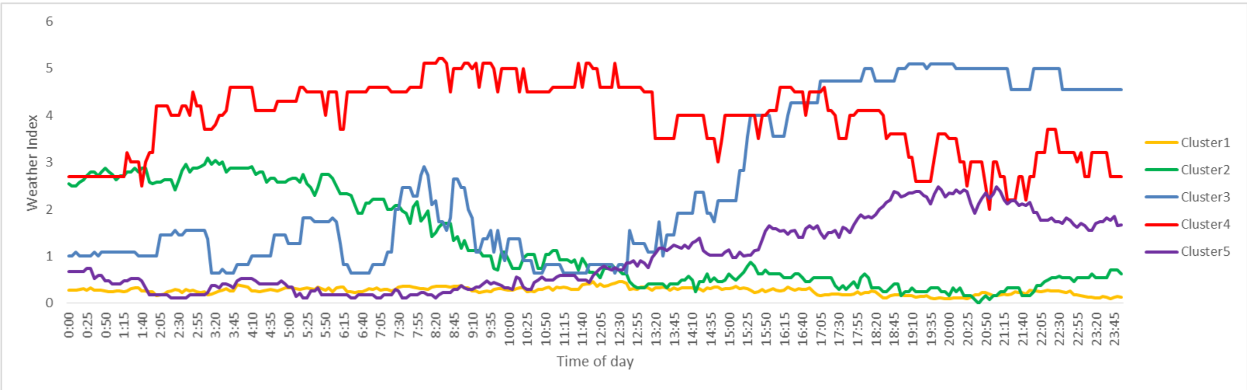

Figure A - 3: Temporal Profiles of Weather Condition Cluster Centroids. [Source: NWU]

Traffic Flow Pattern Recognition Given Weather Condition

Figure A - 4 presents a plot of the minimized objective function value from the historical traffic flow data under each weather condition, J(K). The decreasing trend becomes slow after K=3. The rate reaches the 5% threshold when K=4. Therefore, K=4 is selected as the number of clusters.

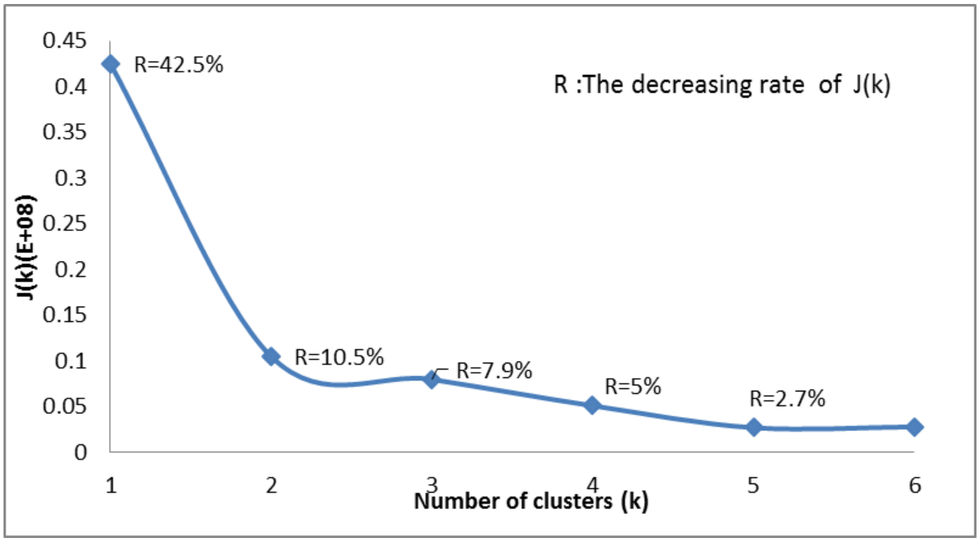

Figure A - 4: Minimized within-cluster Sum of Squares (WCSS) Value with Respect to the Number of Clusters. [Source: NWU]

Table A - 9 shows the traffic flow (sub)patterns under each clustered weather condition. Four general clusters can been observed, Monday-Tuesday pattern (cluster A), Wednesday-Friday pattern (cluster B), Saturday pattern (cluster C) and Sunday pattern (cluster D). It is also found that most national holidays display a pattern similar to Saturday.

Table A - 9(a): Traffic Flow (Sub)Patterns under Light Rain

	Cluster 1 – Light Rain				
Cluster A	29	249	256	243	146
	34	89	259	231	145
	38	96	266	230	140
	48	110	280	78	139
	65	111	282	67	134
	304				
Cluster B	53	149	195	136	185
	83	155	201	147	187
	86	156	203	130	184
	105	158	210	127	181
	106	159	234	120	179
	112	165	253	284	292
	113	173	281	174	283
	119	300			
Cluster C	3	100	107	278	302
	121	128	137	258	264
	148	150	167	170	189
	211	254			
Cluster D	4	64	108	183	200
	218	236	279	290	303

Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
Holiday

Table A – 9(b): Traffic Flow (Sub)Patterns under Moderate/Heavy Rain Changing to Light Rain

	Cluster 2 – Moderate/Heavy Rain Changing to Light Rain				
Cluster A	8	66	125	20	102
	59	103	58	297	13
Cluster B	28	246	257	263	311
Cluster C	43	56	288	295	321
Cluster D	81	101			

Table A - 9(c): Traffic Flow (Sub) Patterns under Moderate/Heavy Rain Changing to Moderate Snow

	Cluster 3 – Moderate/Heavy Rain Changing to Moderate Snow				
Cluster A	6	12	27		
Cluster B	7	40	47	55	308
Cluster C	17	315	320		
Cluster D	88				

Table A - 9(d): Traffic Flow (Sub) Patterns under Moderate Snow

	Cluster 4 – Moderate Snow			
Cluster A	298			
Cluster B	9	14	299	312
Cluster C	10	309	316	
Cluster D	50	317		

Table A - 9(e): Traffic Flow (Sub) under Light Rain Changing to Moderate/Heavy Rain

	Cluster 5 – Light Rain Changing to Moderate/Heavy Rain				
Cluster A	46	54	79	85	260
Cluster B	42	95	118	153	239
	240	245	251	262	287
	293	294	313		
Cluster C	63	80	241	314	
Cluster D	11	18	44	57	310

Table A - 9(f): Traffic Flow (Sub)Patterns under Clear Weather

	Cluster 0 – Clear Weather				
Cluster A	5	19	21	207	213
	23	26	33	215	221
	35	39	41	227	232
	45	51	52	242	250
	60	61	68	261	267
	72	73	74	273	274
	82	84	90	214	226
	116	123	157	237	255
	268	291			
Cluster B	22	30	49	196	197
	62	69	75	202	208
	91	92	97	216	217
	98	99	104	222	223
	117	124	126	229	233
	131	132	133	244	252
	135	141	142	270	275
	143	152	154	277	301
	160	163	164	306	307

	Cluster 0 – Clear Weather				
	168	169	172	16	198
	175	178	180	209	238
	186	188	191	220	269
	192	193	194	228	276
	305	15			
Cluster C	1	2	24	224	235
	31	32	36	271	285
	70	76	87	318	319
	93	114	144	247	204
	161	166	176	289	199
	182				
Cluster D	25	37	71	286	296
	77	94	115	265	272
	122	129	138	190	205
	151	162	171	219	225
	177	212	248		

Joint Clustering Results Analysis

Operational Condition Selection

Table A - 10 represents the frequency of traffic flow pattern (A to D) under different weather conditions (0 to 5) calculated based on joint clustering results shown in Table A - 9. We selected the most frequently occurring joint cluster under each weather condition as the candidates of the recommended existing operational conditions, which are Cluster B-1, Cluster A-2, Cluster B-3, Cluster B-4, Cluster B-5 and Cluster B-0.

For the purpose of investigating between group dissimilarities across clusters, the cluster centers of the obtained initially selected clusters are depicted in Table A - 5, which plots the centroid value (i.e., mean) of the traffic flow rate of the members of each selected joint cluster. One can observe distinct characteristics of the six selected joint clusters, where Cluster B-0 is the normal case without any weather effect and could be regarded as the base case, and the other clusters all have peak hour shift and/or traffic volume reduction due to snow/rain effect. There is one exceptional case that the traffic volume of afternoon peak in Cluster A-2 is larger than the base case. The reason for this fact is that the normal pattern for Monday and Tuesday, i.e. Cluster A-0 has a larger afternoon peak demand than Cluster B-0 as shown in Table A - 6, and Cluster A-2 maintains this features.

Table A - 10: Joint Clustering Results Statistics

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 0
Cluster A	26	**10**	3	1	5	42
Cluster B	**37**	5	**5**	**4**	**13**	**67**
Cluster C	17	5	3	3	4	26
Cluster D	10	2	1	2	5	23

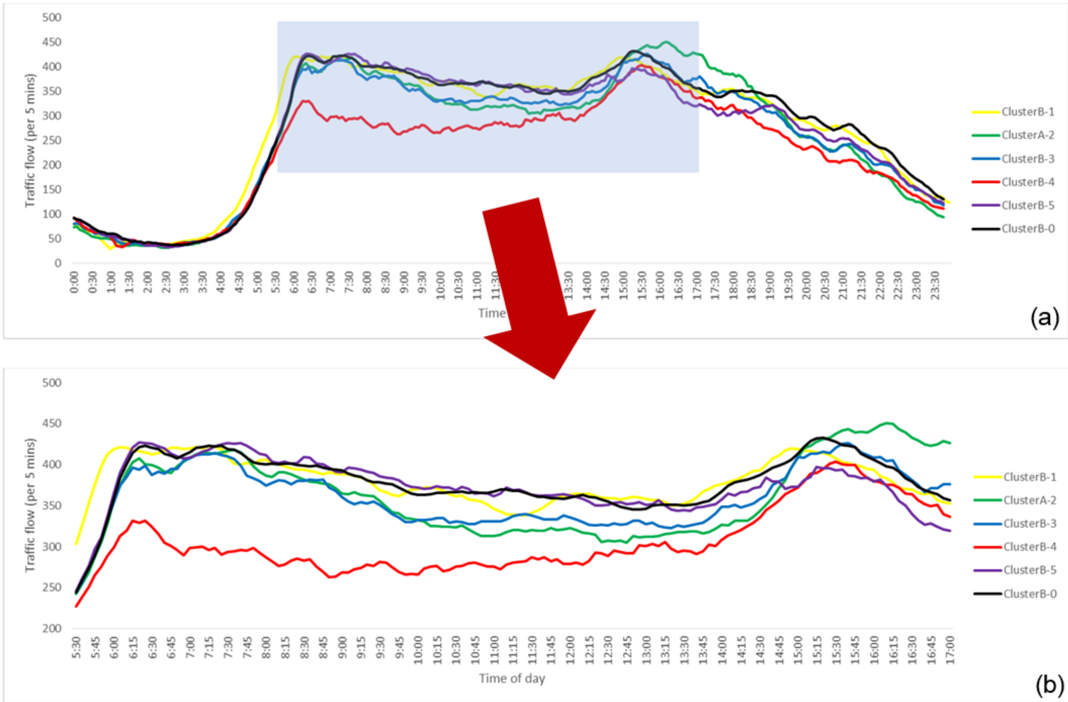

Figure A - 5: Temporal Profiles of Initially Selected Traffic Flow Cluster Centroids: (a) 24-hour pattern, (b) day-time pattern [Source: NWU]

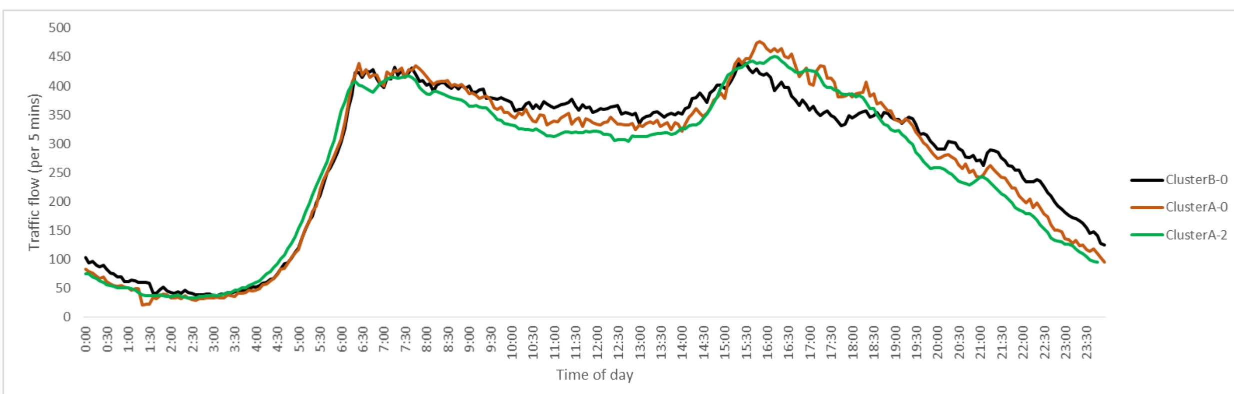

Figure A - 6: Temporal Profiles of Traffic Flow Cluster Centroids [Source: NWU]

With the results statistics, we notice that neither weekend traffic pattern nor heavy snow weather condition are among the candidates of the recommended existing operational conditions. But we also want to capture the impact of heavy snow, which is identified as Cluster 6, and it includes the days with any heavy snow record. Among the two days with heavy snow records, ID=9, January 9 (Friday) and ID=50, February 22(Sunday), 2009, we select the weather condition and traffic flow pattern of January 9, 2009, as the heavy snow operational condition, and the 24-hour weather condition and traffic flow profile in 5-minute time resolution are shown in Figure A - 7. The reasons to do so are 1) the heavy snow precipitation occurred in morning peak hours, which is expected to have much effect on traffic, and 2) it could be compared with the Cluster B (Wednesday to Friday) in other selected candidates and its traffic demand pattern is then defined as cluster B-6. Accordingly, we remove these two days from Cluster 4 and recalculate the centroid of Cluster 4 in Figure A - 8.

Besides, a weekend weather event scenario also belongs to our interests and we are going to include one in our recommended operational conditions to differentiate from weekday patterns. With the emphasis on snow effect and the most frequency selection principle, we are going to include Cluster C-4 in our operational condition lists. Accordingly, due to small effect, two rain scenarios are to be excluded, i.e. Cluster B-1 and Cluster A-2. For the purpose of investigating between group dissimilarities across clusters, the cluster centers of the obtained modified selected clusters are depicted in Figure A - 8.

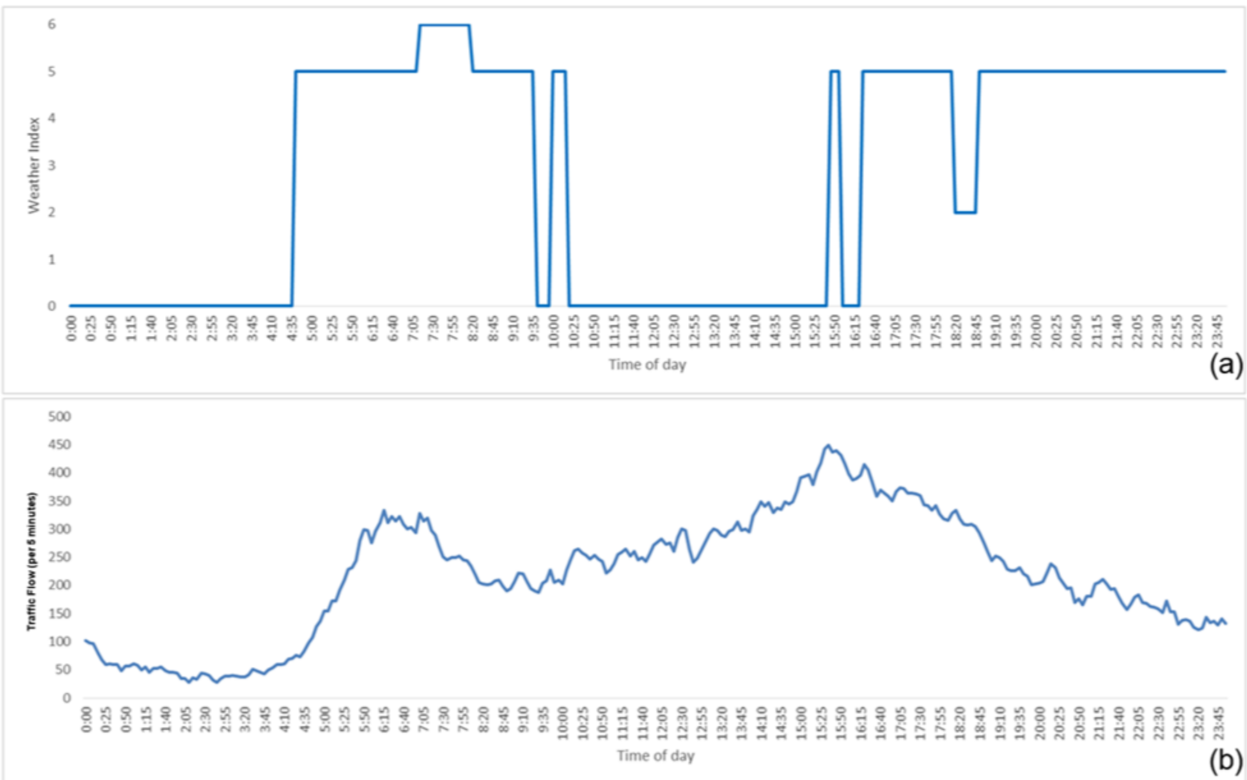

Figure A - 7 (a) Temporal Profiles of Weather Condition. (b)Temporal Profiles of Traffic Flow. [Source: NWU]

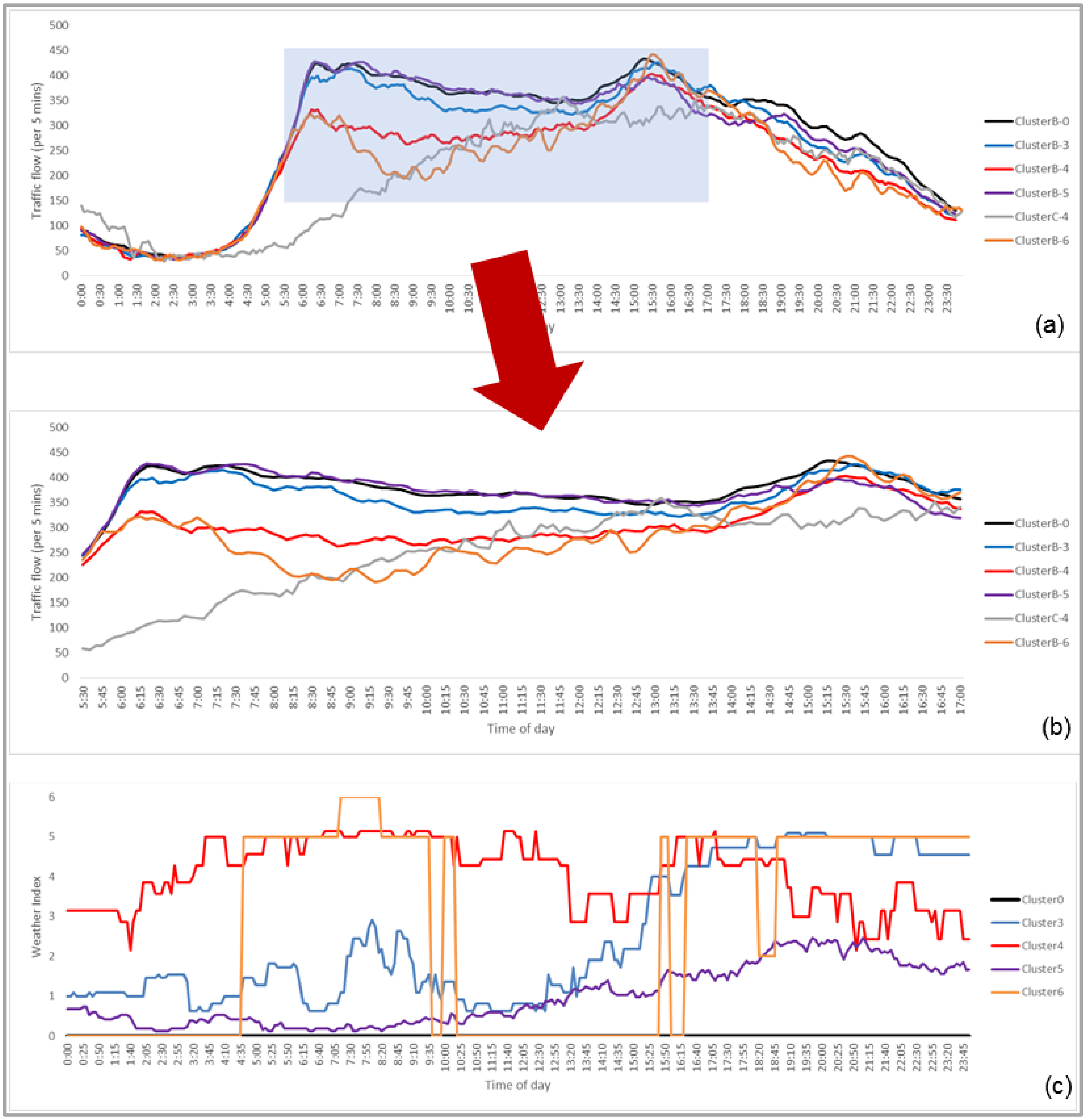

Figure A - 8: Temporal Profiles of Selected Operational Conditions: (a) 24-hour Pattern Traffic Demand Pattern, (b) Day-time Pattern Traffic Demand Pattern, (c) 24-hour Weather Condition [Source: NWU]

System Performance Consistency Checking

If we regard the operational condition as the input of the traffic system, the system performance, i.e. average speed in 5-minute time resolution in this study, is the output. In order to confirm that the selected operational conditions have corresponding and expected effect on the traffic, we check the consistency between the system performance and the given operational conditions in the selected weather effected joint cluster as Figure A-9.

Figure A - 9: Speed Distribution for Selected Scenarios (a) Scenarios in Cluster B-3, (b) Scenarios in Cluster B-4, (c) Scenarios in Cluster C-4, (d) Scenarios in Cluster B-5, (e) Scenarios in Cluster B-6. [Source: NWU]

We could find that the speed distribution are mostly consistent within the clusters and matchable with the demand and weather condition. The only exceptional cases are December 18 (Friday) in Cluster B-3, December 22(Tuesday) in Cluster B-4 and February 13 (Friday), December 23(Wednesday) in Cluster B-5: these cases do not have speed reduction in morning peaks and they are much closer to December 19 in Cluster C-4. The reason to explain this phenomenon is that December 18, 19, 22 and 23 are close to Christmas holiday, and February 13 is close to Valentine's Day and thus their patterns are more likely to be in the weather effected holiday/weekend traffic patterns.

Recommended Existing Operational Conditions

To summarize, the team recommends original selection of the frequently occurring and significantly effecting operational conditions in Figure A - 8. These include 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 to be useful in the cluster analysis, but we still want to include the incident-related delay and compare it with weather effect, we recommend to remove Cluster B-5, which shows least system performance changes in section 4.3.2 and to add Cluster B-7, which is a weather-incident mixed scenario. Table A - 11 finalizes the operational condition candidates, which will be used to test weather related strategies in the Chicago Testbed.

Table A - 11: Existing Operational Condition Candidates

Variables		All	Cluster B-0	Cluster B-3	Cluster B-4	Cluster C-4	Cluster B-6	Cluster B-7 (hypothetical)
Number of 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

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