Estimation of Winter Snow Operation Performance Measures with Traffic Data

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16. Abstract (Limit: 250 words)

This research produced an automatic process to identify the road condition recovered times during snow events from the traffic-flow data. For this study, the traffic data from the past snow events were analyzed and the speed variation patterns indicating the road condition recovery states during the recovery periods were identified. The prototype process developed in this study finds the speed change point indicating the recovery of the road condition by analyzing the speed variations for a given location. The process was then applied to a set of the past snow events and the estimated recovered times were compared with the reported lane-regain time data.

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Final Report

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Executive Summary

The capability to accurately and reliably estimate the performance of winter maintenance activities is of critical importance in improving the efficiency and effectiveness of winter snow-management operations. In this study, a prototype process is developed to determine the road condition recovery time, which could be used as an estimate of the ‘bare-lane-regain time’, from the traffic-flow data being collected from the existing loop detectors on the metro freeways. First, the traffic-flow variation process was analyzed with the traffic data from the past snow events and the speed recovery patterns near the reported lane-regain times were identified. The field data analysis indicates that the speed change patterns at a given location can vary significantly depending on the multiple factors, such as the intensity of snow, the traffic-flow level and the maintenance strategies. For example, the speed change rate and the final recovered speed level during a recovery period are directly affected by the amount of traffic-flow. It was also found out that the road condition recovered time could be considered to be the ‘last significant speed increase point’ before the speed reached the posted limit or a stable value for a given location depending on the speed level when the speed recovery started. Based on the above findings, an automatic process to identify the speed change and the road condition recovered times at each detector station was developed and incorporated into TICAS, Traffic Information and Condition Analysis System, being developed at University of Minnesota Duluth. The computerized process was then applied to a subset of the 2011-12 winter maintenance operations data, which consists of the two routes for four snow events. The example application results show the promising results in terms of identifying the speed change points and estimating the road condition recovered times for the given four events with the traffic data. For the three events tested in this study, 64-65% of all the segments in those two routes have less than 30-minute differences between the ‘estimated road condition recovered times’ and the ‘reported lane-regain times’, while one event on January 23, 2012, has only 44% of all the segments with less than 30-minute differences. It needs to be noted that there was only one reported lane-regain time for each snow event for all the routes used in this study. Future study needs include the enhancement of the prototype process developed in this study to be able to identify the traffic-flow recovery patterns under the various weather and operational conditions, such as those evens with long recovery periods with multiple speed drops. Collecting detailed maintenance operation data including the exact times and methods of plowing operations would also be needed.

1. Introduction

1.1 Background

The most common measure for winter snow-management performance currently being used by state DOTs is 'Time to bare pavement', which is defined as the recovery time to the snow-free lanes after a snow event ends (1). However, it has been found out that, at this point, most state DOTs are relying on the visual inspection of the field crew in estimating the bare pavement recovery time. While it has been well known that there is a clear link between snow storm and traffic-flow parameters, the use of traffic data in estimating winter maintenance performance has not been a common practice yet. The only state agency that currently uses a traffic data-related performance measure is the Iowa DOT, which determines the success of winter snow operation by comparing the actual measured speed drop to the 'acceptable speed reduction' that varies depending on a given storm's severity (2). Several researchers in the past tried to quantify the effects of snow storm on the traffic volume reduction with varying results. Hanbali and Kuemmel (3) noted 7 – 17% reduction of average hourly traffic volumes during weekdays with snowfalls of less than 1 in. Knapp and Smithson (4) found an average reduction of hourly traffic volumes approximately 29%. Knapp and Smithson (5) also found that during snow storms the average traffic speed was reduced approximately 16%. The most notable effort was conducted by Lee et al. (6,7), who developed a set of regression models using the data from Wisconsin to estimate 'speed recovery duration' as a function of several variables including the maximum speed reduction (%), time to maximum speed reduction, and snow depth due to a given snow storm. While their effort needs to be recognized as one of the first ones in applying traffic-flow data for quantifying the performance of snow operations, using the piecewise linear regression method resulted in questionable models, e.g., negative parameter for the 'snow depth' variable.

The capability to accurately and reliably estimate the performance of winter maintenance activities is of critical importance in improving the efficiency and effectiveness of winter snow-management operations. In this study, a prototype process is developed to determine the traffic data-based speed recovery time that can be used as an estimate for the 'bare-lane-regain time' on a freeway network. Testing of the prototype process with the real snow event data from the metro freeways in the Twin Cities, Minnesota, will be also conducted.

1.2 Research Objectives

The main objectives of this study include:

- Development of a process to determine traffic data-based 'speed recovery time' that can be used as an estimate for the 'bare-lane-regain time' for the metro freeway corridors in Twin Cities, Minnesota,
- Development of an automatic procedure to estimate and visualize the speed recovery time data for selected segments of freeway corridors.

1.3 Report Organization

Chapter 2 includes the review results of the current traffic data-based processes at the selected state DOTSs to determine winter maintenance measures. The research efforts found from the literature were also reviewed in this chapter. The traffic-flow patterns during snow events are analyzed in Chapter 3 using the archived traffic data from the past snow events. In particular, the traffic-flow behavior around the reported bare-lane-regain time was analyzed in detail with the 2011-12 event data set, where the lane-regain time was reported in 15 min increments. Based on the data analysis results, a prototype procedure was developed to identify the speed change points and the road condition recovery time at each detector station using the traffic-flow data. The prototype procedure was incorporated into the Traffic Information and Condition Analysis System (TICAS), a computer system for estimating traffic-flow measures with the detector data from the Twin Cities' metro freeway network, in Chapter 4. In Chapter 5, the new computerized process is applied to estimate the speed change points for the selected snow events in 2011-12 and the estimated road condition recovered points are compared with the lane-regain time reported by the field crew. Finally Chapter 6 includes the conclusions and further research needs.

2. Review of Traffic-Data-Based Winter Maintenance Measures

2.1 Overview of Existing Winter Maintenance Measures

In this task, a literature search and review was conducted to identify the types of the winter maintenance performance measures, currently being used by the state DOTs, which have direct relevance to traffic-flow data. The state DOTs included in this literature review are California, Colorado, Indiana, Kansas, Massachusetts, Virginia, Wisconsin and Iowa. Table 2.1 show the list of the performance measures identified in this review.

Table 2.1.1 Types of Winter Snow Maintenance Operations Performance Measures

	Winter Maintenance Operation Performance Measures
Input	Personal hours including overtime, Tons of materials used, Amount of equipment deployed, Number of people assigned to snow duty during storm, % of equipment operable at the beginning of storm, Cost of winter operations per lane-mile (including materials, equipment, labor and administrative costs), Accuracy of weather forecasts, timing and amount of snow received.
Output	***Time to bare pavement (wheel paths) after a storm,*** ***Difference between Actual Observed Speed and 'Acceptable' Speed Levels during a storm,*** Time for the maintenance crew to get on the road after the start of a storm, Traffic-flow level of service, Crash rates, Lane-miles plowed, Number/Total time of road closures, Number/Hours of chain restriction events,
Outcome	Customer satisfaction (through survey)

As indicated in Table 2.1.1, the performance measures with direct relevance to traffic data are as follows:
1) Time to bare pavement (wheel paths) after a storm,
2) 'Acceptable' Speed Reduction during a storm.

Among the above two measures, the first one, i.e., 'Time to bare pavement' is the most commonly used measure by the state DOTs reviewed in this study. However, it has been found out that, at this point, no state DOT is directly applying traffic-flow data to determine 'the time to bare pavement', i.e., most state DOTs are relying on the visual inspection of the field crew in estimating the bare pavement recovery time. The only state DOT that uses a traffic data-related performance measure is the Iowa DOT, which determines the success of winter snow operation by comparing the actual measured speed drop to the 'acceptable' speed reduction level during a storm. The acceptable speed reduction levels vary depending on a given storm's severity, which is defined with the consideration of the weather-related factors.

The research effort applying traffic data to measure the performance levels of winter snow operations is still in its infancy. Only two notable approaches have been found in the literature. In what follows, the acceptable speed reduction level estimation method of the Iowa DOT and two research efforts to quantify the performance levels with traffic data are summarized.

2.2 Traffic-Flow-Data-Based Winter Maintenance Measures

'Acceptable Speed Reduction Estimation Method' by Iowa DOT

Iowa DOT estimates the acceptable speed reduction during a storm as follows (Iowa DOT, 2009):

*Acceptable Seed Reduction = 'BVSR' * 'SSI'*

BVSR (Base Value of Speed Reduction) indicates the maximum acceptable speed reduction for a given route under the worst storm. The severity level of a storm is quantified with the 'SSI (Storm Severity Index)', which considers the storm type, wind level and pavement temperatures during and after the storm. The Table 2.2.1 shows the different values of the Base Value of Speed Reduction for different route categories in terms of their priorities. The SSI formula currently being used is also included in Table 2.2.1.

Table 2.2.1 Base Value of Speed Reduction and SSI formula (Iowa DOT, 2009)

	Priority A	Priority B	Priority C
Base Value of Speed Reduction (mph)	17	22	24

$$\text{SSI} = [\frac{1}{b} * [ST * Ti * Wi) + Bi + Tp + Wp - a]]^{0.5}$$

a = 0.0005, b = 1.6995

Storm Type (ST)	Freezing rain 0.72	Light Snow 0.35	Medium Snow 0.52	Heavy Snow 1
Storm Temperature (Ti)	Warm 0.25	Mid Range 0.4	Cold 1	
Wind Conditions in Storm (Wi)	Light 1	Strong 1.2		
Early Storm Behavior (Bi)	Starts as Snow 0	Starts as Rain 0.1		
Post Storm Temperature (Tp)	Same 0	Warming -0.087	Cooling 0.15	
Post Storm Wind Conditions (Wp)	Light 0	Strong 0.25		

For example, for a storm with the following characteristics, i.e., Heavy Snow (ST=1), cold storm temperature (Ti=1), strong winds (Wi=1.2) and starting as snow (Bi=0), with the warming post storm temperature (Tp=-0.087) and strong winds (Wp=0.25), the resulting SSI = 0.9322. Therefore, the acceptable speed reduction for an A route will be 0.9322*17 = 16 mph, while that of a C route will be 0.9322*24 = 22 mph. If measured speed drop for an A route is within 15 mph during a storm period, then the snow operation is considered as 'successful'.

2.3 Research Efforts to Quantify Winter Maintenance Performance with Traffic Data

Research by Ohio University group

A group at the Ohio University tried to categorize the level of service for the winter operations by measuring the surface traffic speed levels during a storm and by comparing those values with the average dry surface speed (Zwahlen, et al., 2006). Table 2.3.1 shows the different levels of service as a function of the speed levels. The LOS categories in this table were determined with the findings from a driver survey conducted by the same research group with a total of 136 drivers at two freeway sits and six street sites in Ohio. The underlying assumption in the proposed LOS table is that the average wet/salted surface speeds are approximately 85% of the speed levels on the dry surface. I.e., if the measured wet/salted speed level is 90% of the winter average speed, then it results in 76% of the dry surface speed level, which is considered as 'adequate' in terms of the level of service. It can be also noted that a linearly distributed speed reduction scheme was used in identifying different speed levels in this LOS table. However, as the researchers acknowledged in their report, 'due to the lack of winter storms in the Cleveland\Akron area during the 2004, 2005 and 2006 years, the findings of the study are somewhat limited and based on a small sample of winter conditions. Therefore the recommendations proposed must be considered as fairly general'. Further, the authors concluded that, based on their survey findings, 'most drivers are capable of perceiving dangerous, bad road conditions during a winter storm and most of them will lower their speeds to maintain an acceptable level of safety. Therefore the use of the current average speeds appears to be a fairly good tool to determine the level of service. In addition, having the average RWIS speeds available on a near real time basis enables winter operations managers to adjust their assignments of resources in a more optimal manner while the winter storm is in progress.' At this point, the proposed LOS method has not been adopted by the Ohio DOT.

Table 2.3.1 LOS Categories Proposed by Ohio University

% of Average Dry Surface Speed	**Level of Service**
76 – 100 %	Adequate
68 – 75 %	Slightly inadequate
60 – 67 %	Moderately inadequate
51 – 59 %	Inadequate
42 – 50 %	Highly inadequate
< 41 %	Extremely inadequate

Research by University of Wisconsin, Madison

The most notable effort to apply traffic speed data to quantify the winter snow operation performance was conducted by a group at the University of Wisconsin Madison (Lee et al. 2004, 2008), who developed a set of regression models using the data from Wisconsin to estimate 'speed recovery duration' as a function of several variables including the maximum speed reduction (%), time to maximum speed reduction, and snow depth due to a given snow storm, i.e.,

$$\text{Speed Recovery Duration} = 9.68 + 9.926*\text{MSRPCENT} - 0.086*\text{StoS2MSR} + 0.493*\text{crewdelayed} - 0.222\ \text{snowdepth}$$

where,

MSR = Maximum speed reduction,
StoS2SD = Time lag to speed drop after snow storm starts
StoS2MSR = Time to MSR after snow storm starts
Crewdelayed = Time lag to deploy maintenance crew after snow storm starts
Snowdepth = snow precipitation.

The above regression model estimates the duration of the speed recovery as a function of the % of maximum speed reduction (MSR), time taken to MSR after a storm started, crew deploy time and snow depth. The hourly speed data from 954 winter maintenance logs in 24 counties were used to develop the proposed model. While their effort needs to be recognized as one of the first ones in applying traffic-flow data for quantifying the performance of snow operations, using piecewise linear regression method resulted in questionable models, e.g., negative parameter of the 'snow depth' variable.

3. Development of Speed Recovery Time Identification Process from Traffic-Flow Data

3.1 Analysis of Traffic-Flow Behavior during Snow Events

3.1.1 Traffic Speed Variation Patterns during Snow Events

As a first step towards developing a process to determine the speed recovery time, a set of traffic speed data during the past snow events in the Twin Cities metro freeway network were analyzed and the speed variation patterns under different snow conditions were identified. The Table 3.1.1 shows the snow events whose speed variation data were downloaded and analyzed in this study using the TICAS, Traffic Information and Condition Analysis System, developed at UMD. Further, for each snow event, the following data were also collected from the Program and Project Management System (PPMS) Reports, which were provided by the Metro District, MnDOT. It needs to be noted that, in this data set, the Lane-Regain Date/Time is in 30 min increments:

- Plow Route, Weather Condition, Event Begin Date, Event End Date, Event Duration
- Lane Lost Date/Time, Lane-Regain Date/Time, Lost Duration, Recovery Hours

Table 3.1.1 Snow Events Used for Speed Data Analysis

	Station	Event Begin Date	Event End date	Event Duration (hr)
I94WB	88	12/01/2007 09:00AM	12/02/2007 12:00AM	15
		02/26/2009 12:00PM	02/26/2009 10:30AM	10.5
		11/13/2010 12:00AM	11/14/2010 12:00AM	24
I494EB	70	12/01/2007 09:00AM	12/02/2007 12:00AM	15
		02/26/2009 12:00PM	02/27/2009 11:00AM	35
		11/13/2010 12:00AM	11/14/2010 12:00AM	24
I694WB	45	12/23/2007 04:00AM	12/23/2007 07:00PM	15
		12/30/2008 1:30AM	12/30/2008 5:00PM	15.5
		12/30/2009 7:00AM	12/30/2009 2:00PM	7
T.H. 169NB	46	01/21/2008 8:00AM	01/21/2008 10:00PM	14
		02/28/2008 2:00PM	02/28/2008 7:00PM	5
		11/13/2010 12:00AM	11/14/2010 12:00AM	24

Figure 3.1.1 shows three representative speed-change patterns during snow events, i.e., V-type, U-type, and Wide-type, identified in this study. As noted in this figure, the speed variation pattern of a given event can be described with the inter-relationship of the following points in the speed-time space: Speed Reduction Starting Time (SRST), Low Speed Time (LST), Recovery Starting Time (RST) and Speed Recovered Time (SRT). It can be further noted that, while the locations of the first three speed-change points can be clearly determined in a speed-time space, the exact Speed Recovered Time Point may not be as clearly identified as the other points. For example, Figures 3.1.2 and 3.1.3 show the speed variations during two snow events under the different traffic conditions, i.e., uncongested and congested. It can be seen that, under the uncongested traffic, the speed recovers to a relatively constant value (SRTF), which is lower than that of the pre-snow period. However, as shown in Figure 3.1.3, when the traffic is

congested during the recovery period, the speed level continuously fluctuates as a function of the density and the determination of the ‘speed recovery point (SRTC)’ would not be as straightforward as in the uncongested condition. Further, even with the cases where the recovered speed shows stable patterns, the magnitude of the speed reduction after the road condition is recovered appears to vary significantly depending on the amount/intensity of snow fall and the traffic-flow conditions during a given snow event. Figure 3.1.4 shows the distribution of the recovered speed levels, defined as the stable speed value continued for at least one hour after the bare-lane was regained, for a total of 65 snow events in the Twin Cities’ metro freeway corridors during 2008-2011. As noted in this figure, there are significant variations in the recovered speed levels, while approximately 43% of the total cases have their recovered speeds between 85 and 90% of their pre-snow level.

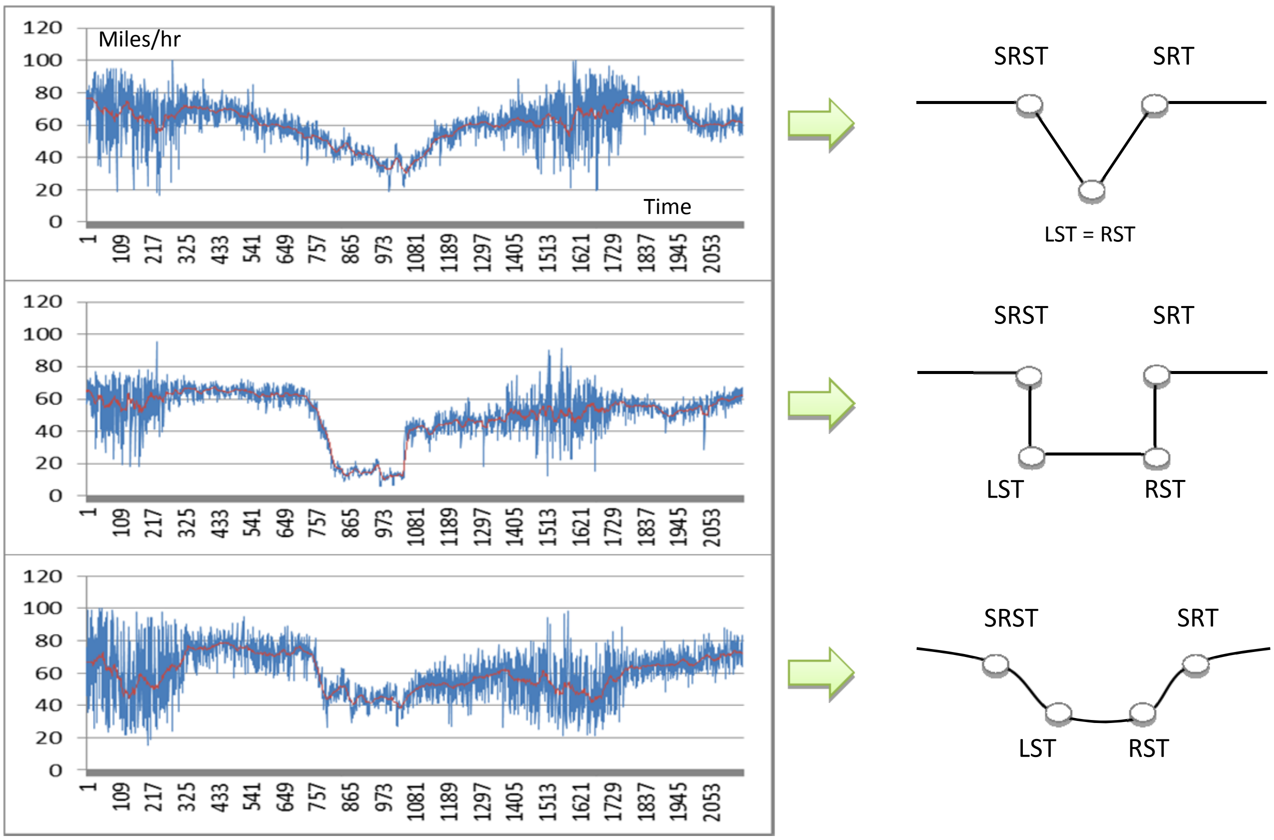


Figure 3.1.1 Speed variation patterns during Snow Events

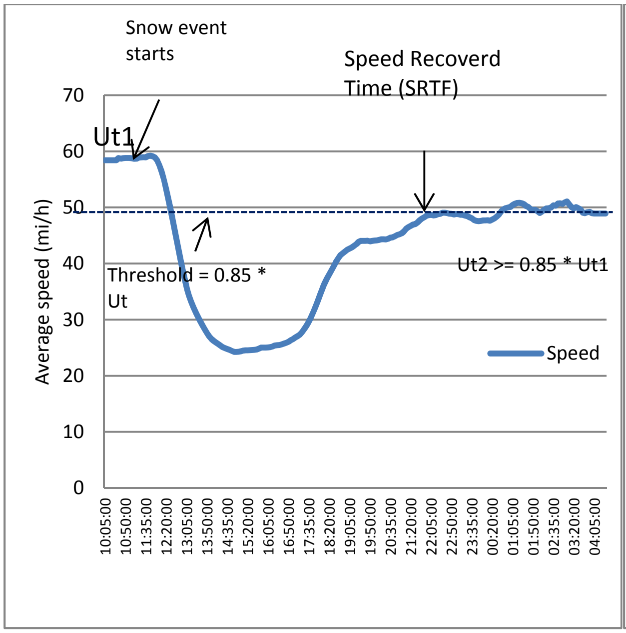


Figure 3.1.2 Speed variations at I-94WB snow event (February 26, 2009: Free flow speed recovered)

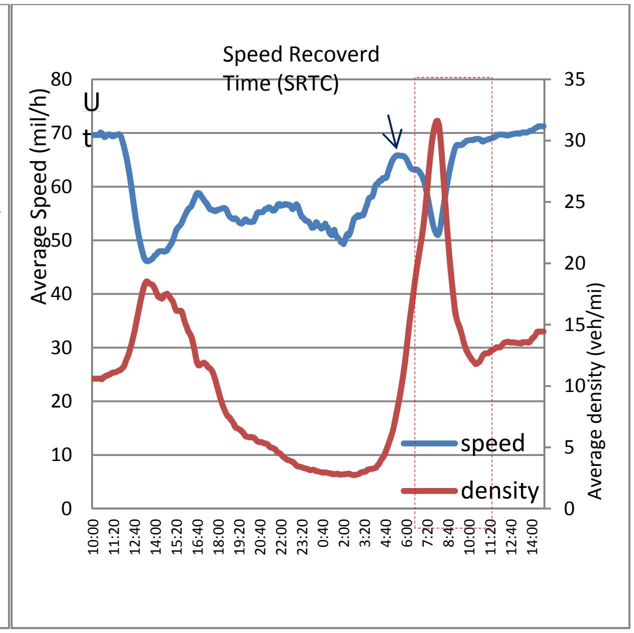


Figure 3.1.3 Speed Variations at 1-494 EB snow event (February 26-27, 2009: Congested)

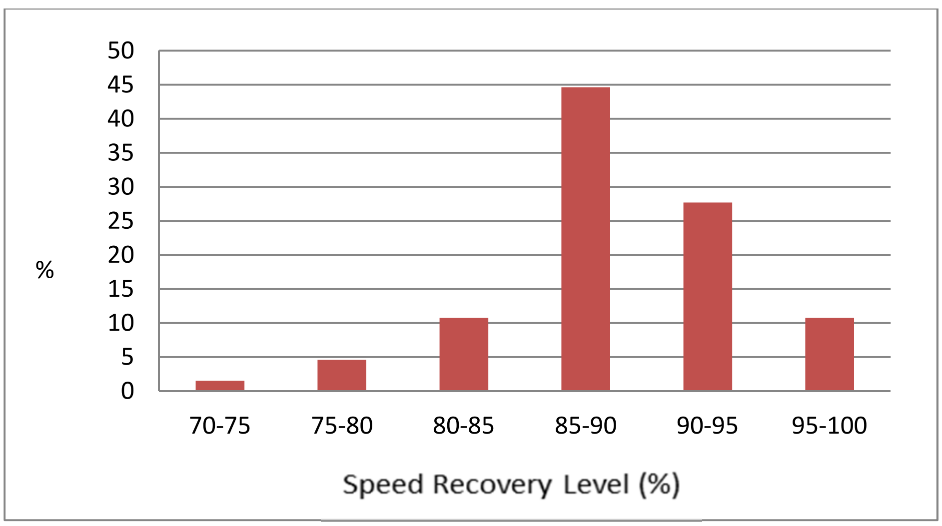


Figure 3.1.4 Distribution of recovered speed levels as % of pre-snow speed

3.1.2 Detailed Analysis of Traffic-Flow Behavior during Speed Recovery Period

As discussed in the previous section, identifying the exact speed recovery point in a speed-time space presents substantial difficulties especially when the speed levels are affected by both the road conditions and the traffic-flow during the recovery period. In this section, a detailed analysis of the traffic-flow variation patterns during the recovery process was conducted using the special set of snow event data provided by the MnDOT Metro District from the selected routes during the 2011-12 winter period. In particular, the bare-lane-regain time data for the snow routes used in this analysis were collected in 15 minute increments. Table 3.1.2 includes the selected snow routes used for the q-k variation analysis.

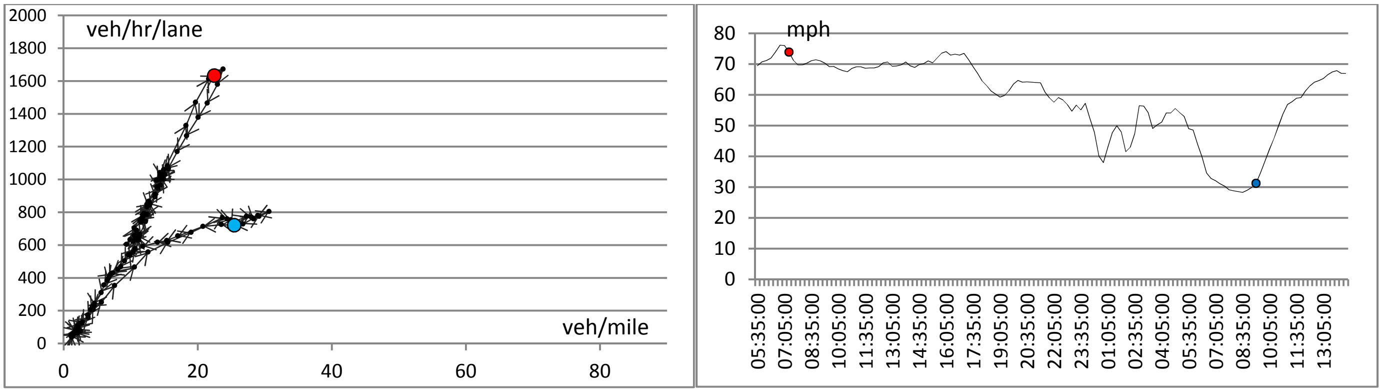
Table 3.1.2 Snow Routes Used for Detailed Analysis

Plow route ID	TP9F0251				TP9F0253			
Route	I-35E		T.H. 694		T.H. 52		T.H. 94	
	NB	SB	WB	EB	NB	SB	WB	EB
Station No.	S626 - S1485	S1549 – S637	S1457 - S1085	S1078- S1453	S1175 - S1178	S1152- S1154	S500 - S551	S469- S499

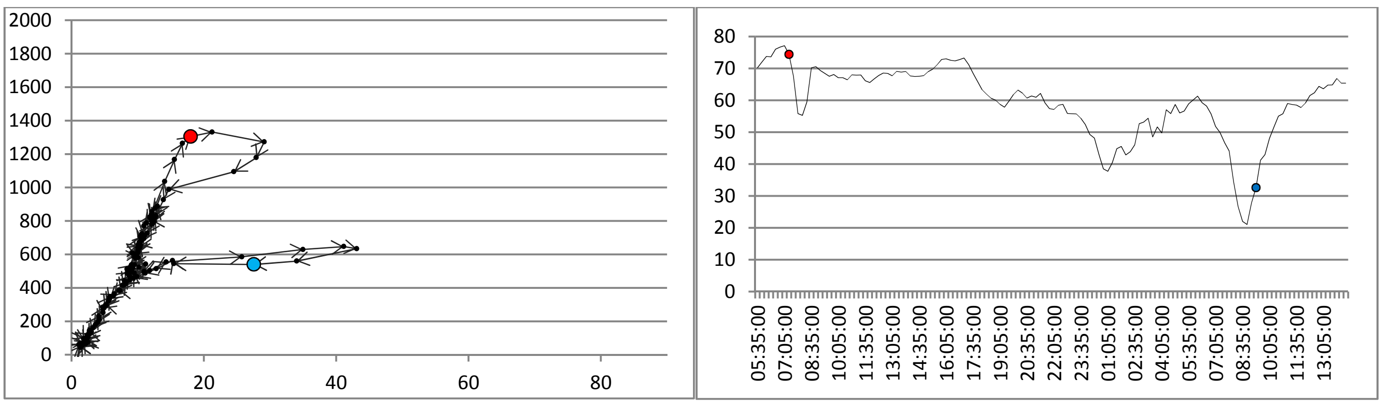
Figures 3.1.5 – 3.1.16 show the traffic-flow variations of the above routes during two snow events in 2012, i.e., January 20 and February 28, in terms of the flow rate-density and speed-time variations. The red and blue dots in each graph indicate the snow event start time and the reported bare-lane-regain time at each location. The analysis of these data resulted in the following findings:

- There are two types of speed recovery patterns:
  Type 1: Speed recovery is only affected by the road condition. In this case, the speed continuously recovers to its free flow speed level.
  Type 2: Speed recovery is affected by both the road condition and the traffic-flow. In this case, the speed recovery stops at a certain level before it reaches its free flow speed. The recovered speed level and its variation pattern depend on the combined effects of the road surface traffic-flow conditions.
- For each type of recovery pattern, there are generally multiple speed change points from the Recovery Starting Time (RST) until the time the speed is recovered either at or below free flow speed. The number of these speed change points may depend on the amount of snow, plowing operational strategies, and the traffic-flow conditions at a given location.
- Each of those speed change points during the recovery period under low density flows could indicate the time when the road surface condition changes. In most cases, the reported bare-lane-regain time at each station is located very close to or overlaps with the 'nearest speed change point' to the speed limit at that location.
- When the speed level at RST is relatively high, i.e., higher than 50 mph, it was noted that the speed levels at the reported bare-lane times could have higher values than the posted speed limits.

The above finding implies that drivers tend to travel below the speed limit during the snow event until the road surface condition is recovered to a certain level at which the traffic speed can be comfortably increased to the speed limit of a given location. Therefore, it can be considered that, when the speed level at any location is at or above its speed limit value, the road surface condition has already reached the bare-lane status or the road condition has been recovered. In this research, the nearest speed change time before the traffic speed level reaches the speed limit at a given location is defined as the Road Condition Recovered (RCR) Time. The above assumption is relaxed for the light snow events, i.e., the speed levels at the recovery start times are higher than 50 mph, so that the RCR times can be found after the speed level exceeds the posted speed limit at given location. Figure 3.1.17 shows the speed change points during the recovery process at the Station 548 on 94 WB, where the nearest change point to the speed limit overlaps with the bare-lane-regain time reported by the field crew during the 2-28/29, 2012, snow event.



S1457 (694WB at I-35E) 2012.Feb.28-29



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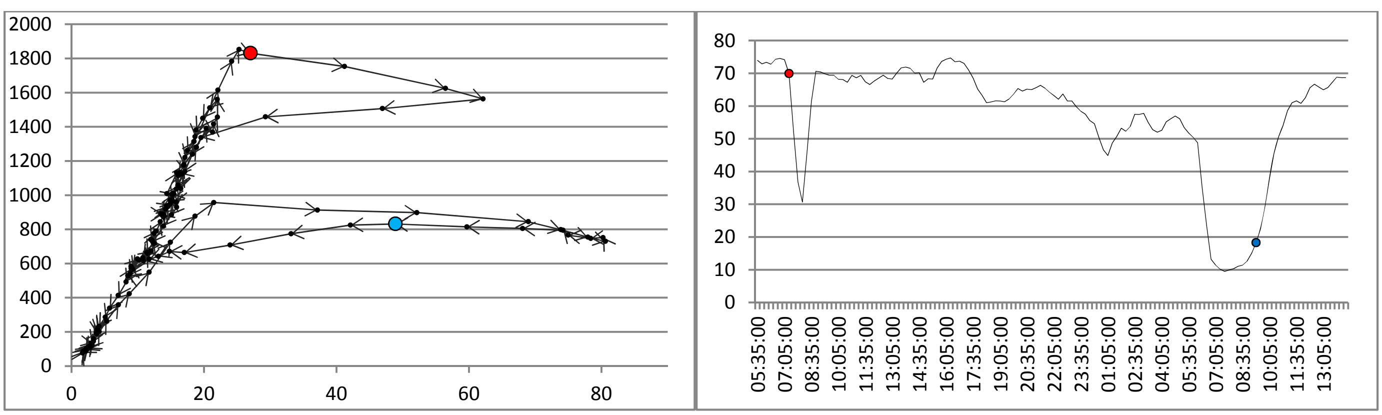
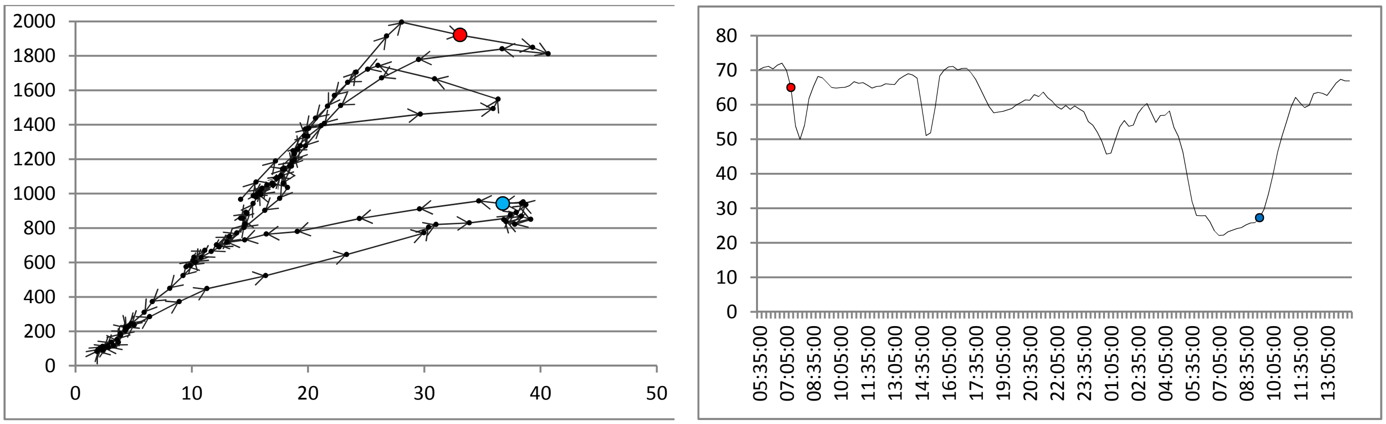
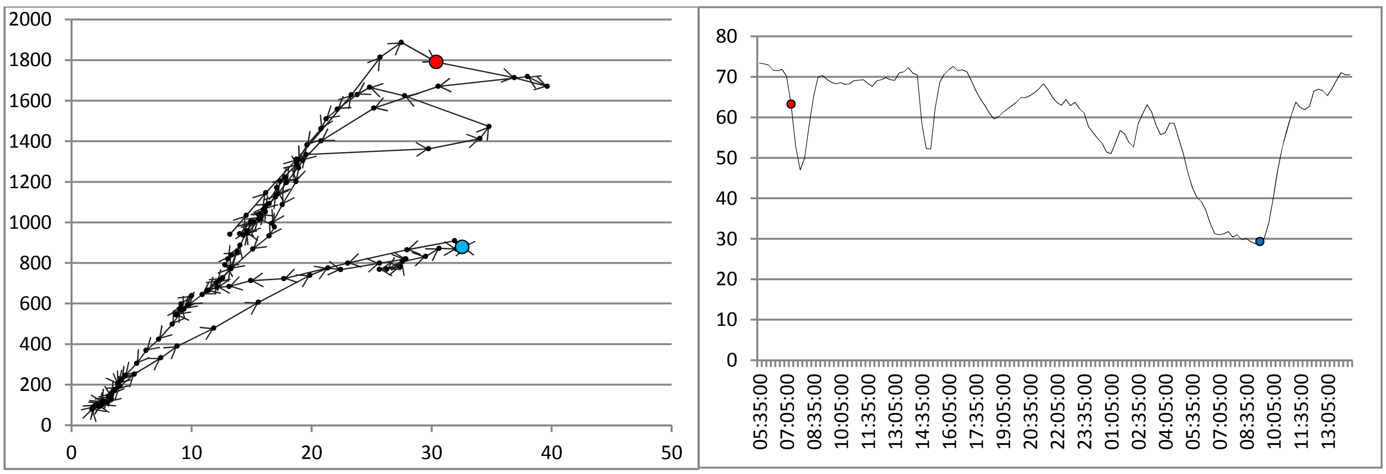


S1461 (694WB at Rice St) 2012.Feb.28-29

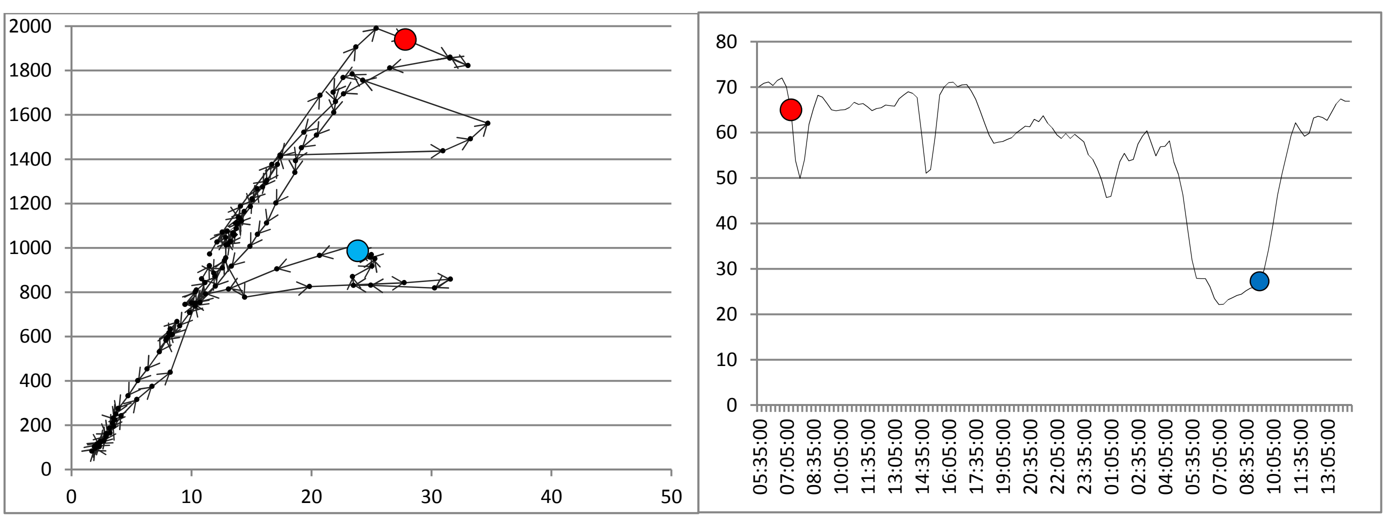
Figure 3.1.5 Traffic-flow variations (q-k, u-t) during February 28-29, 2012, snow event: 694 WB (1)



S1083 (694WB at Rice St) 2012.Feb.28-29

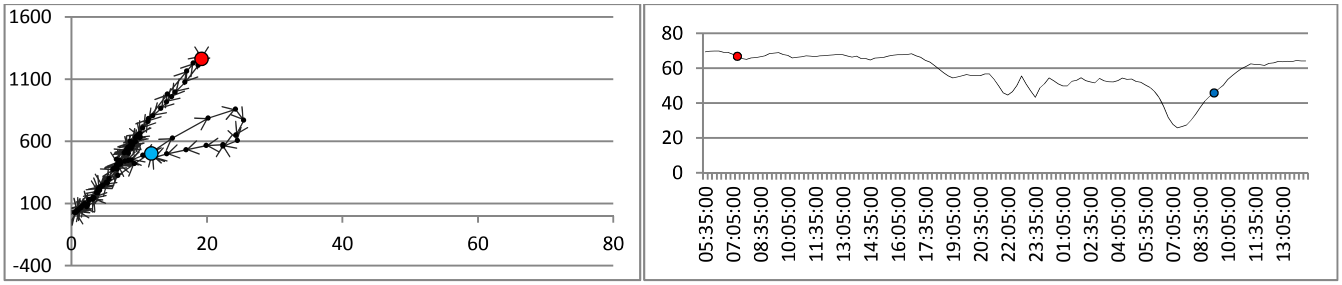


S1084 (694WB at Victoria St) 2012.Feb.28-29

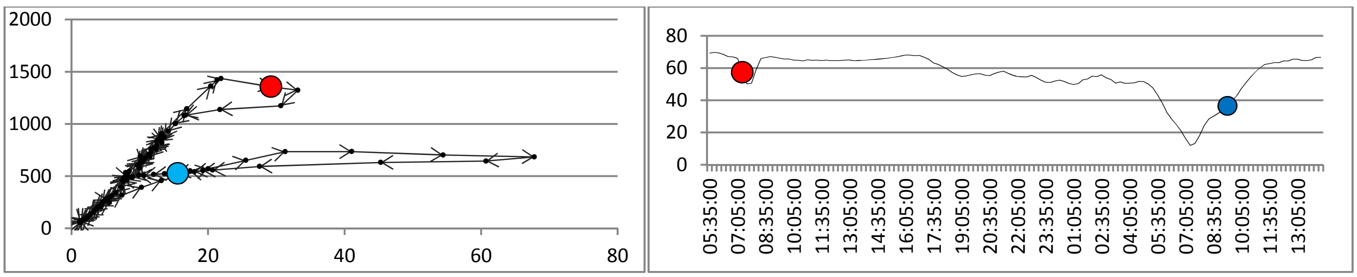


S1085 (694WB at Lexington Ave) 2012.Feb.28-29

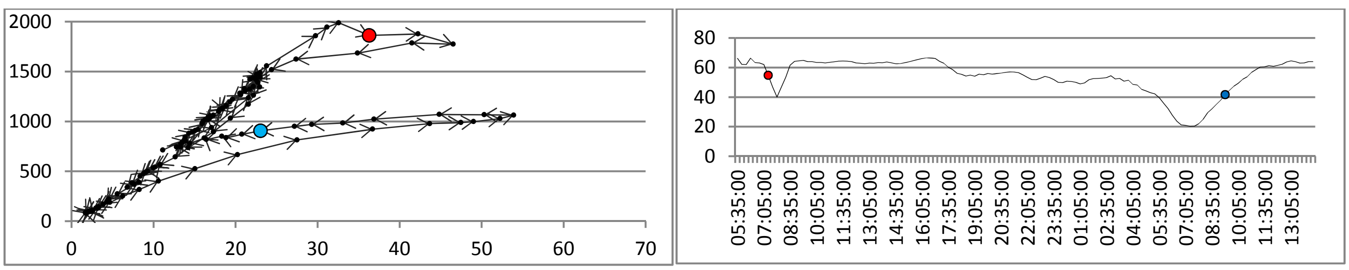
Figure 3.1.6 Traffic-flow variations (q-k, u-t) during February 28-29, 2012, snow event: 694 WB (2)



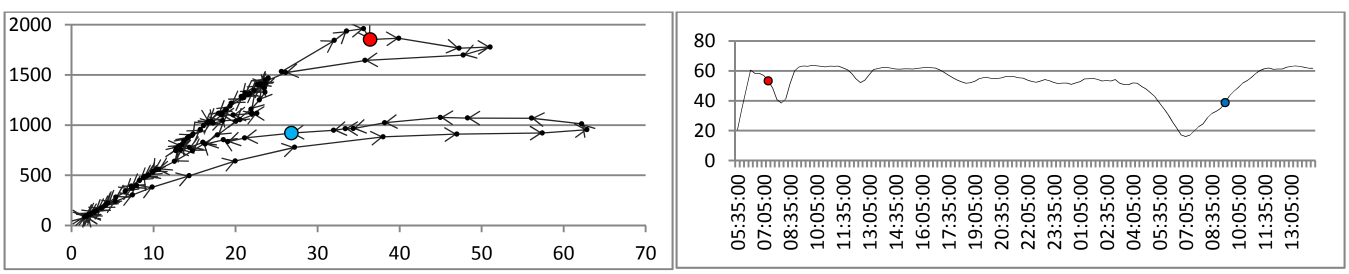
S1464 (35E SB at I-694) 2012.Feb.28-29



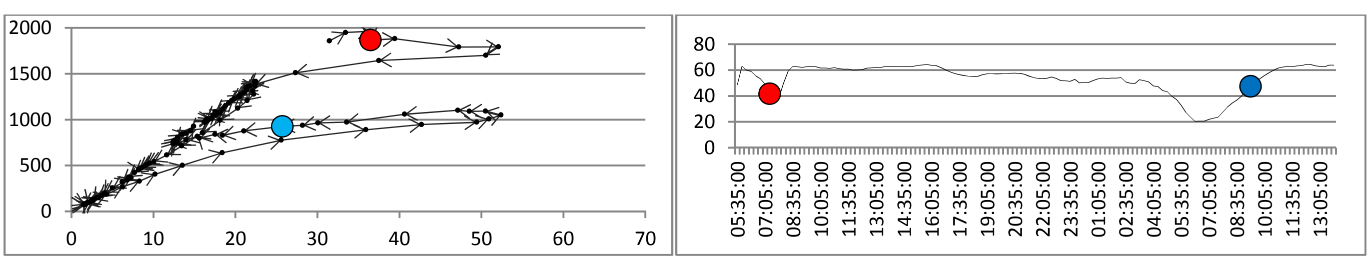
S633 (35E SB at Little Canada Rd) 2012.Feb.28-29



S635 (35E SB at Co Rd B) 2012.Feb.28-29

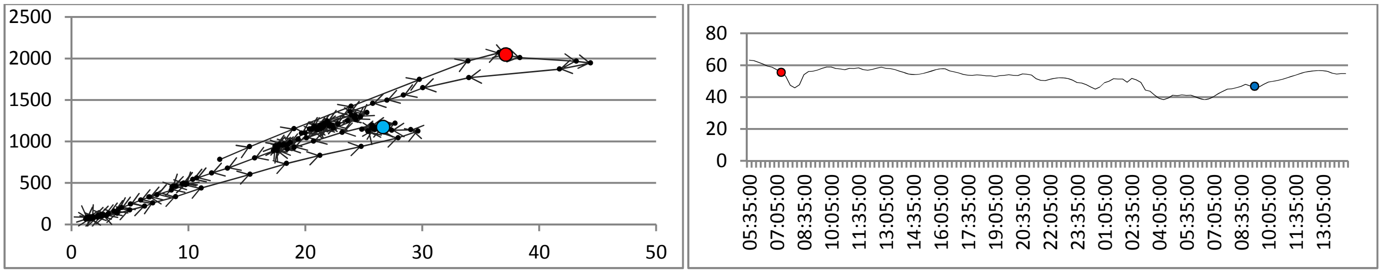


S636 (35E SB at Roselawn Ave) 2012.Feb.28-29

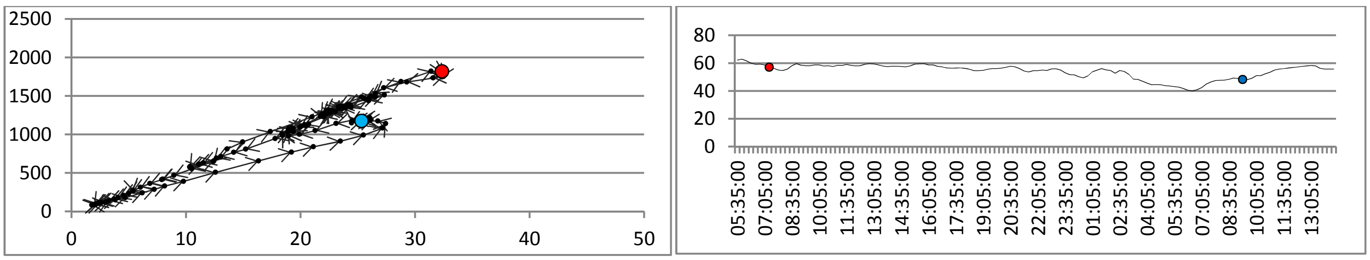


S637 (35E SB at Larpenteur Ave) 2012.Feb.28-29

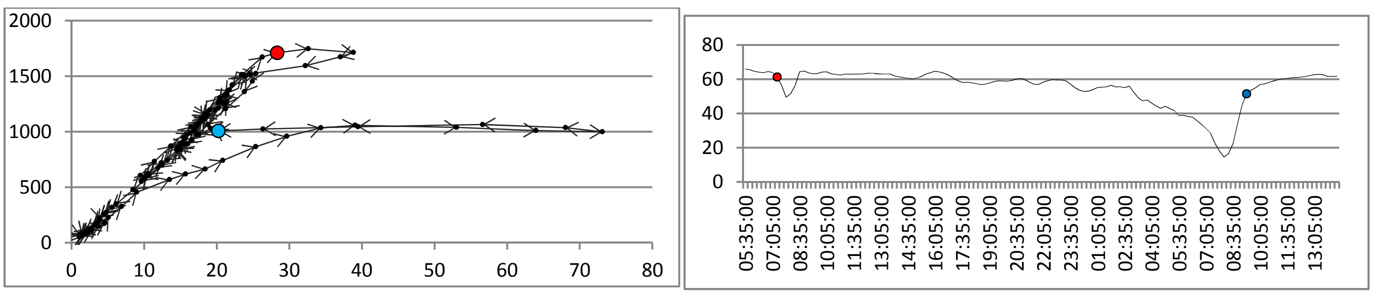
Figure 3.1.7 Traffic-flow variations (q-k, u-t) during February 28-29, 2012, snow event: 35E SB



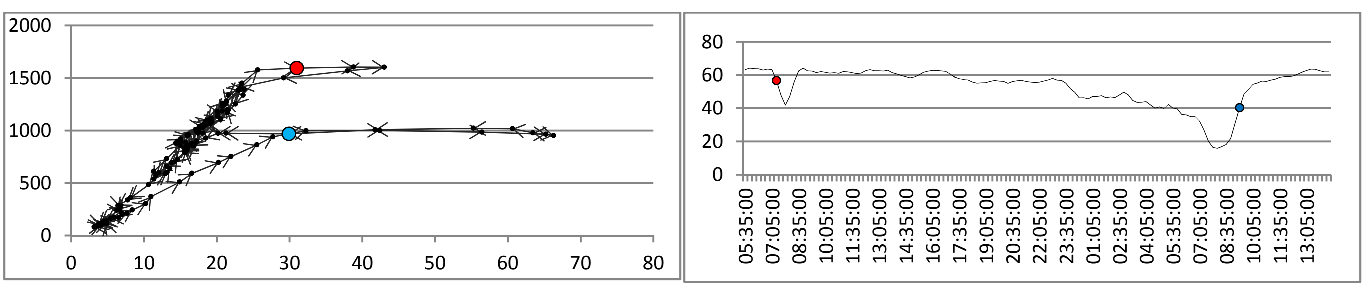
S500 (94WB at John Ireland Blvd) 2012.Feb.28-29



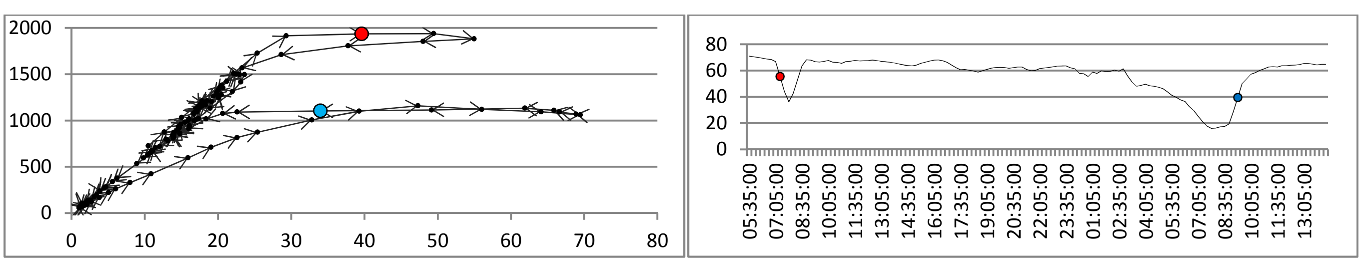
S546 (94WB at Marion St) 2012.Feb.28-29



S788 (94WB at Victoria St) 2012.Feb.28-29

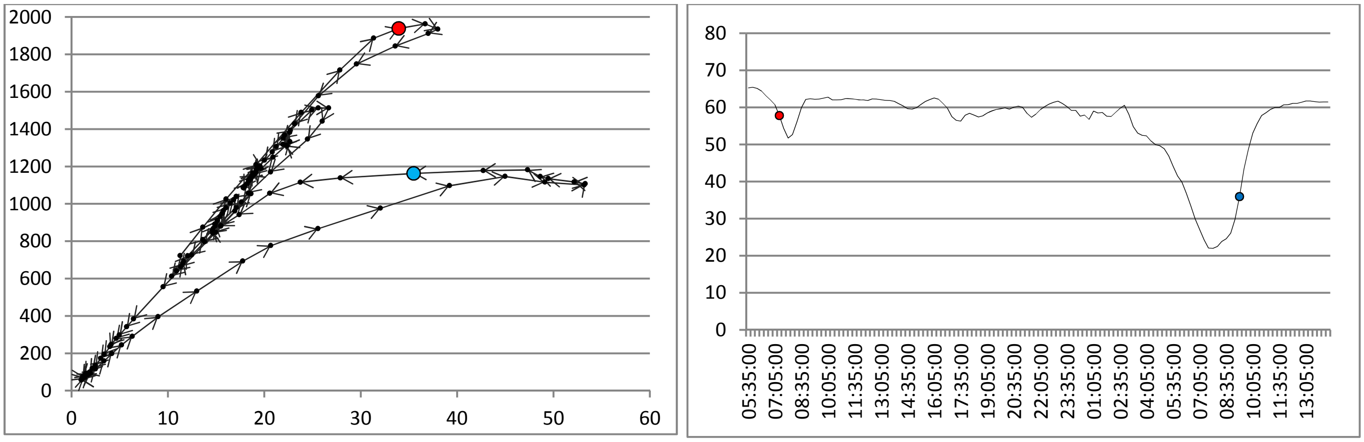


S548 (94WB at Lexington Ave) 2012.Feb.28-29

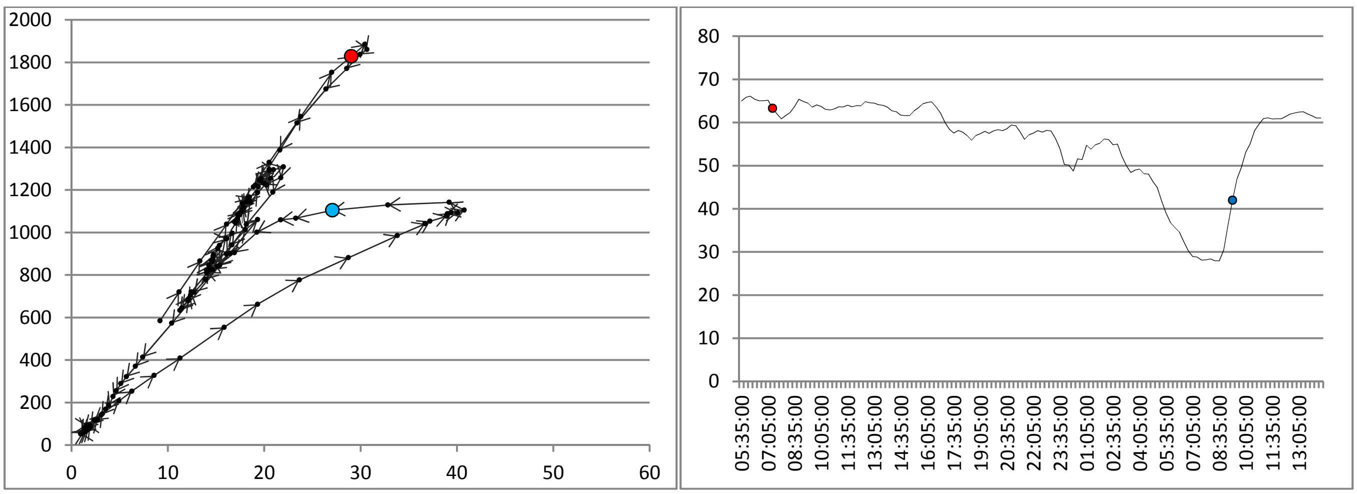


S787 (94WB at Hamline Ave) 2012.Feb.28-29

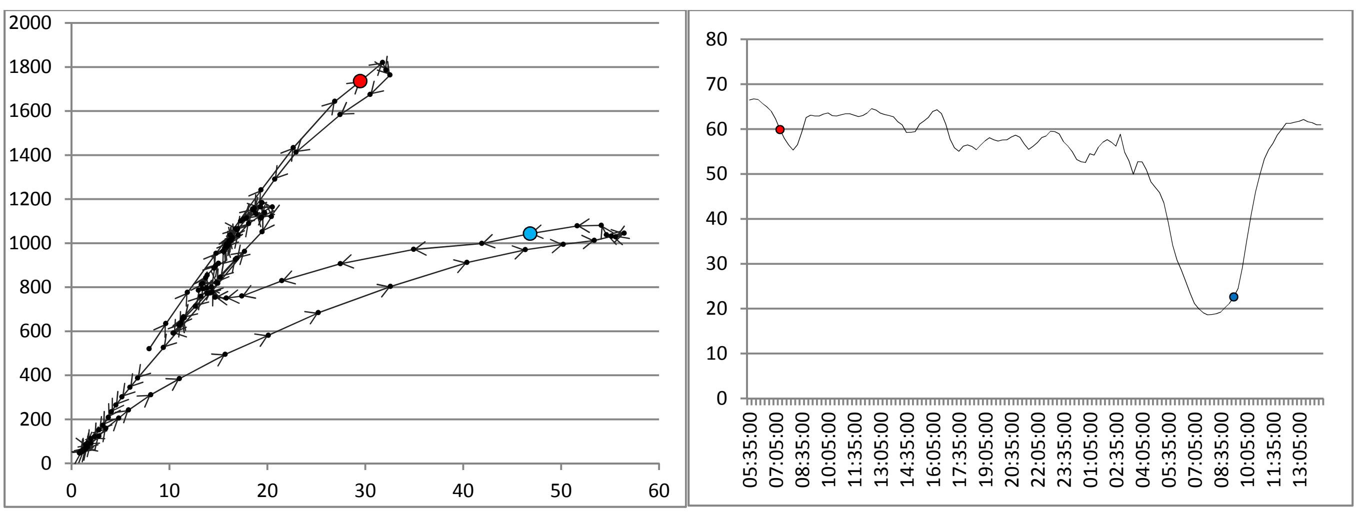
Figure 3.1.8 Traffic-flow variations (q-k, u-t) during February 28-29, 2012, snow event: 94 WB (1)



S549 (94WB at Snelling Ave) 2012.Feb.28-29

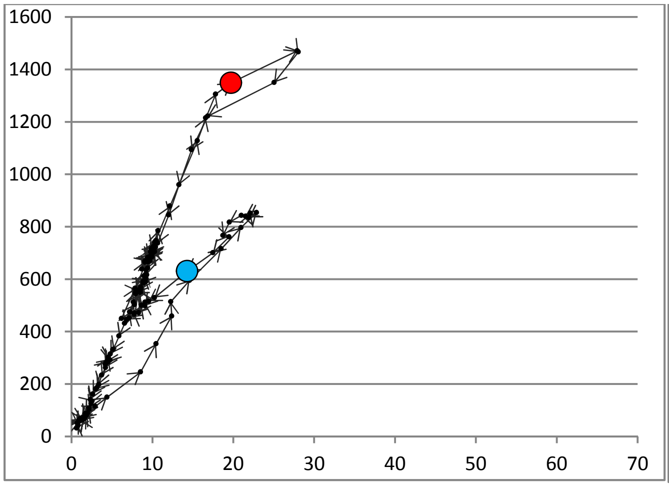


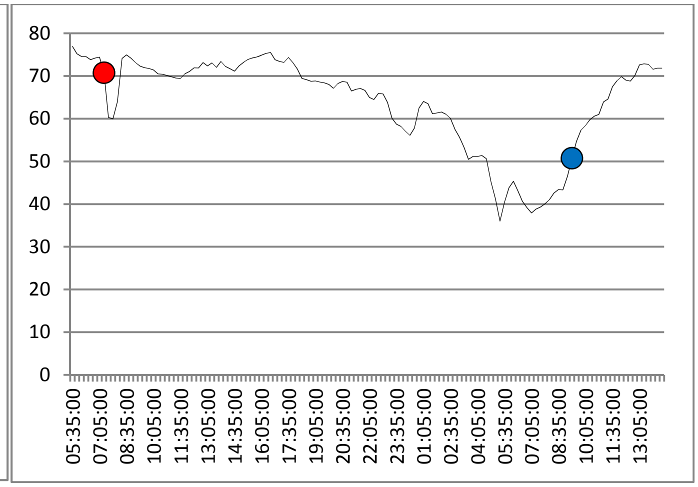
S786 (94WB at Prior Ave) 2012.Feb.28-29



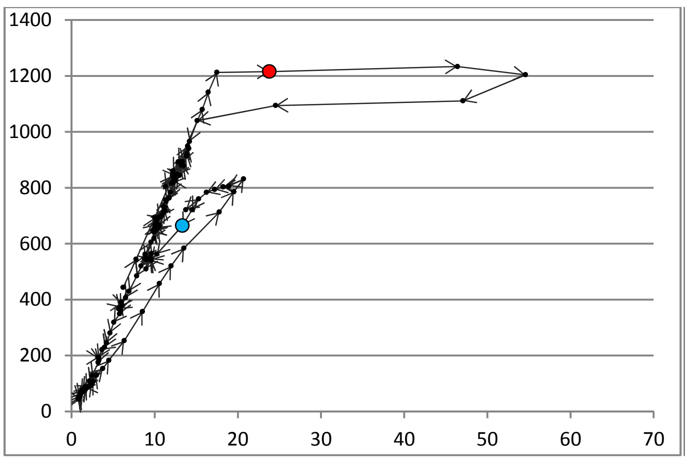
S550 (94WB at Vandalia Ave) 2012.Feb.28-29

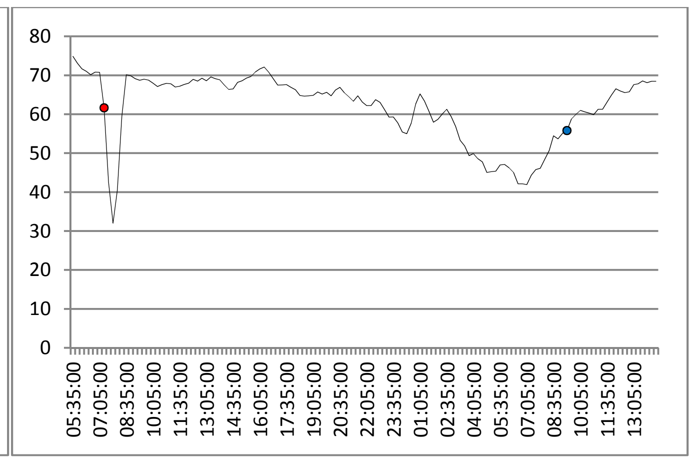
Figure 3.1.9 Traffic-flow variations (q-k, u-t) during February 28-29, 2012, snow event: 94 WB (2)



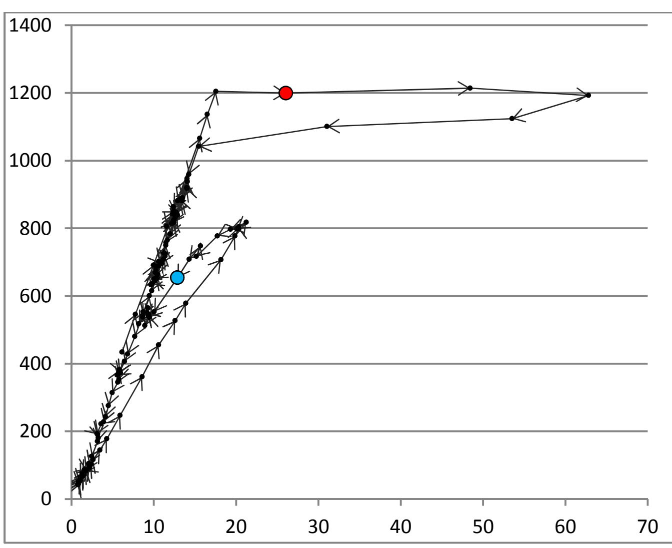


S1175 (52NB at Concord St) 2012.Feb.28-29





S1176 (52NB at Eaton St) 2012.Feb.28-29



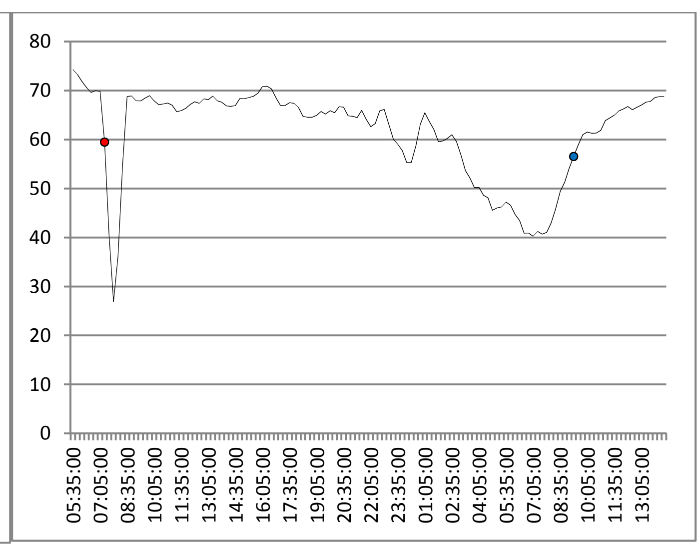
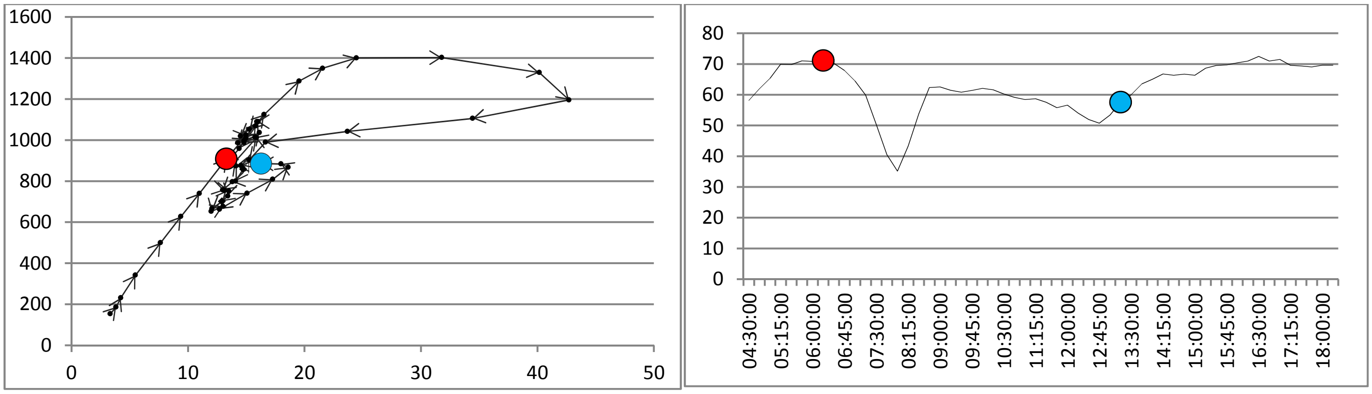
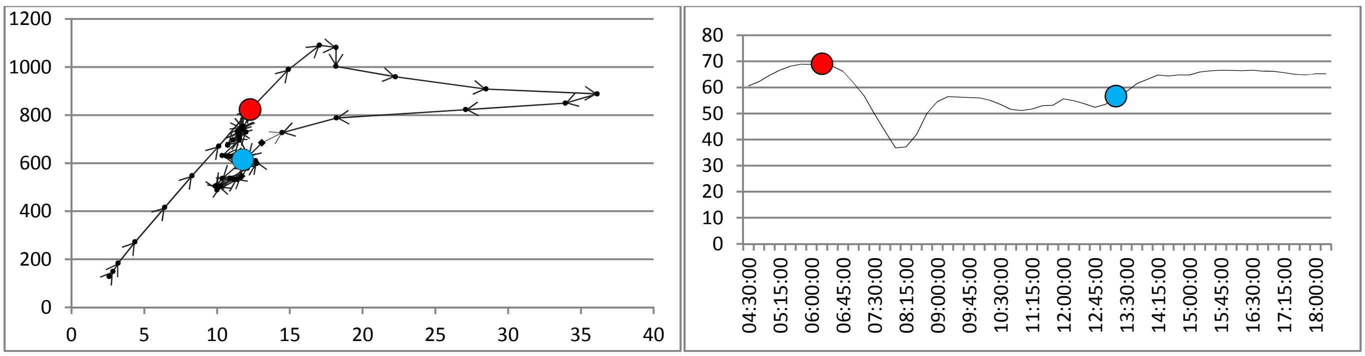


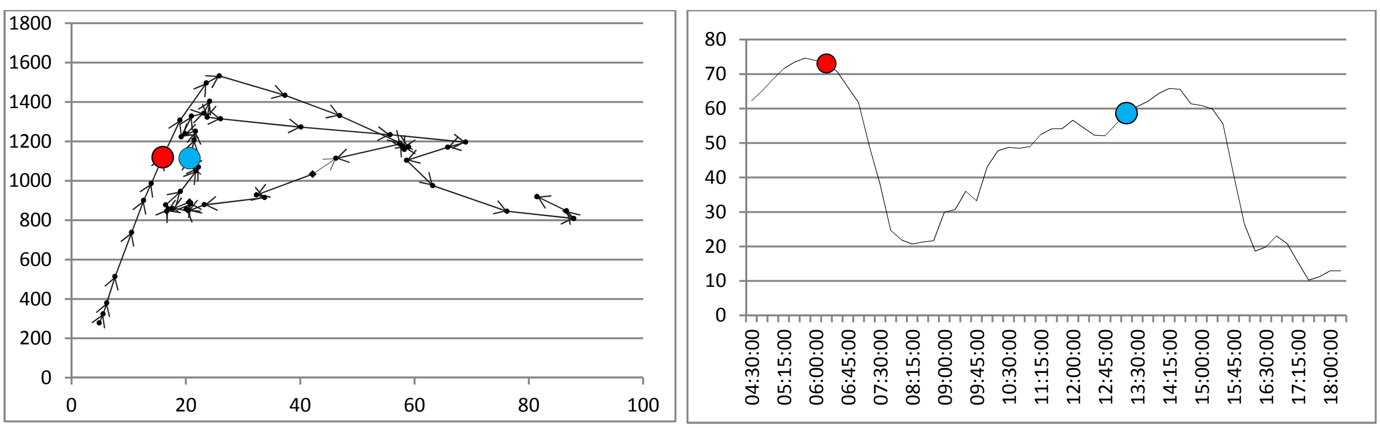
Figure 3.1.10 Traffic-flow variations (q-k, u-t) during February 28-29, 2012, snow event: 52 NB



S1457 (694WB at I-35E) 2012.Jan.20

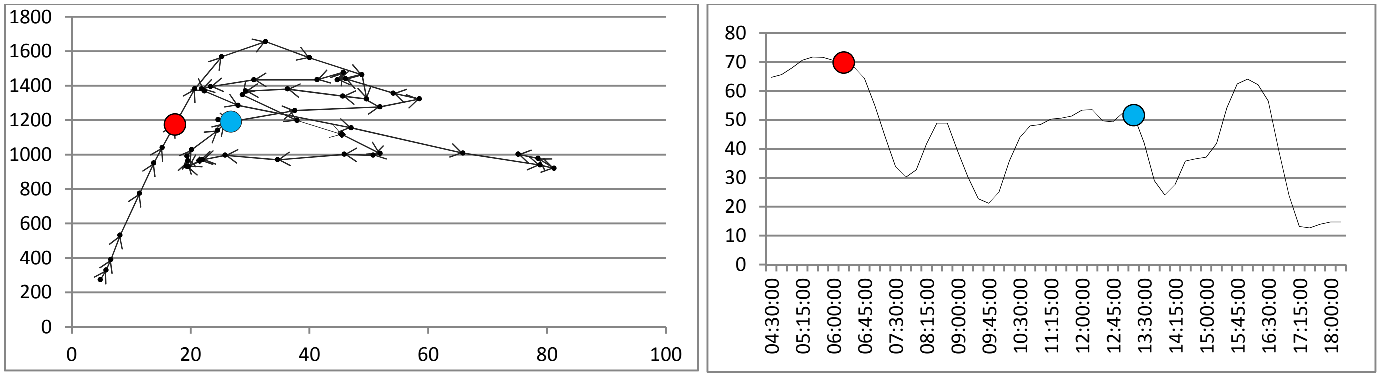


S1459 (694WB at I-35E) 2012. Jan.20

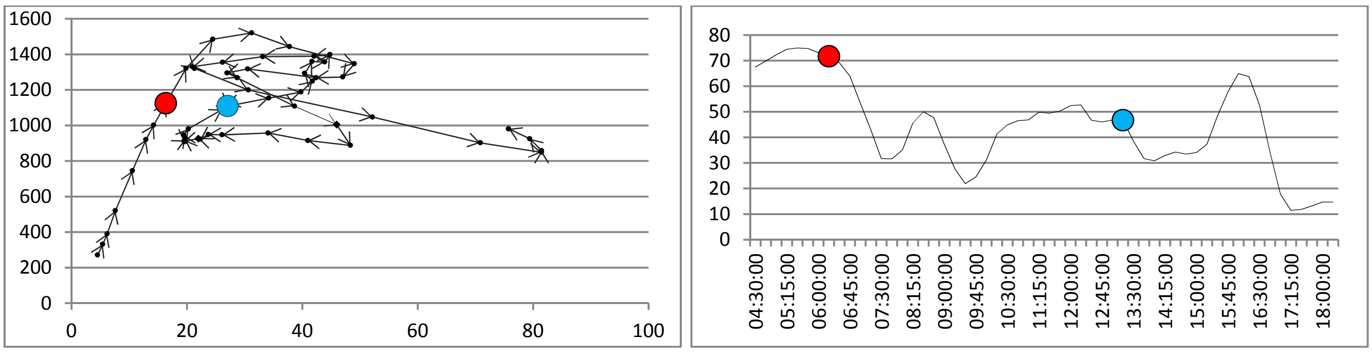


S1461 (694WB at Rice St) 2012. Jan.20

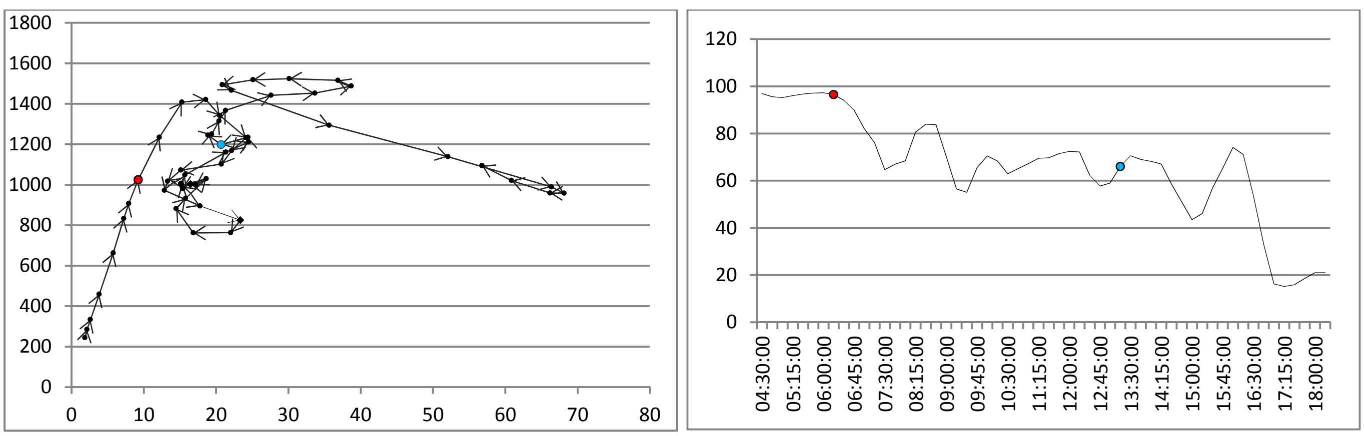
Figure 3.1.11 Traffic-flow variations (q-k, u-t) during January 20, 2012, snow event: 694 WB (1)



S1083 (694WB at Rice St) 2012. Jan.20

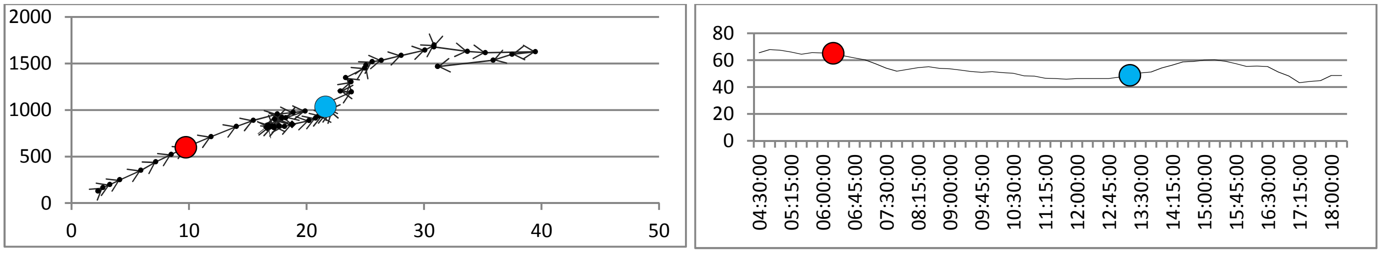


S1084 (694WB at Victoria St) 2012. Jan.20

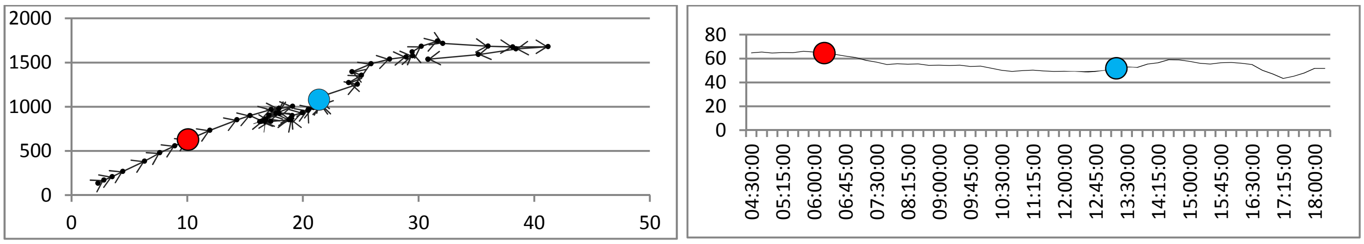


S1085 (694WB at Lexington Ave) 2012. Jan.20

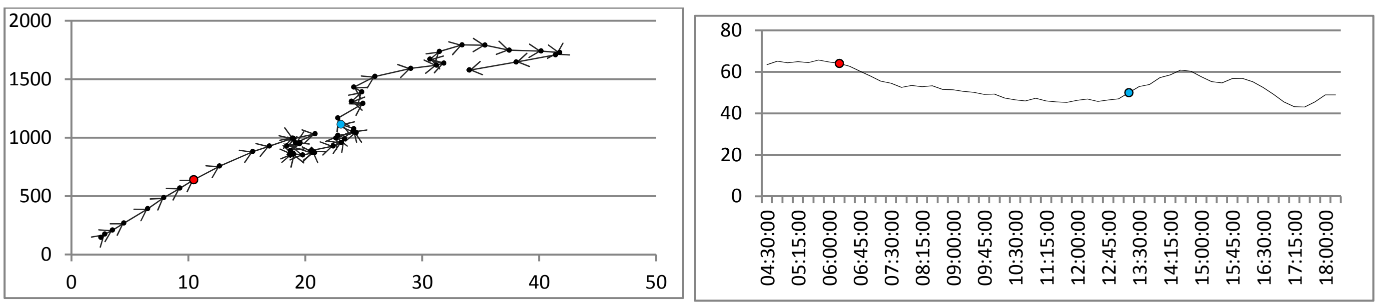
Figure 3.1.12 Traffic-flow variations (q-k, u-t) during January 20, 2012, snow event: 694 WB (2)



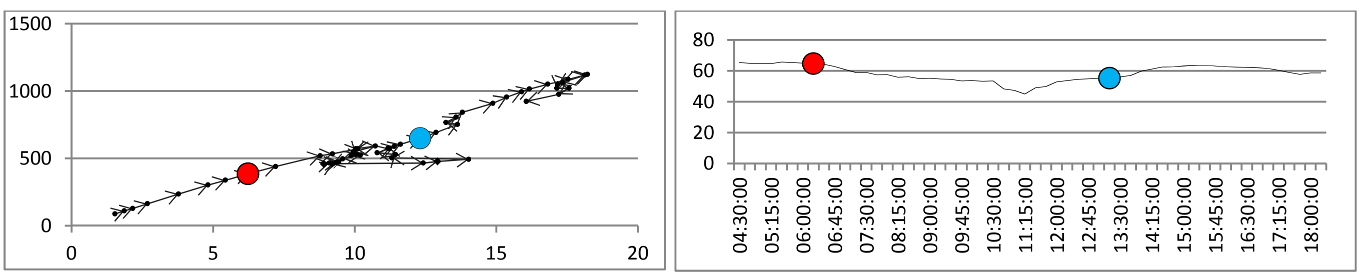
S626 (35E NB at Larpenteur Ave) 2012. Jan.20



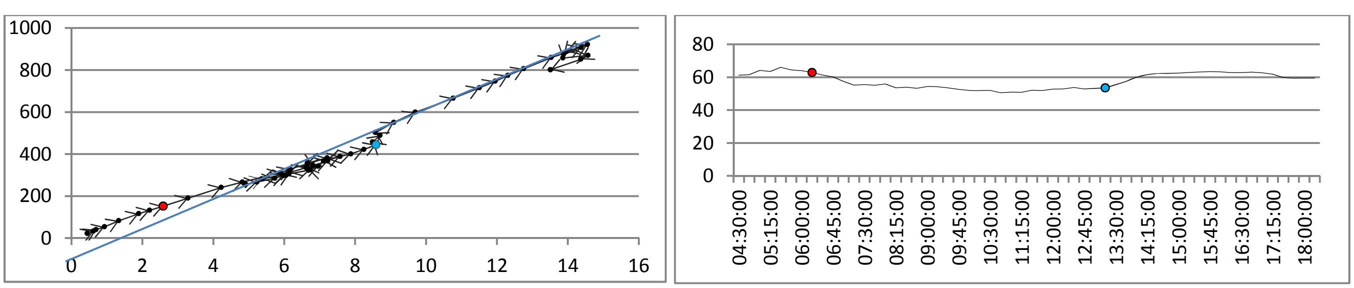
S627 (35E NB at Roselawn Ave) 2012. Jan.20



S628 (35E NB at Co Rd B) 2012. Jan.20

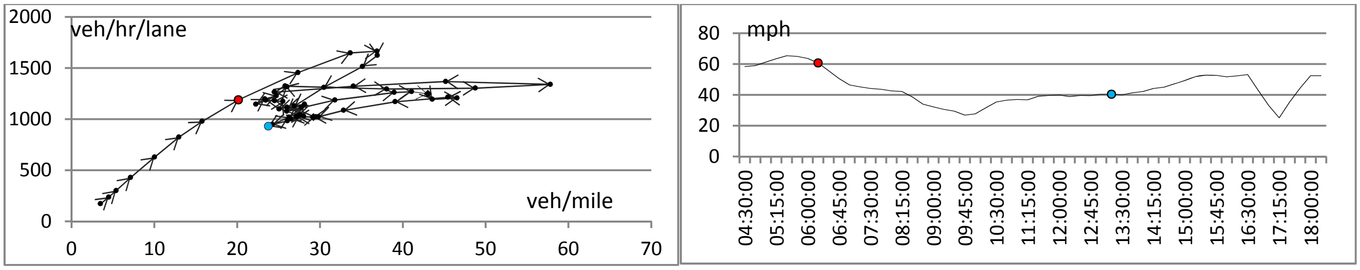


S630 (35E NB at Little Canada Rd) 2012. Jan.20

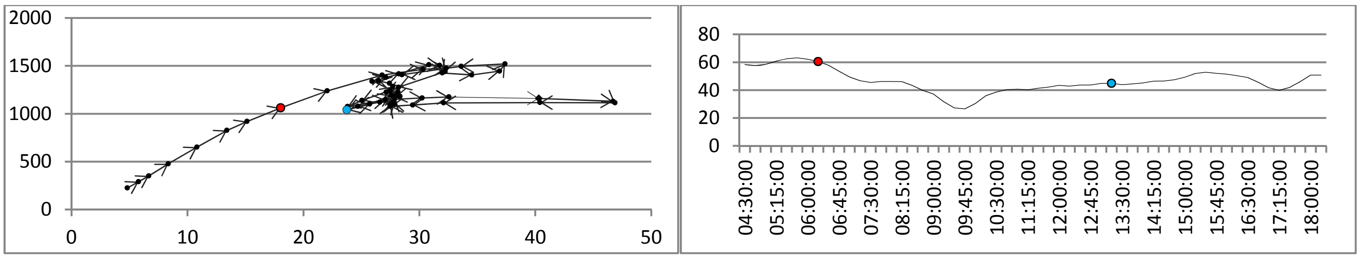


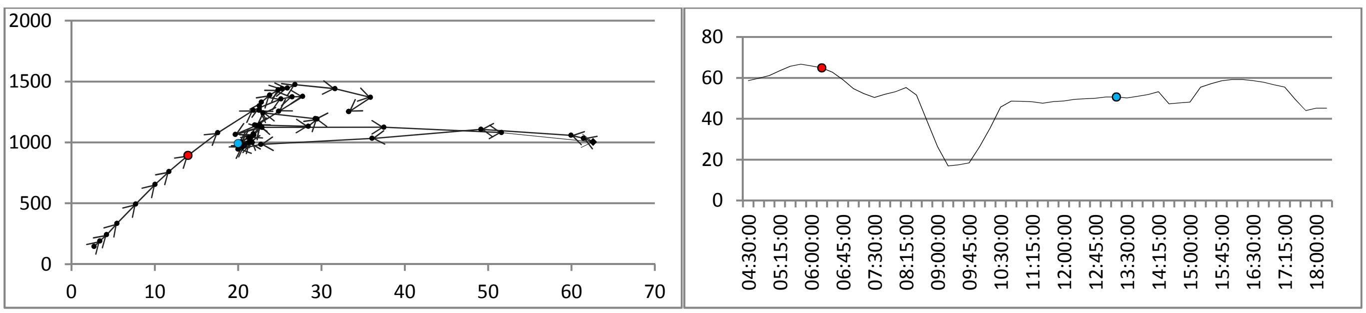
S1447 (35E NB at I-694) 2012. Jan.20

Figure 3.1.13 Traffic-flow variations (q-k, u-t) during January 20, 2012, snow event: 35E NB



S500 (94WB at John Ireland Blvd) 2012. Jan.20


S546 (94WB at Marion St) 2012. Jan.20


S788 (94WB at Victoria St) 2012. Jan.20

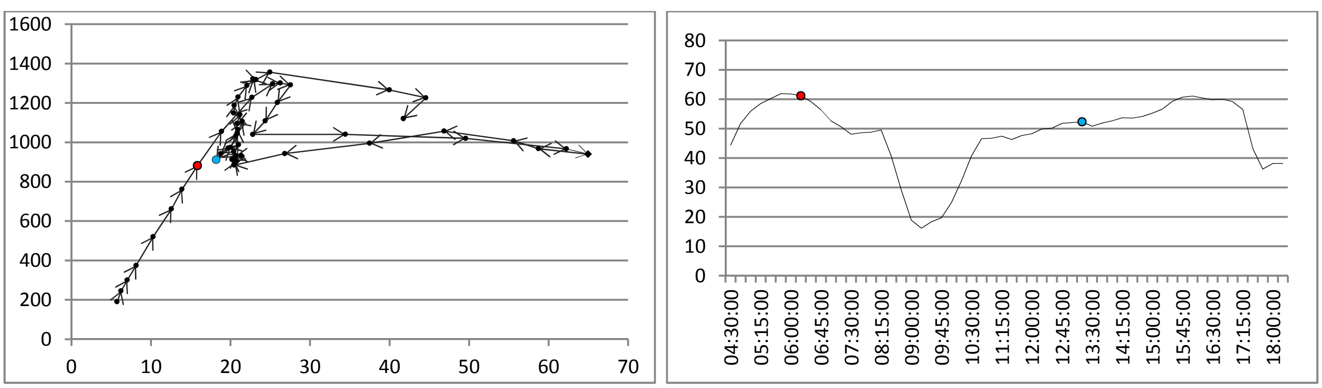
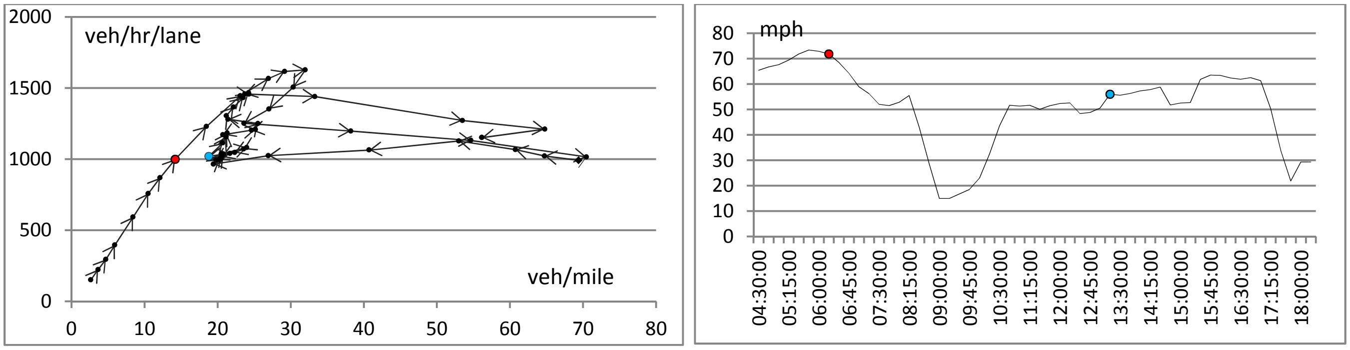
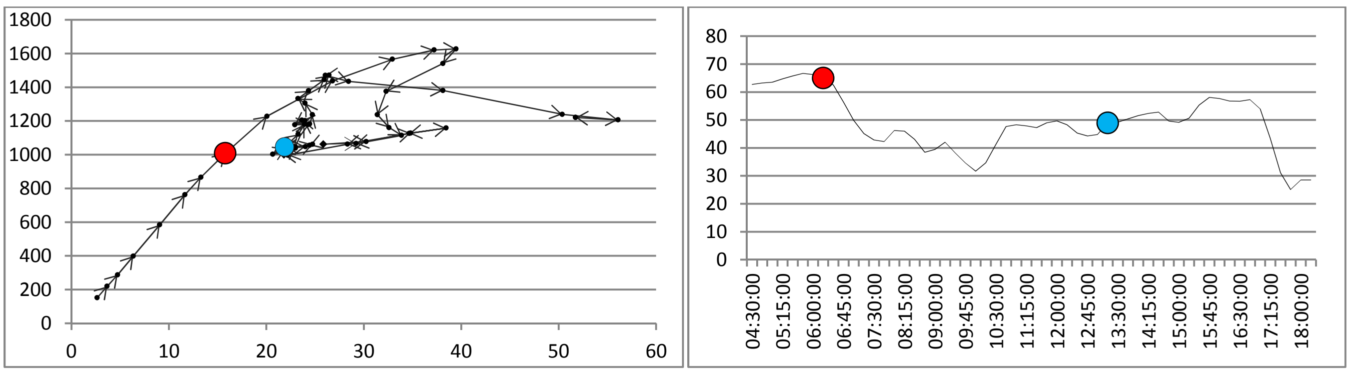

S548 (94WB at Lexington Ave) 2012. Jan.20

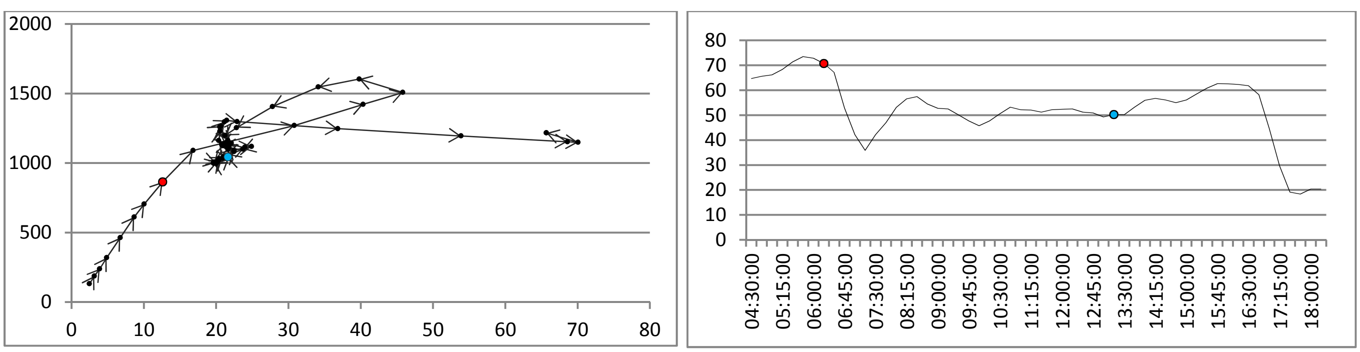
Figure 3.1.14 Traffic-flow variations (q-k, u-t) during January 20, 2012, snow event: 94 WB (1)



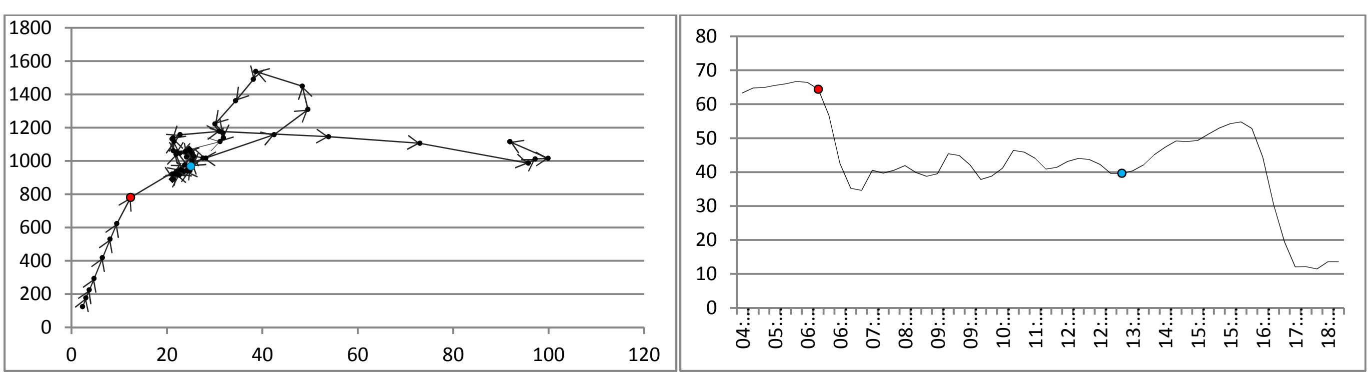
S787 (94WB at Hamline Ave) 2012. Jan.20



S549 (94WB at Snelling Ave) 2012. Jan.20

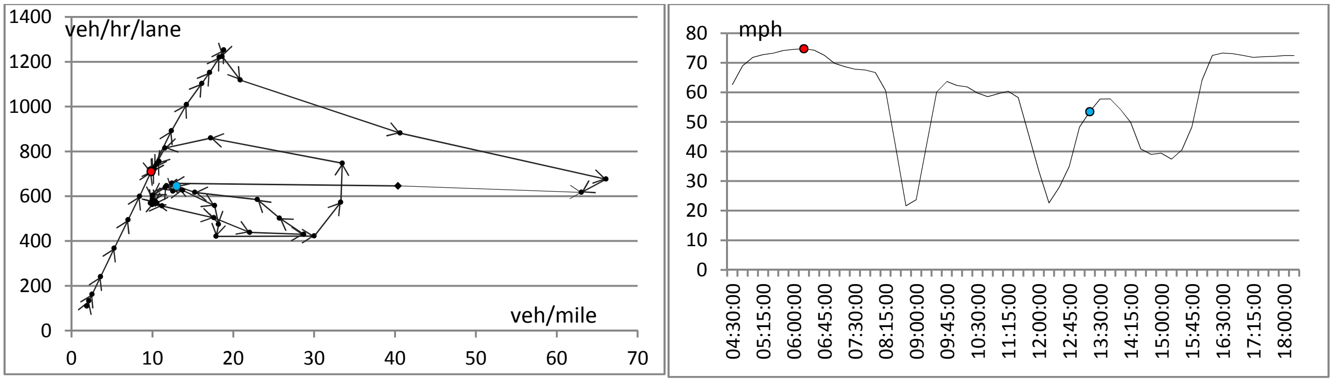


S786 (94WB at Prior Ave) 2012. Jan.20

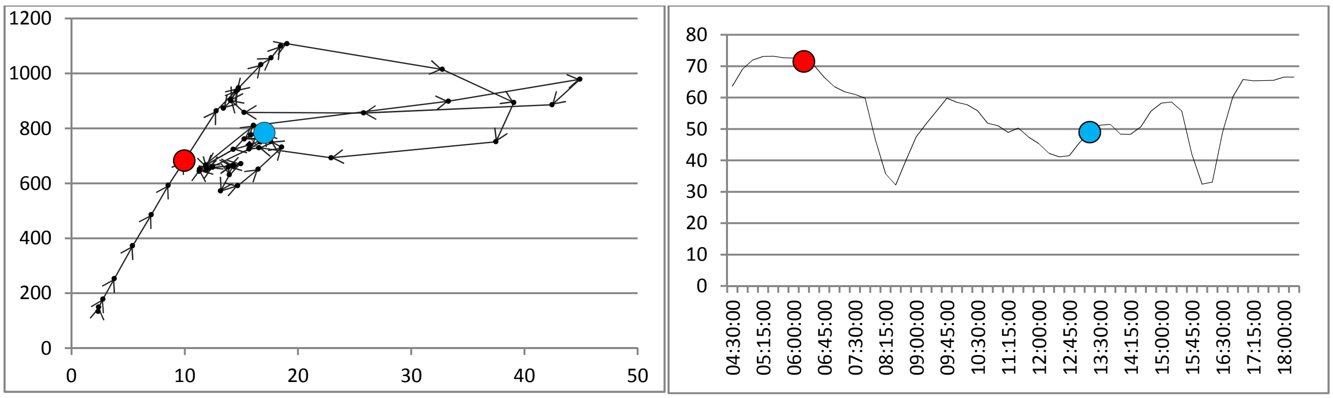


S550 (94WB at Vandalia Ave) 2012. Jan.20

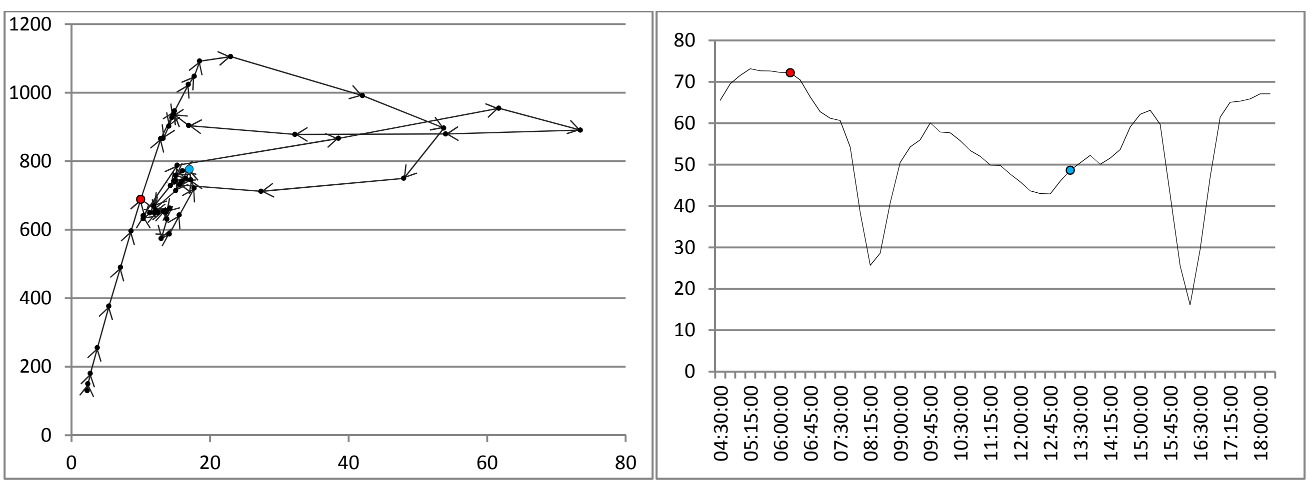
Figure 3.1.15 Traffic-flow variations (q-k, u-t) during January 20, 2012, snow event: 94 WB (2)



S1175 (52NB at Concord St) 2012. Jan.20



S1176 (52NB at Eaton St) 2012. Jan.20



S1177 (52NB at Plato Blvd) 2012. Jan.20

Figure 3.1.16 Traffic-flow variations (q-k, u-t) during January 20, 2012, snow event: 52 NB

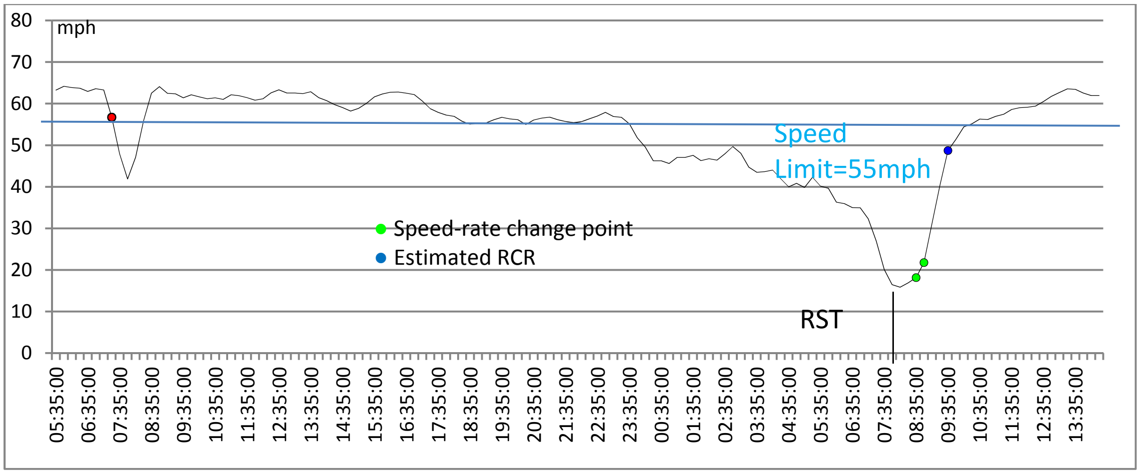


Figure 3.1.17 Speed-change points during the speed recovery period: 94 WB S548 on February 28-29, 2012

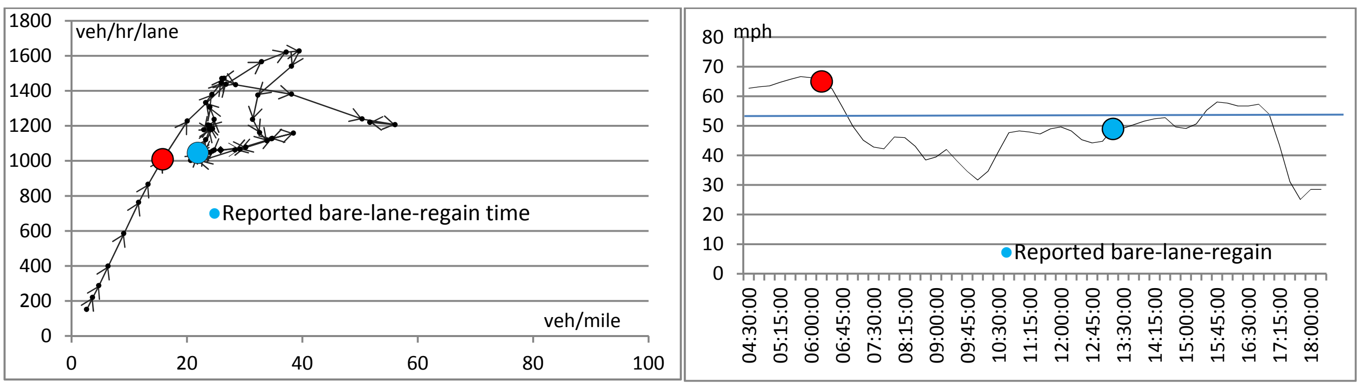


Figure 3.1.18 Flow rate-density and speed variation patterns at Station 549 (94WB at Snelling), January 20, 2012

Figure 3.1.18 shows the traffic variation patterns at the Stations 549 on 94WB, where the speed recovery was influenced by both the road surface and traffic-flow conditions as indicated in the flow rate-density (q-k) plot. As indicated in the q-k plot, after the bare-lane is regained, the flow rate starts to increase vertically, i.e., the speed increases significantly while the density level remains relatively same. This implies that, in case of the uncongested medium-level traffic-flow, the speed level starts to increase right after the road condition is improved until it reaches an appropriate level, i.e., below its free flow speed, for the given density. The q-k plot also indicates that, as the traffic density increases, the traffic speed starts to decrease. In this study, for those cases where the traffic speed does not recover to the free flow level, the RCR time point is defined as the time when a significant speed change occurs before the speed level starts to decrease because of the increased traffic-flow.

3.2 Development of an Automatic Procedure to Identify Traffic-Flow Variation Process during Snow Events

In this section, an automatic procedure to identify the speed change and the road condition recovered times is developed using the traffic detector data that can be collected from the metro freeway network. In the proposed procedure, 15- min flow rate, density and speed measurements from the detector stations on the freeway mainline for a given snow event are used as the input data. Figure 3.2.1 shows the overall process developed in this study. The rest of this section describes the detailed procedure of the individual modules, which are incorporated into the TICAS (Traffic Information and Condition Analysis System) in the next chapter.

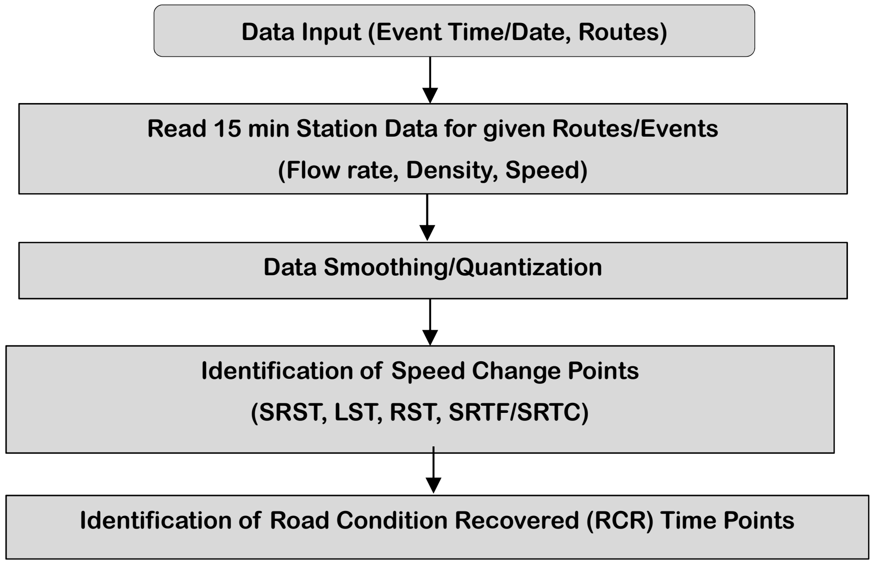


Figure 3.2.1 Overview of identification procedure

3.2.1 Speed Change Point Identification Process

Data Smoothing

First, the 15-min speed measurements from each detector station are smoothed to filter out the random fluctuations in the raw traffic data. The specific formula for smoothing used in this study is as follows:

$$U_{s,i,t} = \text{Average}\ [U_{i,t-1}, U_{i,t}, U_{i,t+1}]$$

where, $U_{s,i,t}$ = Smoothed speed at station i for time interval t,

$U_{i,t}$ = Measured speed at station i for time interval t.

The above method tries to extract the speed variation trend while reducing the time lag in the smoothed data.

Data Quantization

Quantization refers to the process of approximating the continuous set of values in a given speed data with a finite set of values. This method is used to find out the approximate locations where there are substantial changes in speed values. First, it identifies a reference speed value by averaging the first *n* data points. The initial reference value is compared with each data point through time, and if the difference between the reference value and a speed at time *t* is greater than the pre-determined threshold, then time *t* is identified as the speed change point and the reference value is updated with the speed at *t*. This process continues for all the data points and results in the discontinuous line graph as shown in Figure 3.2.2.

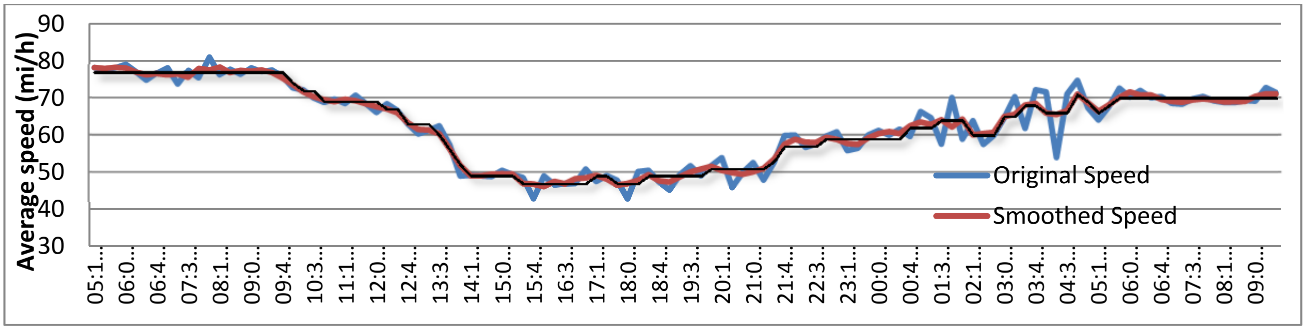


Figure 3.2.2 Example smoothing and quantization with I-35E snow event data

Identification of Speed Change Points

Speed Reduction Starting Time (SRST), Low Speed Time (LST) and Recovery Starting time (RST)

Figure 3.2.3 illustrates the identification process of the speed change points in a speed-time space with both smoothed and quantized speed data. The initial SRST (Speed Reduction Starting Time) is found as the first point of speed reduction in a quantized graph. In this study, the SRST is searched from two hours before the starting time of a given snow event to reflect the variations in the local weather conditions. This value is further refined by searching back for the highest speed point from the initial SRST on the smoothed speed graph as illustrated in Figure 3.2.3. The Low Speed Time (LST) is defined as the time when the speed reaches the lowest level in a smoothed graph and the time point where the speed starts to increase continuously after the LST is identified as the Recovery Starting Time (RST). If there are multiple speed recovery starting points within a given data range, the nearest one to the end time of a given event is selected as the RST. The RST can also happen after the end time of a given event depending on the plowing operations. Both LST and RST points are first identified from the quantized graph and then refined with the smoothed data as shown in Figure 3.2.3.

Speed Recovered Time Points (SRTF/SRTC)

After the bare-lane is regained, the recovered speed level can or cannot reach the free flow speed depending on the traffic-flow conditions at a given location. I.e., under the light traffic conditions, the speed level could reach its free flow speed level, while medium to heavy traffic flows would force the speed values to be at certain levels below its free flow speed. In this study, two types of the speed recovered time are defined: Speed Recovered Time to Free flow speed (SRTF) and Speed Recovered Time to Congested speed (SRTC).

SRTF

Figure 3.2.4 shows the case where the recovered speed reaches the free flow speed level. In this study, the time *t* satisfying the following condition is considered as SRTF:

$U_{s,i,t} >= (U_{i,limit} - \Delta)$ for one hour, where, $U_{i,limit}$ = speed limit at location i,

Δ = parameter to reflect the measurement error, only for $U_{i,limit} >= 60$ mph.

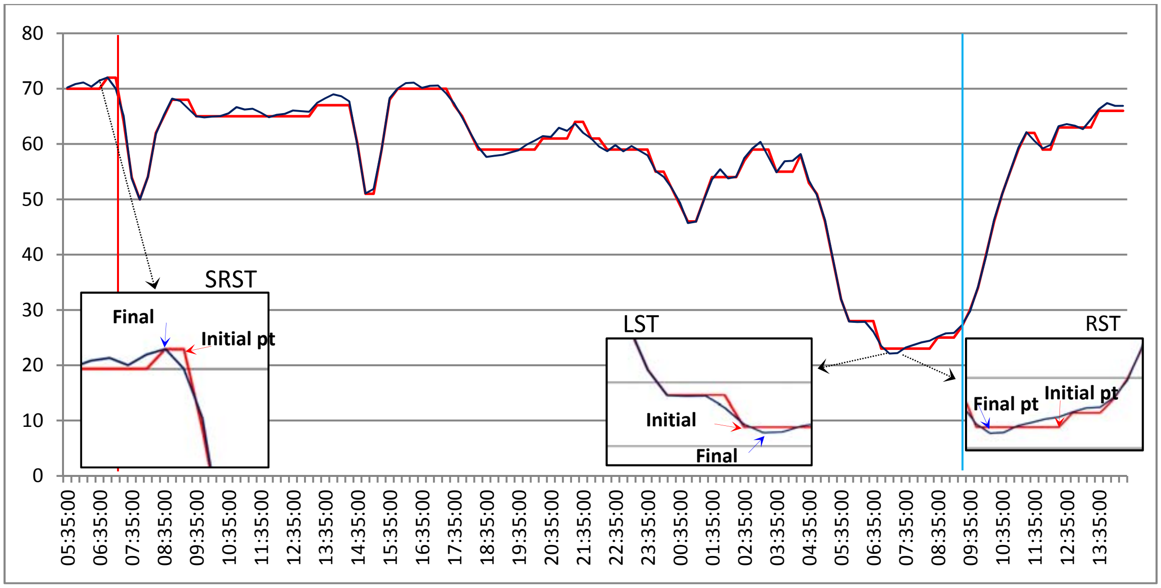


Figure 3.2.3 Identification of SRST, LST, RST of speed variation during snow event

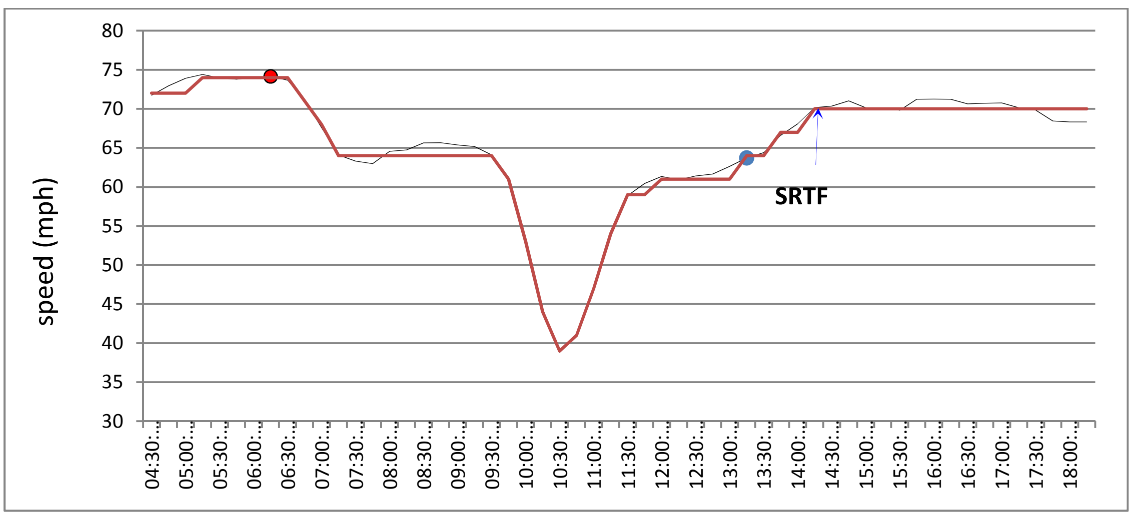


Figure 3.2.4 Speed variation patterns which has SRTF (I-35E SB S1462 on January 20, 2012)

SRTC

Figure 3.2.5 shows the case where the speed does not recover to its free flow speed level because of the increase in traffic density. First, the time point *i* that satisfies the following conditions in the quantized speed-time graph is found as the initial SRTC:

$$\begin{cases} U_j - U_i < 0 \\ K_j - K_i > 0 \end{cases} \quad \textit{where, } j > i \textit{ for at least 2 time intervals.}$$

After the initial SRTC is identified, the final SRTC is determined as the highest speed point before the initial SRTC on the smoothed speed-time graph as illustrated in Figure 3.2.5.

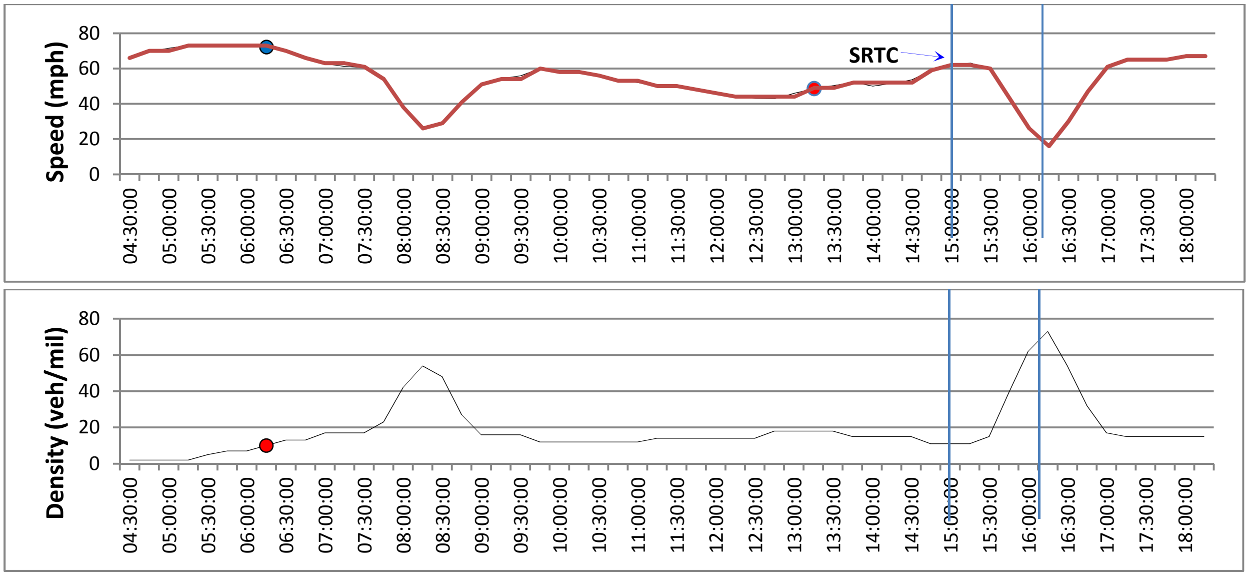


Figure 3.2.5 Example quantized speed and density variations with SRTC (T.H.52 NB S1177 on January 20, 2012)

3.2.2 Identification of Road Condition Recovered Time

Cases with SRTF:

Based on the analysis of the traffic behavior in Section 3.1, the Road Condition Recovered (RCR) time is defined as follows:

If speed level at RST <= (50 – β) mph,

RCR time = the last significant speed change point before the speed reaches its posted speed limit,

Else, RCR time = the last significant speed change point before SRTF.

where, β = threshold range parameter, e.g., 2 mph.

The above process is to reflect the possibilities of having the RCR times at or above the posted speed limits under the light snow conditions. Further, depending on the speed recovery patterns after RST, two different procedures are developed to identify the RCR time at each station. Figure 3.2.6 show two different speed recovery patterns, while in each case the recovered speed reached its free flow speed level.

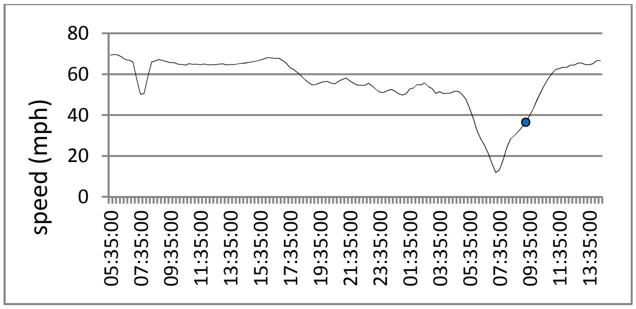
RCR time with Continuous Recovery

For the cases with the continuous speed recovery, as shown in Figure 3.2.6 (a), two highest speed change points are first determined by examining the speed differences between two consecutive time intervals from RST until the time the speed reaches its speed limit. Between those two speed change points, the one close to the speed limit is selected as the RCR point for a given location. The speed differences between two time intervals are calculated as follows:

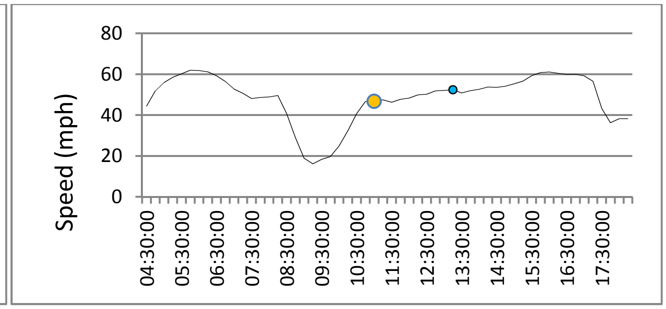
$$[|U_{t+1} - U_t| - |U_t - U_{t-1}|]$$

RCR time with Delayed Recovery

Figure 3.2.6 (b) shows an example case where the speed level at a given location recovers in a discontinuous pattern, As illustrated in this case, in a delayed recovery mode, there can be multiple time points with substantial changes in the speed recovery pattern before the speed recovers to its free flow level. Based on the field data analysis, it is determined that, for this type of situation, the RCR time point is located between the major speed variation pattern change point, shown as a yellow dot in Figure 3.2.6. (b), and the time the traffic speed reaches the speed limit of a given location. After the RCR point search range is determined, the same procedure as with the continuous recovery case is applied to identify the RCR time point.



(a) Station 633 :2/28-29, 2012



(b) Station 788: 1/20, 2012

Figure 3.2.6 Speed recovery patterns with SRTF

Cases with SRTC:

As discussed in 3.1, for the cases with SRTC, the speed recovery is affected by both road and traffic conditions. In this study, the RCR time point with SRTC is defined as the time when the significant speed change is occurred between RST and SRTC, as illustrated in Figure 3.2.7. After SRTC is identified as described in the previous section, the top two high-speed change points are selected between RST and SRTC. The one near the SRTC is finally determined as the RCR point.

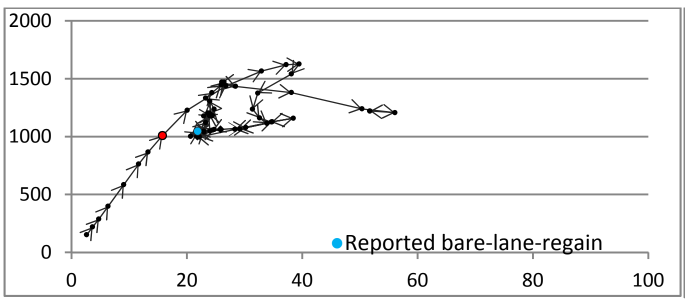


Figure 3.2.7 (a) Flow rate-density plot of St. 549

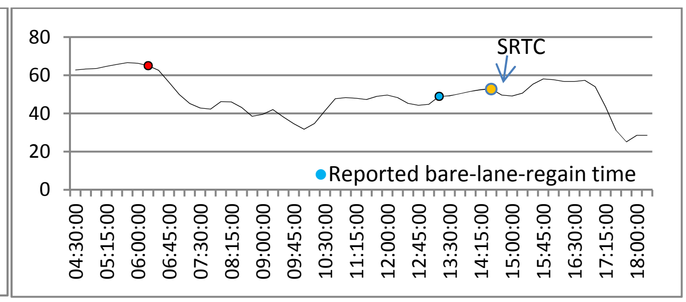


Figure 3.2.7 (b) Speed-time plot of St. 549

Figure 3.2.7 Example case with SRTC: Station 549 (94WB, January 20, 2012)

4. Incorporation of Speed Recovery Identification Process into TICAS

In this chapter, the process developed in this study to automatically identify the speed recovery times from the archived traffic data is incorporated into the TICAS, Traffic Information and Condition Analysis System, being developed in a separate study. TICAS has been developed as the comprehensive analysis system for the Twin Cities' metro freeway network traffic data. Using TICAS, a section of freeway can be defined and all the traffic data for the selected time periods can be downloaded and processed. First, the process from Chapter 3 is refined and coded to be suitable for TICAS. Next, the interface of TICAS is modified to add a set of the input data windows needed for the speed recovery time estimation application. Figure 4.1 shows the main window of the new TICAS that has a new plug-in module for Speed Recovery Time Estimation (SRTE), which can be run inside TICAS.

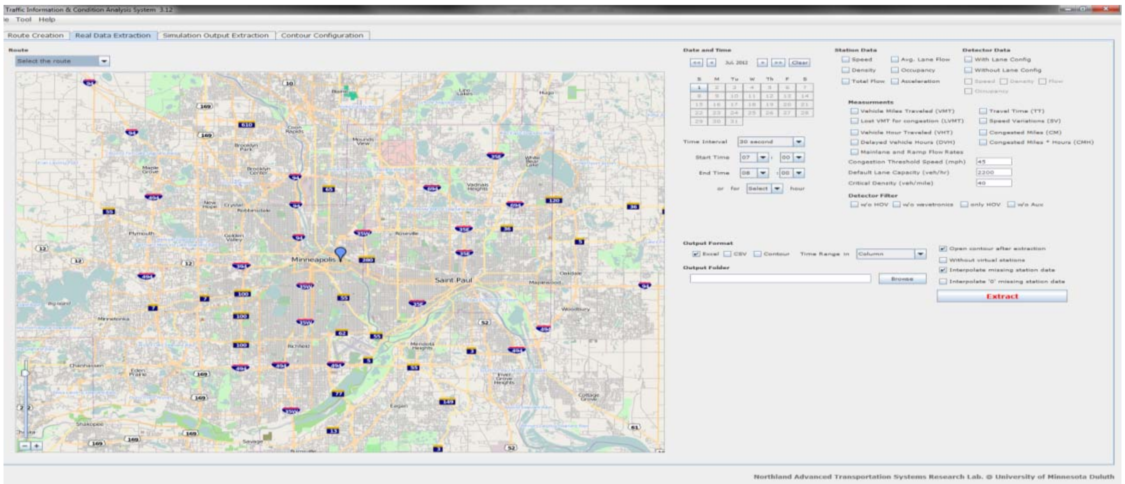


Figure 4.1 TICAS main window

Data Input Process for Speed Recovery Estimation Module (SRTE)

Figure 4.2 shows the main data input window of the SRTE module in TICAS. As shown, it consists of three sections; Event Edition panel, Parameter panel and Debugging window. Figures 4.2-4 illustrates each sub-window for entering data and route information. The data input process and the types of the data for the SRTE application is as follows:

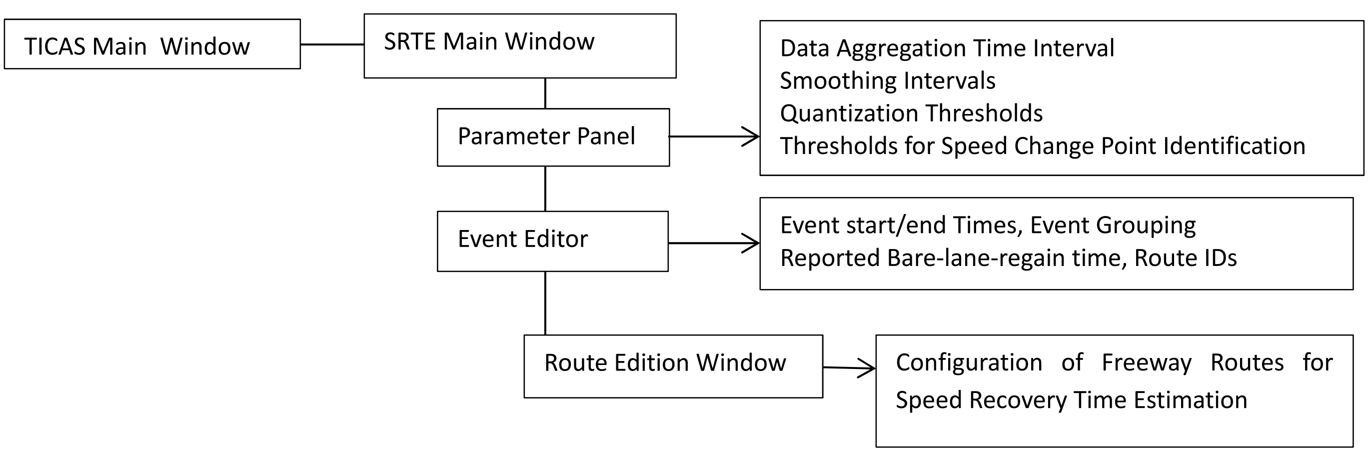


Figure 4.2 SRTE data input process

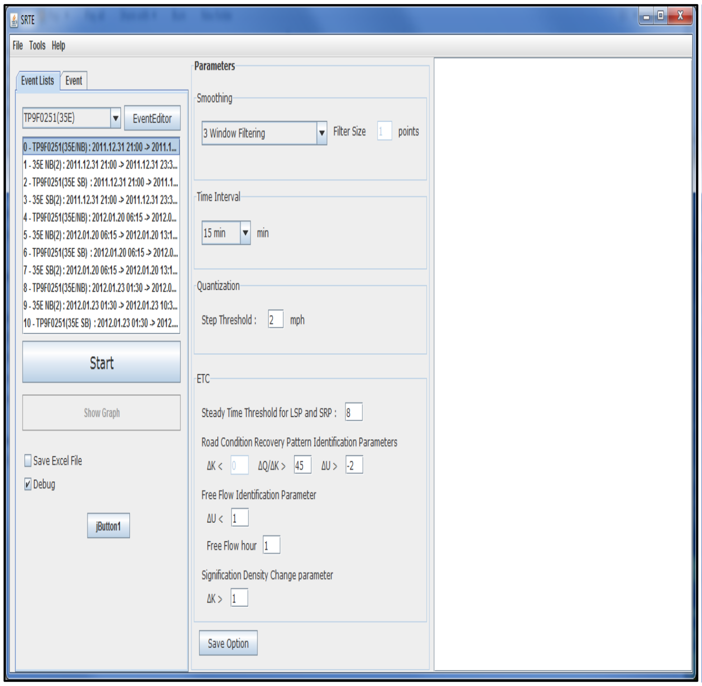


Figure 4.3 Main menu window for SRTE module

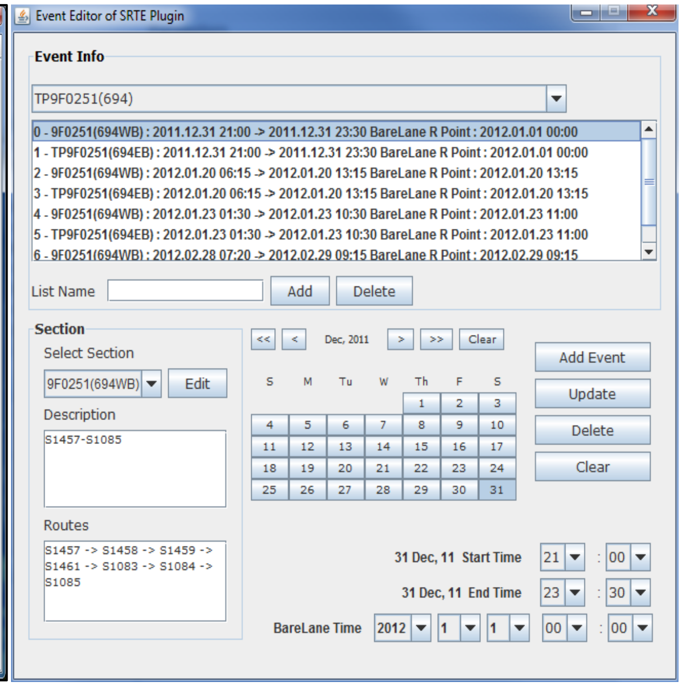


Figure 4.4 Event editor window

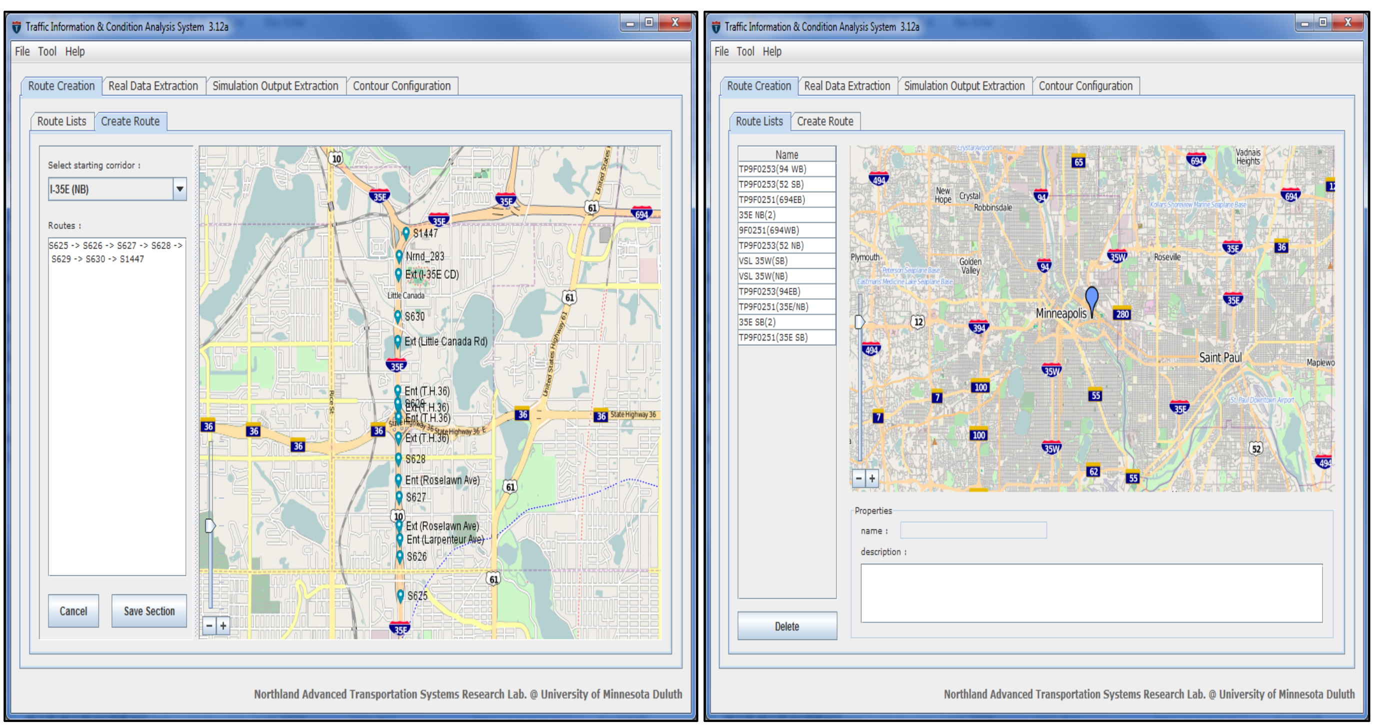


Figure 4.5 Route editor within event editor

Output from SRTE Module

The current version of the SRTE module has two types of output formats: Excel and Graphical. The output data presented in the Excel format includes:

1) Summary Results of All the Routes included in a Given Event (Figure 4.6)
   For all the detector stations included in a route
   : Estimates of SRST, LST, RST, SRT and RCR Time points
   : Estimates of the Time points when the recovered speed reached certain pre-specified levels, e.g., 40 mph, 45 mph, 50 mph, 55 mph, etc.
2) Individual Detector Station Output (Figure 4.7)
   : flow rate, density, and speed data, raw/smoothed and quantized, for each station in the routes

The graphical output from SRTE includes the variations of the speed data through time for each detector station in a route. Figure 4.8 shows example output graphs for a station with raw, smoothed and quantized speed data through time. Further, the estimated speed change points are also shown in each graph, where the event start/end times are shown in grey lines and the blue lines represent four speed change points such as SRST, LST, RST and SRT. The green line refers reported bare-lane-regain time and the red line refers the estimated RCR point. If RCR matches with the reported bare-lane, only the red line is shown.

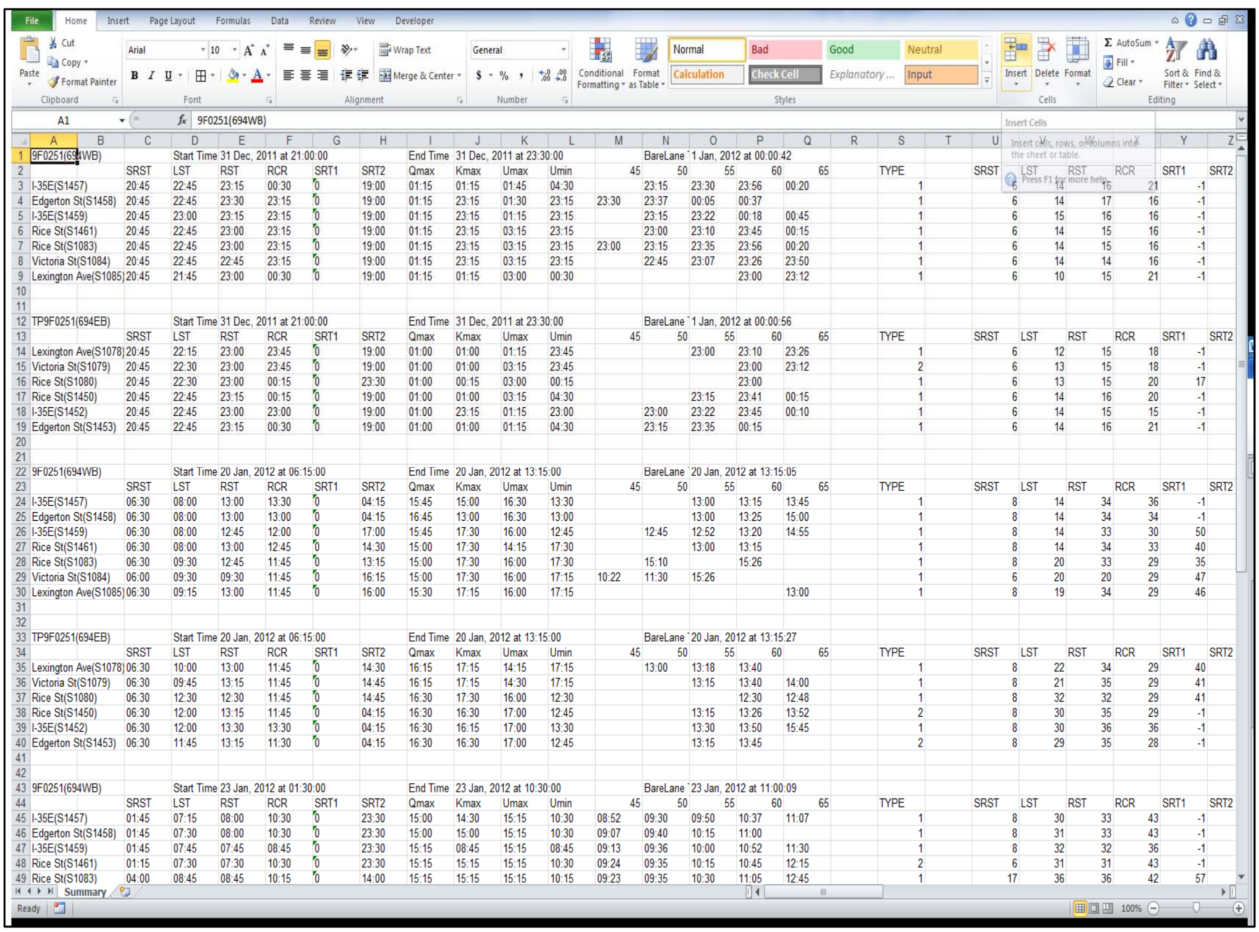


Figure 4.6 Example summary results output

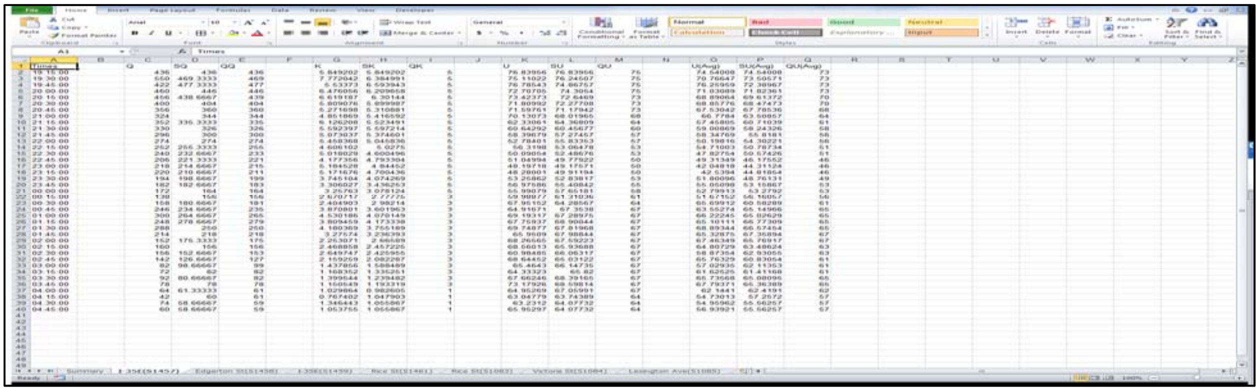


Figure 4.7 Example individual station traffic data output (raw, smoothed and quantized)

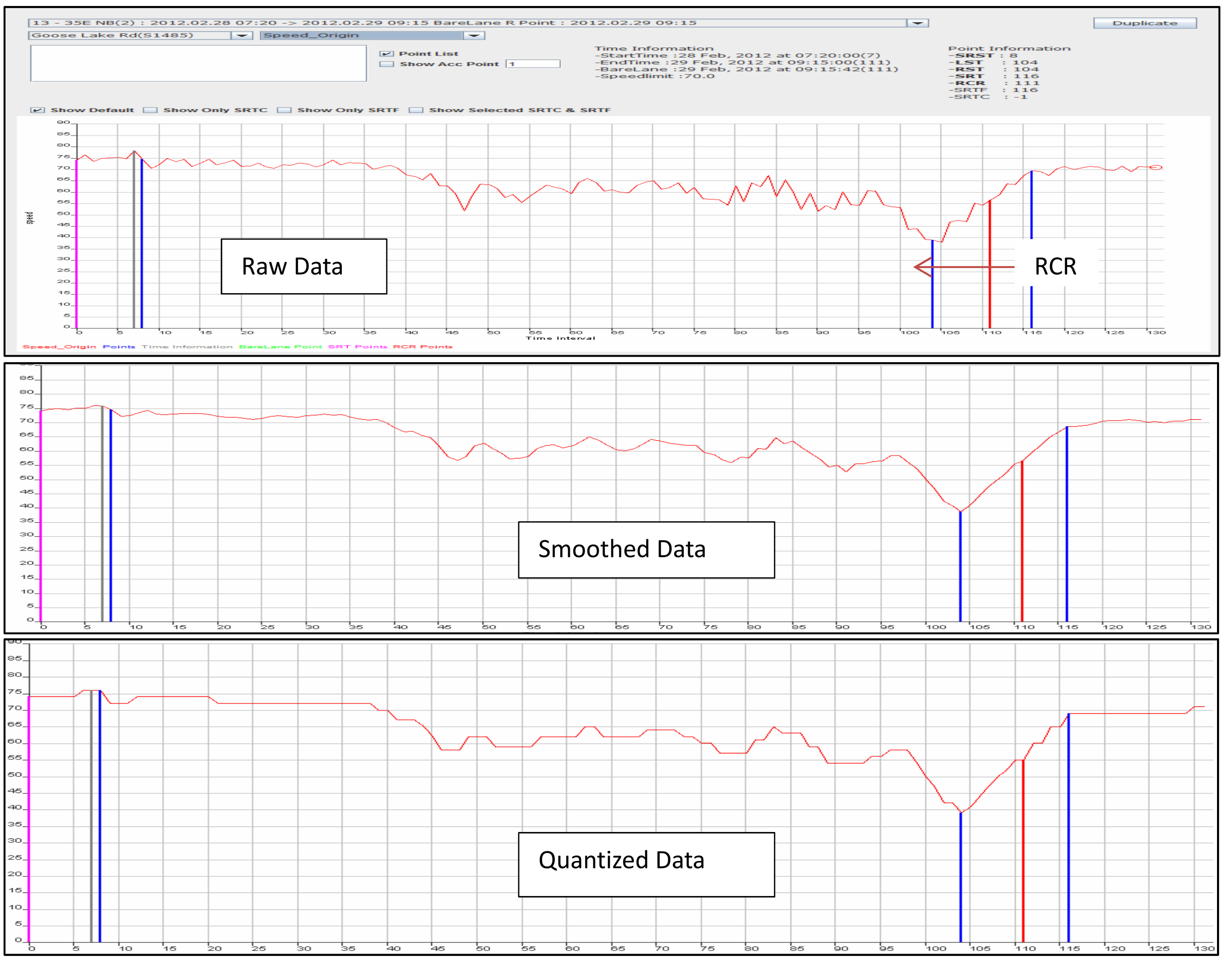
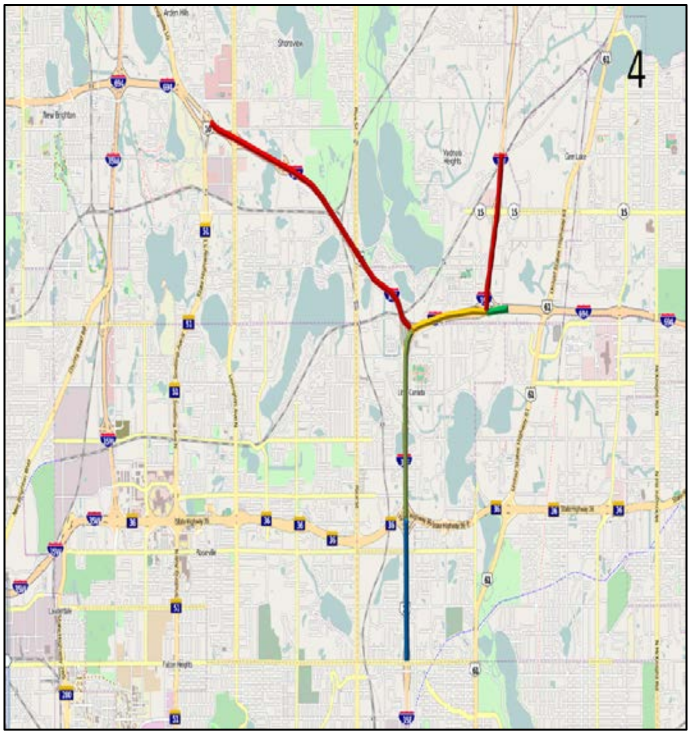


Figure 4.8 Example graphical output for speed variation and estimated speed change points/RCR

5. Example Estimation of Speed Recovery Times for Selected Winter Maintenance Events

In this chapter, the speed variation identification process developed in the previous chapters was applied to the selected set of four snow events during the 2011-12 winter period. For this study, a set of detailed snow maintenance operations data were provided by the MnDOT Metro District for the two routes in the metro freeway network. Figures 5.1 and 5.2 show the locations of those two routes. In particular, the reported bare-lane-regain time of each route were collected in 15 minute increments for those four snow events and summarized in Table 5.1. First, the geometry and traffic distribution patterns of each snow route were examined and, if necessary, multiple segments were identified within a route. A total of 14 segments were identified for the both directions of the route TP9F0251, while the other route, TP9F0253, was considered as single segment for each direction. This 'segmentation' is to reflect the potential traffic-flow differences within a route in identifying speed change times. Figures 5.1 and 2 also show the segments defined for each route for this study. The automatic identification process was then applied with the traffic-flow data collected from the detector stations on each route and the speed change time points, including the road condition recovery (RCR) times, at each station were identified for each snow event. Finally, the RCR times of the detector stations located in a same segment are combined to estimate the segment-wide road condition recovery times, which are then compared with the reported bare-lane-regain time for each route.

Tables 5.2 – 5.9 show the speed change time identification results for all the segments of those two routes for each snow event. The time differences between the estimated RCR and the reported bare-lane-regain times are summarized in Figure 5.3-6 for each snow event. The RCR times used in this comparison are the average RCR times of each segment, while the reported bare-lane-regain times are route-wide values, i.e., each route has only one reported bare-lane-regain time. As noted in these figures, in case of the Event 1, all the segments have less than 30 minute time differences between the estimated RCR times and the reported bare-lane-regain time. The results with Event 2 show 64% of all the segments with less than 30 minute differences and 93% of them within 45 minutes. In case of Event 4, 65% of all the segments show less than 30 minute differences and 72% of them within 45 minutes. However, the estimation results for the Event 3 show the significant gaps between the estimated RCR and the reported bare-lane-regain times, i.e., 44% of all the segments have less than 30 minute differences. To address this issue, the speed levels at the reported bare-lane time each detector station during the Event 3, i.e., January 23, 2012, are collected and compared with the speed limit values at each location as shown in Table 5.8. It can be noted that, during the Event 3, at most locations the speed levels at the reported bare-lane time are either very close to or exceed the speed limits, while the speed levels at RST show relatively low values indicating significant amount of speed reduction before the recovery started. The feasibility of having speed values that exceed the speed limits when the bare-lane is regained needs to be studied with additional field data. Another future study area identified from this application is the need to improve the procedure to locate the recovery start time (RST), especially when RST happens after the end time of a given snow event and for the cases with the long recovery periods during which there are multiple speed drops.



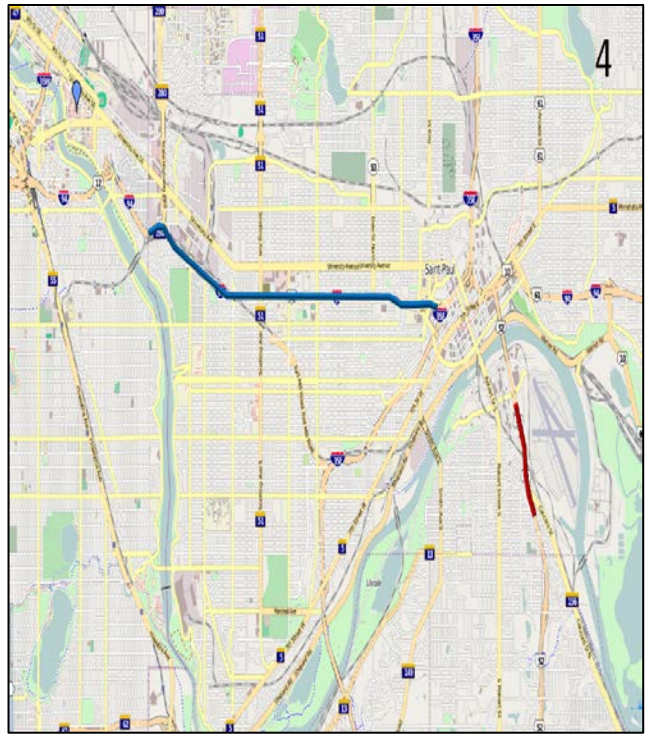


Figure 5.1 Location of Route TP9F0251: I-694, I-35E

Figure 5.2 Location of Route TP9F0253:T.H.94, 52

Table 5.1 Reported Bare-Lane-Regain Time Data for Example Snow Events

Event	Event Start	Event End	Bare-Lane-Regain	Event Duration	Lane Lost Duration	Recovery Hour
1	2011.12.31 21:00	2011.12.31 23:30	2011.12.31 24:00	2.5	2	0.5
2	2012.1.20 6:15	2012.1.20 13:15	2012.1.20 13:15	7	6.4	0
3	2012.1.23 1:30	2012.1.23 10:30	2012.1.23 11:00	9	7.5	0.5
4	2012.2.28 7:20	2012.2.29 9:20	2012.2.29 9:20	26	5.7	0

(unit:hr)

Table 5.2 Estimation Results for Route 9F0251 on December 31, 2011-January 1, 2012

Route	Bound	Station	Speed Change Points					Difference in RCR	RCR averaged by segment	Difference in RCR
			SRST	LST	RST	RCR	SRT			
I-694	WB	I-35E(S1457)	19:45	23:00	23:15	00:00	00:45	00:00	23:52	0:08
		Edgerton St(S1458)	19:45	23:00	23:30	23:45	01:15	-00:15		
		I-35E(S1459)	19:45	23:00	23:15	23:45	01:15	-00:15	23:54	0:06
		Rice St(S1461)	19:45	22:45	23:00	00:30	00:45	00:30		
		Rice St(S1083)	19:45	23:00	23:00	23:15	00:45	-00:45		
		Victoria St(S1084)	19:45	22:45	22:45	00:15	00:45	00:15		
		Lexington Ave(S1085)	19:45	21:45	22:45	23:45	00:45	-00:15		
	EB	Lexington Ave(S1078)	19:45	22:30	23:00	00:00	01:00	00:00	23:48	0:12
		Victoria St(S1079)	19:45	22:45	23:00	00:00	00:30	00:00		
		Rice St(S1080)	19:45	22:45	23:00	23:15	23:30	-00:45		
		Rice St(S1450)	19:45	23:00	23:15	00:00	01:45	00:00		
		I-35E(S1452)	20:00	22:45	23:00	23:45	01:15	-00:15		
		Edgerton St(S1453)	20:00	22:45	23:15	00:00	02:15	00:00	0:00	0:00
I-35E	NB	Larpenteur Ave(S626)	19:45	22:30	22:45	00:30	00:45	00:30	23:50	0:10
		Roselawn Ave(S627)	19:45	22:45	23:00	23:45	00:45	-00:15		
		Co Rd B(S628)	19:45	22:30	23:00	23:15	00:15	-00:45		
		T.H.36(S629)	19:45	22:45	23:00	00:15	01:00	00:15	23:40	0:20
		Little Canada Rd(S630)	19:45	22:45	23:00	23:30	00:45	-00:30		
		I-694(S1447)	20:00	22:45	23:00	23:15	01:15	-00:45		
		I-694 E Jct(S1448)	19:45	22:45	22:45	23:30	00:30	-00:30	23:55	0:05
		Co Rd E(S1449)	20:00	22:45	23:00	00:15	01:00	00:15		
		Goose Lake Rd(S1485)	19:45	22:30	23:15	00:00	01:00	00:00		
	SB	Goose Lake Rd(S1549)	19:45	22:45	22:45	23:30	00:30	-00:30	0:00	0:00
		Co Rd E(S1462)	-	-	-	-	-	-		
		I-694 E Jct(S1463)	19:45	22:45	23:45	00:30	01:45	00:30		
		I-694(S1464)	19:45	22:30	23:30	00:30	02:00	00:30	0:15	0:15
		Little Canada Rd(S1446)	-	-	-	-	-	-		
		Little Canada Rd(S633)	19:45	22:45	23:00	00:00	02:00	00:00		
		T.H.36(S634)	19:45	22:45	23:00	00:30	01:45	00:30	0:00	0:00
		Co Rd B(S635)	20:00	22:45	23:00	00:00	00:45	00:00		
		Roselawn Ave(S636)	19:45	22:45	23:00	00:15	01:15	00:15		
		Larpenteur Ave(S637)	19:45	22:45	23:00	23:15	01:00	-00:45		

Table 5.3 Estimation Results for Route 9F0253 on December 31, 2011-January 1, 2012

Route	Bound	Station	Speed Change Points					Difference in RCR	RCR averaged by segment	Difference in RCR
			SRST	LST	RST	RCR	SRT			
T.H.94	WB	John Ireland Blvd(S500)	19:45	22:45	23:00	23:15	00:45	-00:45	23:51	0:09
		Marion St(S546)	19:45	22:45	23:15	00:00	00:30	00:00		
		Dale St(S789)	19:45	22:45	23:15	00:15	00:45	00:15		
		Victoria St(S788)	19:45	22:45	23:15	23:30	00:15	-00:30		
		Lexington Ave(S548)	19:45	22:45	23:00	23:45	00:15	-00:15		
		Hamline Ave(S787)	19:45	22:45	23:15	00:45	02:15	00:45		
		Snelling Ave(S549)	19:45	22:30	23:15	00:00	00:30	00:00		
		Prior Ave(S786)	19:45	22:30	22:45	23:15	01:00	-00:45		
		Vandalia St(S550)	19:45	22:30	22:45	00:00	00:30	00:00		
	EB	Cretin Ave(S469)	19:45	22:30	22:45	23:45	01:30	-00:15	23:33	0:27
		Prior Ave(S776)	19:45	22:30	23:00	23:30	00:15	-00:30		
		Snelling Ave(S479)	19:45	22:45	23:00	23:30	00:15	-00:30		
		Hamline Ave(S777)	19:45	22:30	22:45	23:15	00:15	-00:45		
		Lexington Ave(S489)	19:45	22:45	22:45	23:15	01:30	-00:45		
		Victoria St(S778)	19:45	22:45	23:00	23:30	01:15	-00:30		
		Dale St(S490)	19:45	22:45	22:45	23:45	01:45	-00:15		
		Marion St(S491)	19:45	22:45	23:00	23:45	01:00	-00:15		
		John Ireland Blvd(S499)	19:45	22:45	23:15	23:45	01:30	-00:15		
T.H.52	NB	Concord St(S1175)	20:15	22:45	23:00	23:45	01:15	-00:15	23:55	0:05
		Eaton St(S1176)	20:15	22:45	23:00	00:00	01:15	00:00		
		Plato Blvd(S1177)	19:45	22:45	23:00	00:00	01:00	00:00		
	SB	Plato Blvd(S1152)	20:45	22:45	23:00	01:00	01:45	01:00	0:25	0:25
		Eaton St(S1153)	21:00	22:45	23:15	00:00	00:30	00:00		
		Concord St(S1154)	21:00	23:00	23:15	00:15	00:45	00:15		

Table 5.4 Estimation Results for Route 9F0251 on January 20, 2012

Route	Bound	Station	Speed Change Points					Difference in RCR	Segment RCR	Difference in RCR
			SRST	LST	RST	RCR	SRT			
I-694	WB	I-35E(S1457)	06:15	08:00	13:00	13:45	14:15	00:30	13:45	0:30
		Edgerton St(S1458)	06:15	08:00	13:00	13:45	14:15	00:30		
		I-35E(S1459)	05:45	08:00	12:45	15:00	15:45	01:45	13:41	0:26
		Rice St(S1461)	05:45	08:15	13:00	13:45	14:00	00:30		
		Rice St(S1083)	05:30	09:45	12:45	12:45	13:00	-00:30		
		Lexington Ave(S1085)	06:00	09:30	13:00	13:15	13:30	00:00		
	EB	Lexington Ave(S1078)	06:15	10:00	13:00	13:15	14:15	00:00	13:30	0:15
		Victoria St(S1079)	04:30	10:00	13:15	14:15	14:30	01:00		
		Rice St(S1080)	06:15	12:30	12:30	12:45	14:15	-00:30		
		Rice St(S1450)	06:00	12:30	13:15	13:45	14:45	00:30		
		I-35E(S1452)	06:15	12:30	13:00	13:30	14:30	00:15		
		Edgerton St(S1453)	06:15	11:45	12:45	13:15	14:30	00:00	13:15	0:00
I-35E	NB	Larpenteur Ave(S626)	05:45	11:45	12:30	13:45	14:30	00:30	13:50	0:35
		Roselawn Ave(S627)	05:45	10:45	12:30	14:00	14:30	00:45		
		Co Rd B(S628)	05:45	10:45	12:30	13:45	14:30	00:30		
		T.H.36(S629)	04:30	11:15	12:45	14:00	14:30	00:45	13:55	0:40
		Little Canada Rd(S630)	05:30	11:15	11:15	13:45	14:30	00:30		
		I-694(S1447)	05:30	10:15	12:45	14:00	14:30	00:45		
		I-694 E Jct(S1448)	06:00	11:00	12:45	13:30	14:45	00:15	13:50	0:35
		Co Rd E(S1449)	05:45	10:45	11:45	14:00	14:30	00:45		
		Goose Lake Rd(S1485)	05:45	10:45	13:00	14:00	14:30	00:45		
	SB	I-694 E Jct(S1463) *	05:45	10:45	11:15	11:45	12:00	-01:30		
		I-694(S1464)	06:00	08:30	08:30	13:00	14:00	-00:15	13:00	0:15
		Little Canada Rd(S633)	05:45	08:30	09:00	13:00	14:15	-00:15		
		T.H.36(S634)	05:00	08:15	08:30	13:15	14:30	00:00	13:22	0:07
		Co Rd B(S635)	06:00	08:15	08:15	13:30	14:30	00:15		
		Roselawn Ave(S636)	05:45	08:15	08:15	13:45	15:00	00:30		
		Larpenteur Ave(S637)	05:45	08:00	08:15	13:00	14:45	-00:15		

Table 5.5 Estimation Results for Route 9F0253 on January 20, 2012

<table>
<tr><th rowspan="2">Route</th><th rowspan="2">Bound</th><th rowspan="2">Station</th><th colspan="5">Speed Change Points</th><th rowspan="2">Difference in RCR</th><th rowspan="2">Segment RCR</th><th rowspan="2">Difference in RCR</th></tr>
<tr><th>SRST</th><th>LST</th><th>RST</th><th>RCR</th><th>SRT</th></tr>
<tr><td rowspan="17">T.H.94</td><td rowspan="9">WB</td><td>John Ireland Blvd(S500)</td><td>05:30</td><td>09:45</td><td>10:00</td><td>15:15</td><td>15:30</td><td>02:00</td><td rowspan="9">13:30</td><td rowspan="9">0:15</td></tr>
<tr><td>Marion St(S546)</td><td>05:45</td><td>09:45</td><td>09:45</td><td>15:15</td><td>15:30</td><td>02:00</td></tr>
<tr><td>Dale St(S789)</td><td>05:45</td><td>09:30</td><td>09:30</td><td>10:00</td><td>13:00</td><td>-03:15</td></tr>
<tr><td>Victoria St(S788)</td><td>05:45</td><td>09:15</td><td>09:45</td><td>13:00</td><td>14:15</td><td>-00:15</td></tr>
<tr><td>Lexington Ave(S548)</td><td>05:45</td><td>09:15</td><td>09:15</td><td>12:45</td><td>16:00</td><td>-00:30</td></tr>
<tr><td>Hamline Ave(S787)</td><td>05:45</td><td>09:00</td><td>12:45</td><td>13:00</td><td>13:15</td><td>-00:15</td></tr>
<tr><td>Snelling Ave(S549)</td><td>05:45</td><td>10:00</td><td>13:00</td><td>13:30</td><td>14:30</td><td>00:15</td></tr>
<tr><td>Prior Ave(S786)</td><td>05:45</td><td>07:15</td><td>13:30</td><td>13:45</td><td>14:00</td><td>00:30</td></tr>
<tr><td>Vandalia St(S550)</td><td>05:45</td><td>07:15</td><td>13:30</td><td>15:00</td><td>16:00</td><td>01:45</td></tr>
<tr><td rowspan="8">EB</td><td>Cretin Ave(S469)</td><td>05:45</td><td>13:00</td><td>13:00</td><td>13:30</td><td>14:00</td><td>00:15</td><td rowspan="8">13:58</td><td rowspan="8">0:43</td></tr>
<tr><td>Prior Ave(S776)</td><td>05:45</td><td>12:45</td><td>13:00</td><td>13:15</td><td>14:00</td><td>00:00</td></tr>
<tr><td>Snelling Ave(S479)</td><td>05:45</td><td>12:45</td><td>13:30</td><td>14:15</td><td>14:45</td><td>01:00</td></tr>
<tr><td>Hamline Ave(S777)</td><td>05:45</td><td>13:15</td><td>13:30</td><td>14:00</td><td>14:45</td><td>00:45</td></tr>
<tr><td>Lexington Ave(S489)</td><td>05:00</td><td>12:00</td><td>13:15</td><td>13:45</td><td>15:00</td><td>00:30</td></tr>
<tr><td>Victoria St(S778)</td><td>05:00</td><td>12:00</td><td>13:15</td><td>14:00</td><td>15:00</td><td>00:45</td></tr>
<tr><td>Marion St(S491)</td><td>05:45</td><td>09:15</td><td>14:15</td><td>14:45</td><td>15:00</td><td>01:30</td></tr>
<tr><td>John Ireland Blvd(S499)</td><td>05:45</td><td>09:15</td><td>12:00</td><td>14:15</td><td>15:00</td><td>01:00</td></tr>
<tr><td rowspan="6">T.H.52</td><td rowspan="3">NB</td><td>Concord St(S1175)</td><td>06:15</td><td>08:45</td><td>12:15</td><td>13:00</td><td>13:45</td><td>-00:15</td><td rowspan="3">13:25</td><td rowspan="3">0:10</td></tr>
<tr><td>Eaton St(S1176)</td><td>05:30</td><td>08:30</td><td>12:45</td><td>14:00</td><td>15:15</td><td>00:45</td></tr>
<tr><td>Plato Blvd(S1177)</td><td>05:15</td><td>08:15</td><td>13:00</td><td>13:15</td><td>15:15</td><td>00:00</td></tr>
<tr><td rowspan="3">SB</td><td>Plato Blvd(S1152)</td><td>05:15</td><td>11:30</td><td>12:00</td><td>12:00</td><td>12:15</td><td>-01:15</td><td rowspan="3">13:25</td><td rowspan="3">0:10</td></tr>
<tr><td>Eaton St(S1153)</td><td>06:00</td><td>13:00</td><td>13:00</td><td>14:15</td><td>14:45</td><td>01:00</td></tr>
<tr><td>Concord St(S1154)</td><td>05:45</td><td>13:15</td><td>13:45</td><td>14:00</td><td>17:15</td><td>00:45</td></tr>
</table>

Table 5.6 Estimation Results for Route 9F0251 on January 23, 2012

Route	Bound	Station	Speed Change Points					Difference in RCR	Segment RCR	Difference in RCR
			SRST	LST	RST	RCR	SRT			
I-694	WB	I-35E(S1457)*	23:45	07:30	08:00	09:30	11:15	-01:30	9:15	1:45
		Edgerton St(S1458)*	23:45	07:30	08:00	09:00	11:15	-02:00		
		I-35E(S1459)*	23:45	07:45	07:45	10:15	12:00	-00:45	9:45	1:15
		Rice St(S1461)*	23:45	07:30	07:30	09:45	12:00	-01:15		
		Rice St(S1083)*	23:45	08:45	08:45	10:30	12:00	-00:30		
		Victoria St(S1084)*	23:45	07:15	07:15	09:45	13:15	-01:15		
		Lexington Ave(S1085)*	00:15	07:15	07:30	08:30	12:00	-02:30		
	EB	Lexington Ave(S1078)*	23:45	07:45	10:00	10:15	12:45	-00:45	10:27	0:33
		Victoria St(S1079)*	23:45	07:45	09:45	10:45	12:45	-00:15		
		Rice St(S1080)*	23:45	07:30	09:30	10:15	12:15	-00:45		
		Rice St(S1450)*	23:45	09:30	10:00	10:30	11:15	-00:30		
		I-35E(S1452)*	23:45	08:00	10:00	10:30	12:00	-00:30		
		Edgerton St(S1453)*	23:45	08:00	09:00	10:30	11:45	-00:30	10:30	0:30
I-35E	NB	Larpenteur Ave(S626)	23:45	09:00	09:00	10:45	14:00	-00:15	10:30	0:30
		Roselawn Ave(S627)	23:45	09:00	09:15	11:00	11:15	00:00		
		Co Rd B(S628)	00:30	08:45	09:00	09:45	12:15	-01:15		
		T.H.36(S629)*	23:45	07:45	07:45	09:30	11:15	-01:30	9:25	1:35
		Little Canada Rd(S630)*	23:45	07:45	07:45	09:30	11:30	-01:30		
		I-694(S1447)	01:00	08:00	08:00	09:15	11:15	-01:45		
		I-694 E Jct(S1448)*	00:15	08:00	08:30	09:30	11:15	-01:30	10:25	0:35
		Co Rd E(S1449)*	00:30	07:45	08:45	10:15	12:45	-00:45		
		Goose Lake Rd(S1485)*	00:15	07:45	08:45	11:30	12:45	00:30		
	SB	Goose Lake Rd(S1549)*	00:15	07:30	08:45	09:30	11:30	-01:30	9:45	1:15
		I-694 E Jct(S1463)*	00:30	08:15	08:15	10:15	12:45	-00:45		
		I-694(S1464)*	01:00	07:45	08:00	10:45	13:15	-00:15	10:15	0:45
		Little Canada Rd(S633)*	00:15	08:45	08:45	09:45	11:45	-01:15		
		T.H.36(S634)*	00:15	08:00	08:30	10:00	12:15	-01:00	9:56	1:04
		Co Rd B(S635)*	00:15	08:00	08:30	10:00	11:30	-01:00		
		Roselawn Ave(S636)*	23:45	08:00	08:30	09:30	12:15	-01:30		
		Larpenteur Ave(S637)*	00:15	08:15	08:30	10:15	12:15	-00:45		

Table 5.7 Estimation Results for Route 9F0253 on January 23, 2012

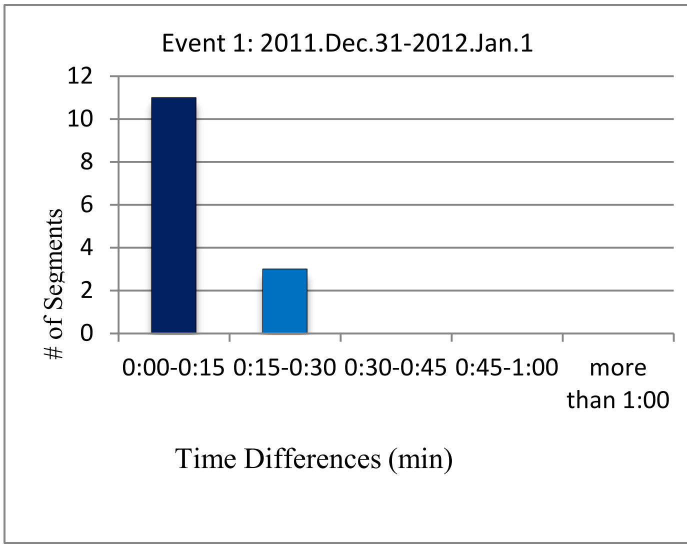
Route	Bound	Station	Speed Change Points					Difference in RCR	Segment RCR	Difference in RCR
			SRST	LST	RST	RCR	SRT			
T.H.94	WB	Marion St(S546)	00:15	07:30	07:30	09:00	12:30	-02:00	9:31	1:29
		Dale St(S789)*	00:15	07:45	08:00	09:00	11:15	-02:00		
		Victoria St(S788)*	00:15	07:30	08:30	10:00	11:15	-01:00		
		Lexington Ave(S548)*	00:15	08:30	08:45	10:15	11:00	-00:45		
		Hamline Ave(S787)*	00:15	08:30	08:45	09:30	0	-01:30		
		Snelling Ave(S549)*	00:15	08:30	08:30	09:15	11:15	-01:45		
		Prior Ave(S786)*	00:15	08:15	08:45	09:30	10:45	-01:30		
		Vandalia St(S550)*	00:15	08:30	08:45	09:45	10:45	-01:15		
	EB	Cretin Ave(S469)	00:30	08:30	08:45	11:45	13:15	00:45	10:03	0:57
		Prior Ave(S776)*	00:15	08:30	08:30	10:30	13:15	-00:30		
		Snelling Ave(S479)*	00:15	08:30	08:45	10:00	10:45	-01:00		
		Hamline Ave(S777)*	00:15	08:30	08:45	09:45	10:45	-01:15		
		Lexington Ave(S489)*	00:15	08:15	08:45	10:00	10:45	-01:00		
		Victoria St(S778)*	00:15	08:30	08:45	09:45	12:45	-01:15		
		Marion St(S491)	00:15	07:30	08:45	09:45	12:45	-01:15		
		John Ireland Blvd(S499)	23:45	07:45	07:45	09:00	12:45	-02:00		
T.H.52	NB	Concord St(S1175)*	00:15	07:45	08:30	09:15	09:30	-01:45	9:15	1:45
		Eaton St(S1176)*	00:30	08:00	08:00	09:00	12:15	-02:00		
		Plato Blvd(S1177)*	00:15	08:00	08:15	09:30	12:30	-01:30		
	SB	Plato Blvd(S1152)*	00:15	07:45	09:45	11:15	11:30	00:15	10:40	0:20
		Eaton St(S1153)*	00:15	07:45	09:45	11:15	11:30	00:15		
		Concord St(S1154)*	00:15	07:45	09:15	09:30	12:30	-01:30		

Table 5.8 Estimation Results for Route 9F0251 on February 28-29, 2012

Route	Bound	Station	Speed Change Points					Difference in RCR	Segment RCR	Difference in RCR
			SRST	LST	RST	RCR	SRT			
I-694	WB	I-35E(S1457)	06:50	08:35	09:20	11:05	13:20	01:45	10:35	1:15
		Edgerton St(S1458)	06:50	07:20	07:50	10:05	11:20	00:45		
		I-35E(S1459)	07:05	08:50	08:50	09:35	11:05	00:15	9:59	0:39
		Rice St(S1461)	06:50	07:35	08:35	10:20	12:20	01:00		
		Rice St(S1083)	06:50	07:05	08:20	10:20	12:20	01:00		
		Victoria St(S1084)	06:50	09:05	09:35	09:50	12:20	00:30		
		Lexington Ave(S1085)	06:05	07:05	07:20	09:50	12:20	00:30		
	EB	Lexington Ave(S1078)	06:20	08:20	08:20	09:05	09:35	-00:15	9:44	0:24
		Victoria St(S1079)	06:05	08:05	08:20	10:20	12:20	01:00		
		Rice St(S1080)	07:05	05:50	08:05	10:20	12:35	01:00		
		Rice St(S1450)	07:05	06:35	06:35	10:35	12:20	01:15		
		I-35E(S1452)	07:05	06:20	06:50	08:20	12:05	-01:00		
		Edgerton St(S1453)	07:05	06:50	07:20	10:20	11:05	01:00	10:20	1:00
I-35E	NB	Larpenteur Ave(S626)	08:05	06:50	06:50	09:50	12:05	00:30	9:15	0:05
		Roselawn Ave(S627)	08:05	06:50	07:05	08:50	09:50	-00:30		
		Co Rd B(S628)	09:20	05:20	07:05	09:05	10:20	-00:15		
		T.H.36(S629)	06:35	06:35	07:35	08:20	10:50	-01:00	8:55	0:25
		Little Canada Rd(S630)	09:05	07:05	07:20	09:05	10:20	-00:15		
		I-694(S1447)	08:20	07:35	07:35	09:20	11:35	00:00		
		I-694 E Jct(S1448)	07:05	07:05	07:35	10:35	11:50	01:15	9:35	0:15
		Co Rd E(S1449)	07:05	07:35	08:05	08:50	11:50	-00:30		
		Goose Lake Rd(S1485)	07:05	07:35	07:35	09:20	10:35	00:00		
	SB	Goose Lake Rd(S1549)	06:05	07:35	07:35	09:05	11:50	-00:15	9:10	0:10
		I-694 E Jct(S1463)	10:35	07:35	07:50	08:35	11:35	-00:45		
		I-694(S1464)	06:20	07:20	07:50	09:50	11:05	00:30	8:57	0:23
		Little Canada Rd(S633)	06:05	07:20	07:35	08:05	12:20	-01:15		
		T.H.36(S634)	06:05	07:35	07:50	08:35	12:20	-00:45	9:23	0:03
		Co Rd B(S635)	05:35	07:20	07:50	10:35	11:20	01:15		
		Roselawn Ave(S636)	06:20	07:05	07:20	09:05	11:20	-00:15		
		Larpenteur Ave(S637)	06:20	06:50	07:35	09:20	11:20	00:00		

Table 5.9 Estimation Results for Route 9F0253 on February 28-29, 2012

Route	Bound	Station	Speed Change Points					Difference in RCR	Segment RCR	Difference in RCR
			SRST	LST	RST	RCR	SRT			
T.H.94	WB	John Ireland Blvd(S500)	06:05	04:20	06:50	10:05	11:50	00:45	9:30	0:10
		Marion St(S546)	06:50	06:35	06:50	10:20	11:05	01:00		
		Dale St(S789)	06:05	08:05	08:05	08:50	12:35	-00:30		
		Victoria St(S788)	06:50	08:05	08:05	09:20	10:50	00:00		
		Lexington Ave(S548)	06:50	08:05	08:20	09:35	11:35	00:15		
		Hamline Ave(S787)	06:05	07:50	08:35	09:35	11:05	00:15		
		Snelling Ave(S549)	06:05	07:50	08:20	09:05	10:50	-00:15		
		Prior Ave(S786)	07:05	07:35	08:35	08:50	11:05	-00:30		
		Vandalia St(S550)	06:05	07:50	09:05	09:50	12:20	00:30		
	EB	Prior Ave(S776)	09:50	08:20	08:20	09:20	11:50	00:00	9:08	0:12
		Snelling Ave(S479)	10:20	07:50	08:20	09:20	11:35	00:00		
		Hamline Ave(S777)	08:50	06:35	07:50	08:35	10:20	-00:45		
		Lexington Ave(S489)	07:05	07:50	08:05	09:20	10:05	00:00		
		Victoria St(S778)	09:50	07:50	08:05	09:20	10:20	00:00		
		Dale St(S490)	05:35	08:05	08:20	09:20	10:20	00:00		
		Marion St(S491)	08:50	07:05	08:05	08:35	12:05	-00:45		
		John Ireland Blvd(S499)	07:05	07:05	07:50	09:05	12:05	-00:15		
T.H.52	NB	Concord St(S1175)*	07:05	05:20	07:35	09:05	11:35	-00:15	8:30	0:50
		Eaton St(S1176)*	06:05	07:50	07:05	07:50	09:35	-01:30		
		Plato Blvd(S1177)*	06:05	07:50	07:35	08:35	09:50	-00:45		
	SB	Plato Blvd(S1152)*	05:35	05:05	07:05	08:20	08:50	-01:00	7:40	1:40
		Eaton St(S1153)*	06:35	04:50	07:05	07:20	08:35	-02:00		
		Concord St(S1154)*	09:05	05:05	05:20	07:20	08:20	-02:00		



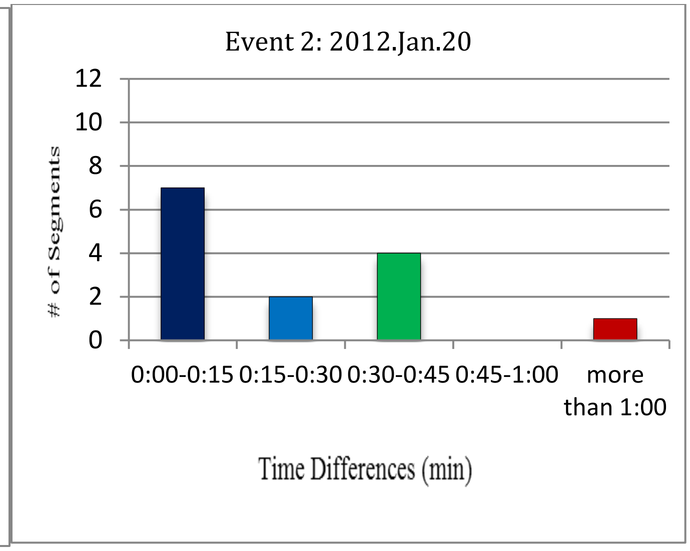
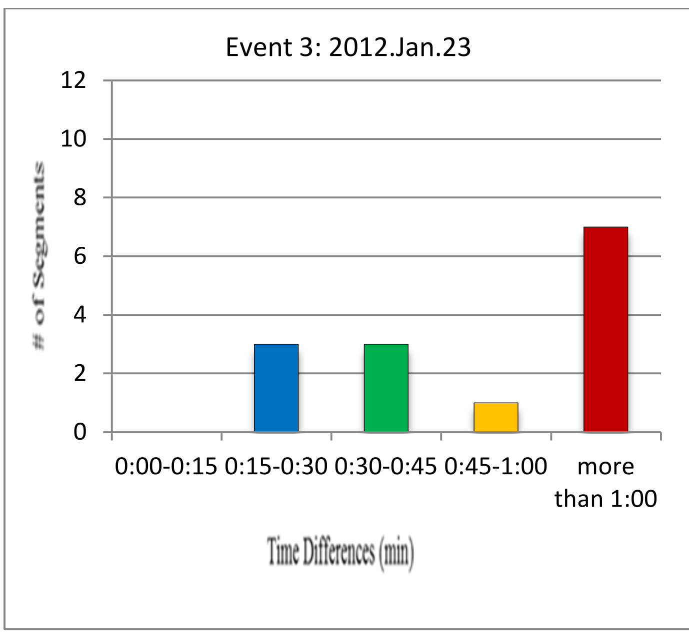


Figure 5.3 Distribution of time differences: event 1

Figure 5.4 Distribution of time differences: event 2



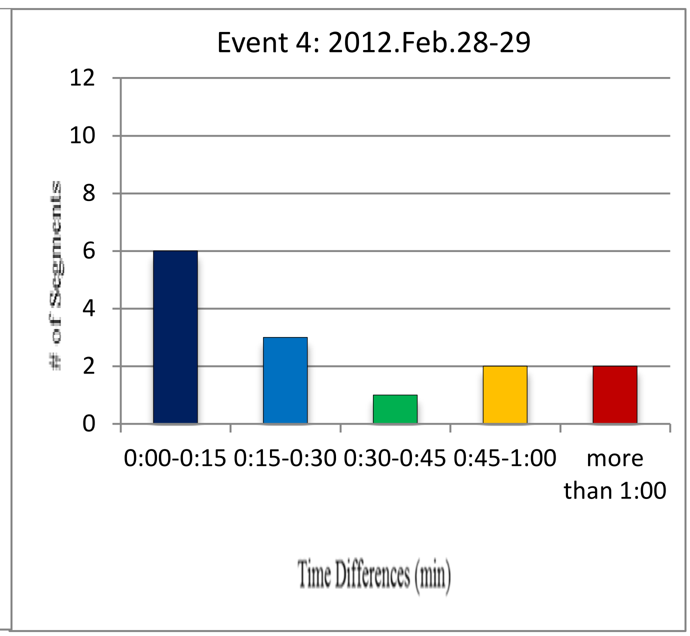


Figure 5.5 Distribution of time differences: event 3

Figure 5.6 Distribution of time differences: event 4

Table 5.10 Comparison between Speed Limit and Speed Levels at Reported Bare-Lane

Plow Route	Route	Bound	Station	Speed limit (mph)	Speed at Reported Bare-Lane-Regain Time (mph)
9F0251	I-694	WB	I-35E(S1457)*	60	62.92
			Edgerton St(S1458)*		58.41
			I-35E(S1459)*		58.76
			Rice St(S1461)*		59.86
			Rice St(S1083)*		56.2
			Victoria St(S1084)*		61.46
			Lexington Ave(S1085)*		82.48
		EB	Lexington Ave(S1078)*	60	62.09
			Victoria St(S1079)*		63.29
			Rice St(S1080)*		66.28
			Rice St(S1450)*		61.72
			I-35E(S1452)*		59.58
			Edgerton St(S1453)*		58.12
	I-35E	NB	Larpenteur Ave(S626)	60	56.65
			Roselawn Ave(S627)		57.2
			Co Rd B(S628)		59.54
			T.H.36(S629)*		58.25
			Little Canada Rd(S630)*		59.45
			I-694(S1447)		56.51
			I-694 E Jct(S1448)*		57.97
			Co Rd E(S1449)*		63.7
			Goose Lake Rd(S1485)*	70	62.82
		SB	Goose Lake Rd(S1549)*	70	71.15
			I-694 E Jct(S1463)*	60	60.39
			I-694(S1464)*		59.4
			Little Canada Rd(S633)*		59.28
			T.H.36(S634)*		56.97
			Co Rd B(S635)*		58.25
			Roselawn Ave(S636)*		58.57
			Larpenteur Ave(S637)*		55.42
9F0253	T.H.94	WB	Marion St(S546)	55	52
			Dale St(S789)*		61.31
			Victoria St(S788)*		57.19
			Lexington Ave(S548)*		57.85
			Hamline Ave(S787)*		59.77
			Snelling Ave(S549)*		58.13
			Prior Ave(S786)*		59.26
			Vandalia St(S550)*		57.18
		EB	Cretin Ave(S469)	55	52.55
			Prior Ave(S776)*		56.65
			Snelling Ave(S479)*		56.75
			Hamline Ave(S777)*		58.65
			Lexington Ave(S489)*		57.72
			Victoria St(S778)*		59.04
			Marion St(S491)		50.24
			John Ireland Blvd(S499)		50.11
	T.H.52	NB	Concord St(S1175)*	55	61.48
			Eaton St(S1176)*		55.89
			Plato Blvd(S1177)*		56.04
		SB	Plato Blvd(S1152)*	55	55.27
			Eaton St(S1153)*		54.32
			Concord St(S1154)*		56.69

6. Conclusions

The capability to accurately and reliably estimate the performance of winter maintenance activities is of critical importance in improving the efficiency and effectiveness of winter snow-management operations. In this study, a traffic data-based automatic process is developed to determine the road condition recovered times that can be used as the estimates for the 'bare-lane-regain time' for given freeway corridors. First, the traffic-flow variation process during snow events was analyzed with the traffic data collected from the loop detector stations on the metro freeway corridors. In particular, the change patterns of the traffic speed, flow rate and density data at each detector station during the recovery periods were analyzed in detail and compared with those at the reported bare-lane-regain times. The results from the field data analysis indicate that, while the speed recovery patterns can vary significantly depending on the multiple factors, such as the intensity of snow, the amount of traffic-flow and the types of the maintenance strategies, the speed variations during a recovery period reflect the state-changes of the road surface conditions at a given location. The detailed analysis of the speed variation patterns before and after the reported lane-regain times led to the finding that the road condition recovered time could be considered to be the 'last significant speed increase time' before the speed reached the posted limits or the stable value for given locations depending on the speed level when the speed recovery started.

Based on the above findings, an automatic process to identify the speed change and the road condition recovered times at each detector station was developed and incorporated into TICAS (Traffic Information and Condition Analysis System) being developed at University of Minnesota Duluth. The computerized process was then applied to a subset of the 2011-12 winter maintenance operations data, which consists of two routes for four snow events. The example application results show promising results in terms of identifying the speed change points and estimating the road condition recovered times with traffic data. For the three events, 64-65% of all the segments in those two routes have less than 30 minute differences between the estimated road condition recovered times and the reported lane-regain times, while one event on January 23, 2012, has only 44% of all the segments with less than a 30 minute difference. It was also observed that the speed levels at the reported lane-regain times on January 23 show significantly high values, while those at the recovery start times were relatively low. It needs to be noted that there was only one reported lane-regain-time for each snow event for all the routes used in this study. More detailed speed variation data during the recovery periods including the exact times and methods of plowing operations needs to be collected in the subsequent phase of this research to conduct an in-depth study for the speed recovery patterns under various weather and operational conditions. Further research needs also include the improvement of the recovery start time identification procedure for the cases with long recovery periods and multiple speed drops. The application of those speed change and road condition recovery time information in improving the efficiency of the winter snow operations is also needed.

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