Using Truck GPS Data for Freight Performance Analysis in the Twin Cities Metro Area

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March 2014

Research Project
Final Report 2014-14

Technical Report Documentation Page

1. Report No.	2.	3. Recipients Accession No.
MN/RC 2014-14		

4. Title and Subtitle	5. Report Date
Using Truck GPS Data for Freight Performance Analysis in the Twin Cities Metro Area	March 2014
	6.
7. Author(s) Chen-Fu Liao	8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Civil Engineering University of Minnesota 500 Pillsbury Drive, SE Minneapolis, MN 55455	10. Project/Task/Work Unit No. CTS Project #2013035 11. Contract (C) or Grant (G) No. (C) 99008 (WO) 47
12. Sponsoring Organization Name and Address Minnesota Department of Transportation Research Services & Library 395 John Ireland Boulevard, MS 330 St. Paul, MN 55155	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes
http://www.lrrb.org/PDF/201414.pdf

16. Abstract (Limit: 250 words)

Building on our previous efforts to study freight mobility and reliability, a GPS-based data analysis methodology was developed to study the freight performance of heavy commercial trucks along 38 key freight corridors in the Twin Cities metropolitan area (TCMA). One year of truck GPS data collected in 2012 was obtained from American Transportation Research Institute (ATRI) to study freight mobility and reliability. Several performance measures, such as truck mobility, delay, and reliability index, were computed and analyzed by route, roadway segment, and time of day. For data quality and reliability verification, average truck speed and hourly volume percentage computed from the truck GPS data were validated with weigh-in-motion (WIM) and automatic traffic recorders (ATR) data at selected locations. The GPS based freight analysis methodology offers potential opportunities for freight planners and managers to generate reliable measures in a timely manner. The resulting performance measures indicate that these measures derived from truck GPS data can be used to support the USDOT performance measure initiative and support regional surface freight planner in identifying freight bottlenecks, infrastructure improvement needs, and operational strategies to promote efficient freight movement. FHWA recently announced the National Performance Measurement Research Data Set (NPMRDS) to support its Freight Performance Measurement (FPM). The NPMRDS includes probe vehicle based travel time data in every 5-minute interval. This report also explored the feasibility of using one month of NPMRDS data in Minnesota to compute freight mobility and speed variations along the National Highway System (NHS) during AM and PM peak periods.

17. Document Analysis/Descriptors	18. Availability Statement
Performance measurement, Trucking, Global Positioning System, Analysis, Mobility, Delays, Reliability	No restrictions. Document available from: National Technical Information Services, Alexandria, VA 22312

19. Security Class (this report)	20. Security Class (this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	153	

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Final Report

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March 2014

Published by:
Minnesota Department of Transportation
Research Services & Library
395 John Ireland Boulevard, MS 330
St. Paul, Minnesota 55155

ACKNOWLEDGMENTS

This research project is sponsored by the Minnesota Department of Transportation (MnDOT). The author would like to acknowledge MnDOT staff and engineers for their invaluable support and providing traffic data. Many thanks to the American Transportation Research Institute (ATRI) for providing truck GPS data and technical support in making this study possible. The author also would like to thank members of the technical advisory panel (TAP) and the following individuals for their invaluable feedback and assistance in making this research possible.

- John Tompkins, technical liaison (TL), MnDOT
- Bruce Holdhusen, project coordinator (PC), MnDOT
- Mark B Nelson, Matthew Pahs, Jesse Larson, Brad Utecht, Jason Junge, Shannon McGrath, and Molly McCartney from MnDOT
- Steven Elmer and Jonathan Ehrlich from Metropolitan Council
- Dan Murray, Jeff Short, and Katie Fender from ATRI
- Stephen Zitzow at the Minnesota Traffic Observatory (MTO), University of Minnesota
- Tara Sasank Sunkara and Dayakar Reddy Singana from the Department of Computer Science and Engineering, University of Minnesota
- Joseph Barbeau from CTS, University of Minnesota

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LIST OF ACRONYMS AND ABBREVIATIONS

AADT	Annual Average Daily Traffic
AADTT	Annual Average Daily Truck Traffic
AASHTO	American Association of State Highway and Transportation Officials
AL	Administration Liaison
ATA	American Trucking Association
ATR	Automatic Traffic Recorder
ATRI	American Transportation Research Institute
BI	Buffer Index
BTI	Buffer Time Index
CMV	Commercial Motor Vehicle
CSAH	County State-Aid Highway
CTS	Center for Transportation Studies
EB	Eastbound
FHWA	Federal Highway Administration
FPM	Freight Performance Measurement
GIS	Geographic Information System
GPS	Global Positioning System
HCAADT	Heavy Commercial Annual Average Daily Traffic
HCADT	Heavy Commercial Average Daily Traffic
IRC	Inter- Regional Corridor
ID	Identification
LUT	Look Up Table
MAP	Moving Ahead for Progress
MHCADT	Monthly Heavy Commercial Average Daily Traffic
MnDOT	Minnesota Department of Transportation
MPH	Mile Per Hour
MPO	Metropolitan Planning Organization
MTO	Minnesota Traffic Observatory
NB	Northbound
N-CAST	National Corridors Analysis & Speed Tool
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHS	National Highway System
NPMRDS	National Performance Measurement Research Data Set
OFCVO	Office of Freight and Commercial Vehicle Operations
PTI	Planning Time Index
RI	Reliability Index
RTMC	Regional Traffic Management Center
SB	Southbound
SCOPM	Standing Committee on Performance Management
SQL	Sequential Query Language
TAP	Technical Advisory Panel
TCMA	Twin Cities Metropolitan Area
TH	Trunk Highway

TL	Technical Liaison
TMC	Traffic Management Center
TTI	Travel Time Index or Texas Transportation Institute
UCR	Urban Congestion Report
UMN	University of Minnesota
UMR	Urban Mobility Report
USDOT	US Department of Transportation
WB	Westbound
WIM	Weigh-in-Motion

EXECUTIVE SUMMARY

As outlined in the Moving Ahead for Progress in the 21st Century Act (MAP-21), the states are required to establish performance targets that reflect performance measures established by the U.S. Department of Transportation (USDOT). The USDOT has identified and recommended critical performance measures, methodologies and standards for data collection, potential issues related to deployment, and usability of performance measures in addressing issues at local, state, and federal levels.

Building on our previous efforts to analyze freight mobility and reliability, an analysis methodology using truck GPS data was developed to study the freight performance of heavy commercial trucks along 38 key freight corridors in the Twin Cities metropolitan area (TCMA). Twelve months of truck GPS data collected in 2012 were obtained from American Transportation Research Institute (ATRI) to compute truck mobility, reliability and delay and to identify bottlenecks.

Average truck traveling speed derived from the GPS data and truck volumes were compared with available benchmark data for data validation. Particularly in urban areas, satellite receptions may be limited and traffic congestion is more common. For data quality validation purposes, average truck speed and hourly volume percentage computed from the truck GPS data were compared with data from weigh-in-motion (WIM) sensors and automatic traffic recorders (ATR) at selected locations in the TCMA.

Several performance measures, such as truck mobility, delay, and reliability index, were identified. Statistical analyses were performed to derive performance measures by route, roadway segment (1-mile), and time of day. In addition to generating performance measures, the research team also identified key freight corridors by comparing the percentage of miles with heavy commercial annual average daily traffic (HCAADT) greater than 7,500 and HCAADT per lane greater than 1,500 in the TCMA. The HCAADT is theoretical estimate of the total number of heavy commercial vehicles using a specific segment of roadway (in both directions) on any given day of the year. This estimate represents the total number of heavy commercial vehicles per year divided by 365 and is developed by MnDOT using factors to adjust for season.

Truck bottlenecks were also identified and ranked based on hours of truck delay and number of hours with speed less than the target speeds (set by MnDOT) during the AM and PM peak periods. For example, Table ES-1 illustrates the top five truck bottlenecks in TCMA during PM peak based on truck delays. Table ES-2 displays the top five truck bottlenecks in TCMA during PM peak based on number of hours of truck average speed below the target speed. The top 5 locations in TCMA with significant truck delays during the combined AM and PM peak periods are listed in Table ES-3. Most of the bottleneck locations are nearby the interchange. The analysis results indicate that I-494 eastbound at between TH-169 and I-35W has the highest combined truck delay of 55.9 hours on a weekday. I-394 eastbound to downtown Minneapolis has the second highest truck delay of 26.2 hours in combined AM & PM peaks. The third highest truck delay (25.2 hours) occurs at I-494 southbound south of I-94 in Maple Grove during the peak periods.

Table ES-1 List of Top 5 Truck Bottleneck in PM Peak (Based on Delay)

Rank	**Location**	**Dir.**	**PM Peak Delay (hours) / Mile**	**PM Peak Reliability RI80**	**HCAADT**	**Number of Lanes**	**Length (miles)**
1	I-35W at I-694	NB	14.08	1.94 - 3.75	7700 - 8500	3	3.30
2	I-35W at I-94	SB	12.94	5.00	3250 - 8300	3	1.01
3	I-494 between I-35W & 169	EB	11.31	2.05 - 4.09	6900 - 9100	2	4.88
4	I-394 between TH 100 & I-94	EB	7.14	2.59 - 3.75	400	3	2.61
5	I-694 between I-35E & I-35W	WB	6.85	2.37 - 3.04	6700 - 7800	2	3.02

Table ES-2 Top 5 List of truck bottleneck in PM Peak (Based on # of Hours below 45 MPH)

Rank	**Location**	**Dir.**	**PM Peak Delay (hours) / Mile**	**PM Peak Reliability RI80**	**HCAADT**	**# of Lanes**	**Length (miles)**	**PM Peak Delay (hours)**
1	I-494 between I-35W & 169	EB	14.45	2.05 - 4.50	6800 - 9100	3	3.14	45.34
2	I-35W at I-694	NB	17.79	3 - 3.75	7200 - 8500	3	2.05	36.47
3	I-394 between downtown and TH 100	EB	4.96	1.93 - 3.75	2100 - 4200	3	4.78	23.69
4	I-94 between Lowry tunnel and TH 280	WB	4.51	2.35 - 3.25	4000 - 6300	3	5.02	22.63
5	I-35E at I-94	SB	5.32	1.50 - 22.5	6200 - 7900	3	2.4	12.76

Table ES-3 Top 5 List of truck bottleneck in Combined AM and PM Peak

Rank	**Location**	**Dir.**	**AM Peak Delay (hours)**	**PM Peak Delay (hours)**	**AM & PM Peak Delay (hours)**
1	I-494 between I-35W & 169	EB	0.7	55.2	55.9
2	I-394 at I-94	EB	7.6	18.6	26.2
3	I-494 S of I-94 (Maple Grove)	SB	25.2	0.0	25.2
4	I-694 at I-35W	EB	4.0	15.3	19.3
5	I-694 at I-94	WB	13.9	5.0	18.9

In addition to the performance measures, the cost of traffic mobility deficiencies as a means of expressing the financial impact of congestion can be estimated. These congestion cost measures can have utility to both transportation decision-makers and system users if they accurately reflect the tangible costs of transportation use on congested facilities.

The annual Urban Mobility Report (UMR) produced by Texas Transportation Institute (TTI) measures the costs of congestion at both the national and the local levels. The 2012 report estimated that the overall cost of congestion in the United States was $121 billion in 2011 based on wasted fuel and lost productivity. In Minneapolis-St. Paul, Minnesota area, annual truck congestion cost was $232 million and the total congestion cost was $1.26 billion in 2011. According to the 2012 UMR, the cost of truck congestion used was $88 per hour.

In addition, the ATRI has been conducted an analysis to assess the operational costs of truck delays since 2008. The recent update of the ATRI study, *An Analysis of the Operational Cots of Trucking: 2013 Update*, reported that the total marginal costs for the industry across all sectors, fleet sizes and regions were $1.63 per mile and $65.29 per hour in 2012.

Of the 38 corridors studied in this project, several of them are county roads or state highways with traffic signals. Total truck congestion cost in the TCMA was about 0.8 million per weekday using the hourly operational cost from ATRI. The corresponding annual congestion cost was about $212 million (assuming no delays on weekends). When using the TTI's congestion cost rate, the total truck congestion cost in the TCMA was about 1.1 million per weekday with corresponding annual congestion cost around $286 million (assuming no delays on weekends). Using the simple cost calculation methodology, daily or annual truck congestion cost measures can be derived by applying industry operating cost rate to truck delays derived from empirical truck speed/time data at a corridor level or in a region.

In July 2013, the FHWA announced the National Performance Measurement Research Data Set (NPMRDS) to support its Freight Performance Measurement (FPM) and Urban Congestion Report (UCR) programs. The NPMRDS includes probe vehicle based travel time data (for both passenger and freight vehicles) in every five-minute interval for all National Highway System (NHS) facilities. The NPMRDS will support transportation agencies' needs by obtaining a comprehensive and reliable set of data that can be broadly deployed for use in measuring, managing, and improving the transportation system in the United States. The research team also explored the feasibility of using one month (November 2013) of NPMRDS data in Minnesota to compute freight mobility and speed variations along the NHS during the AM and PM peak periods.

Performance measures derived from GPS data offer promising opportunities for freight planners and managers to generate reliable measures in a timely manner. The findings from this research indicate that these measures derived from the truck GPS data can be used in supporting the USDOT performance measure initiative and truck/freight modeling in the TCMA. These measures can provide truck specific information to support regional surface freight planner in identifying freight bottlenecks and infrastructure improvement needs and in developing operational strategies to promote efficient freight movement for the industry.

1. INTRODUCTION

The Moving Ahead for Progress in the 21st Century Act (MAP-21) was signed into law by President Obama on July 6, 2012. As outlined in the MAP-21, the States are required to establish performance targets that reflect the performance measures established by the U.S. Department of Transportation (USDOT). Improving efficiency of freight movement is identified as one of the key national goals for performance management. The objective of freight performance management is to improve freight networks, strengthen the ability of rural communities to access national and international trade markets, and support regional and national economic development (FHWA, 2012).

This project extended our previous efforts to generate and analyze freight performance measures along 38 key freight corridors in the Twin Cities metro area (TCMA) and four major freight corridors that connect the Twin Cities to three regional freight centers (St. Cloud, Mankato, and Rochester) outside the TCMA (Liao, 2014). Results from the freight performance analysis in the TCMA will lead to supporting improvement in freight management and planning, complement the existing freight/truck models, and guide regional or statewide transportation decision making on infrastructure development and investment.

1.1 Background

In 2005, the Minnesota Department of Transportation (MnDOT) adopted its statewide freight plan (MnDOT, 2005). This multi-modal plan identifies significant freight system trends, needs and issues. The freight plan provides a framework that includes recommended freight policies, strategies and performance measures to guide decision-making on future investments.

In 2009, the author conducted a surface freight performance study along the I-94/90 between the Twin Cities and Chicago. The interstate 94/90 corridor carries significant amounts of freight from Chicago to Minnesota for consumption and distribution throughout the Upper Midwest. Interstate 94/90 also carries Minnesota-produced freight destined for Chicago, as well as national and international markets. Consolidated air cargo from Minnesota moves on the highway to Chicago for access to dedicated international air freighter service. Major regional distribution centers along the corridor in Wisconsin also drive truck traffic in both directions.

According to a report from the FHWA, the volume of heavy commercial vehicles (vehicles with at least two axles and at least six tires) traversing I-94/90 continues to increase. The annual average daily truck traffic (AADTT) of heavy commercial vehicles along the I-94 segment between the Twin Cities and Chicago reached nearly 10,000 trucks per day in 1998. By 2020, the forecasted AADTT will increase to almost 20,000 trucks per day.

The author utilized the truck GPS data (May 2008 – April 2009) obtained from ATRI to study the freight activities along I-94/90. General traffic data along the corridor were also acquired from MN, WI, and IL DOTs for data validation. Freight performance was evaluated and analyzed to compare truck travel time with respect to duration, reliability, and seasonal variations. These types of analysis results can timely support freight transportation planning and decision-making. Potential applications of the performance measurement analyses were identified in the report of the I-94/90 freight study, such as (1) measuring truck travel time reliability and impact of congestion on cost of freight, (2) identifying truck stop/parking facility needs, and (3) studying the impact of traffic volume with respect to speed gap difference between cars and trucks.

1.2 Research Objectives

The objectives of this study are to integrate private and public freight data sources to generate freight mobility and reliability measures, and identify significant freight node and delays in the TCMA. The outcome will allow freight agency to: (1) better identify system impediments such as traffic congestion or truck bottlenecks; (2) investigate truck volume contributing to traffic congestion and delay; and (3) use the derived measure as a guide to support decision-making on freight related infrastructure investment, freight forecasting and planning.

1.3 Literature Review

The American Association of State Highway and Transportation Officials (AASHTO) established a Standing Committee on Performance Management (SCOPM) to support performance-based management and outcome-driven environment by providing necessary expertise and resources to DOTs and other stakeholders. The NCHRP 20-24(37)G report (2011) has identified and made recommendations for critical performance measures, methodologies and standards for data collection, potential issues related to deployment, and usability of performance measures in addressing issues at local, state and federal levels. However, there is still ongoing debate over concerns and issues with the proposed measures, such as selection of reliability measure, data consistency, availability and adequacy, and federal vs. state role and responsibilities.

NCHRP (2003) synthesis 311 studied highway segments and system performance measures that included a survey of state DOTs and MPOs. The report indicated the need for a national set of core performance measures that consider data quality and collection, system coverage, and the aggregation of results. Key findings from the report include:

- A variety of different definitions of reliability measures are used by different states and MPOs.
- Need to provide a complete explanation of the measure and the data required to make the calculation.
- No standard way to evaluate and collect information in an operational setting and thus making comparison of operational scenarios difficult.
- Need to develop an effective way to present performance measure results.
- Relatively little work on forecasting performance measures and assessing their sensitivity to policy and changes in travel behavior.

1.3.1 Surface Freight Performance Measures

In the U.S., the trucking industry represents the largest portion of domestic freight movement. According to the *U.S. Freight Transportation Forecast to 2021* published by the American Trucking Association (ATA) in 2010, the trucking industry shares about 68% of total tonnage and trucks move more than 80% of freight revenue. Safe, efficient, and reliable trucking services are essential, not only to provide door-to-door freight transportation, but also to ensure the effective operation of other freight modes and facilities.

Trucks usually occupy more than twice of the space of passenger vehicles on the roadway. Truck delays from traffic congestion or adverse weather conditions can have significant impact on truck travel time reliability. Federal Highway Administration (FHWA) has developed national congestion monitoring program that uses archived traffic detector data for measuring traffic congestion and travel time reliability (Pu, 2011; Turner et al., 2004). NCHRP Synthesis Report 384 (Kuzmyak, 2008) identified the challenges that many metropolitan planning organizations (MPOs) are facing in forecasting freight activities and modeling freight movements. NCFRP report #10 (2011) emphasized the importance of freight performance measures to support investment, operations, and policy decisions for both public and private stakeholders.

Many MPOs model heavy trucks as an alternative for modeling freight activity because trucks account for more than 80% of freight movement in most metropolitan areas. FHWA and American Transportation Research Institute (ATRI) released the findings on level of truck congestion at 250 freight significant highway locations in 2011. Five highway interchanges located in the Twin Cities metro area (TCMA) were identified in the study (ATRI, 2011).

Schofield and Harrison (2007) reported the status of freight performance measures used in DOTs nationally and suggested a set of relatively broad performance measures including mobility, reliability, economic, safety/environment, and infrastructure for emerging users (See Appendix A for more details). Varmar (2008) compiled, organized, and analyzed freight data by mode, performance measure and indicator categories. The report suggested that there are needs to, (1) determine what performance measures or indicators are relevant and most important for freight planning support, and (2) identify freight significant strategic corridors and nodes.

The Minnesota Department of Transportation (MnDOT), Office of Freight and Commercial Vehicle Operations (OFCVO) has identified and included travel time by mode as one of the four performance indicators in the statewide freight plan (MnDOT, 2005). Currently, the MnDOT has also deployed Automatic Traffic Recorders (ATR) and Weigh-In-Motion (WIM) systems statewide for measuring truck weight and classifications with varying axle configurations at highway speeds (MnDOT traffic data, http://www.dot.state.mn.us/traffic/data/index.html). Existing ATR and WIM sensors collect truck volume and speed information at selected locations statewide. However, they do provide truck travel time information.

1.3.2 Probe Vehicle Based Performance Measures

With the prevalence of GPS receivers on vehicles and portable navigation devices, probe vehicle based data collection has been increasingly attractive to transportation community. The GPS based vehicle location data has been used to estimate traffic states and derive travel time information for traffic monitoring (Lund and Pack, 2010; Guo et al., 2008; Smith, 2006; Nanthawichit et al., 2003). Probe vehicle data, when fused with loop detector data and other data sources, can provide more complete and continuous coverage of traffic monitoring. Turner et al. (2011) outlined the primary data requirements for congestion-related performance measures and introduced core data elements and various metadata to ensure data consistency among data providers. They also examined legal and institutional issues related to privacy and Freedom of Information (FOIA) with regard to implementation.

Travel time reliability is one of the key measures of freight performance along interstates or interregional corridors in the nation (Lomax et al., 2003; TTI, 2006). Pu (2011) examined several reliability measures and recommended a median-based buffer index or a failure rate estimate is more appropriate to handle heavily skewed travel time distributions. A list of reliability measures is included in Appendix B.

Majority of commercial vehicles are equipped with on-board Automatic Vehicle Location (AVL) systems that collect truck locations at a fixed polling rate. The continuous trajectory information presents an excellent data source for monitoring travel time and reliability. However, GPS-based truck trip data usually are not available and are more difficult to collect due to the proprietary nature of the data. Commercially available travel time information (for example, from INRIX) provides some coverage using aggregated general traffic speed data from loop detectors and other probe vehicle based data sources. However, heavy commercial vehicles are considerably underrepresented in this type of data source.

Since 2002, FHWA has established a partnership with the American Transportation Research Institute (ATRI) and the trucking industry to measure average truck travel speed on major freight-significant corridors using more than 400,000 commercial trucks in North America (Jones et al., 2005). A spatial data processing methodology was evaluated, refined, and assisted by Liao (2008) to improve the effectiveness of generating freight performance measures (FPM). Analyzing truck speed, volume and travel time by location can also help identify network impediments and variations of seasonal flow changes (Liao, 2009). Derived vehicle speed and travel time from the GPS and/or terrestrial wireless systems used by the trucking industry provide potential opportunities to support freight planning and operation on the surface transportation system.

McCormack and Hallenbeck (2006) used 25 portable GPS data collection units with 1-second polling rate to gather truck positioning data for measuring freight movements along freight significant corridors in Washington State. The study concluded that GPS data can be collected cost effectively and can provide an indication of roadway performance. Based on processed truck speed data, a route model including analyses of truck travel time, delay and reliability can be developed to better understand current freight network performance, freight origin to destination flows, and to study possible solutions to future freight demand growth (Short & Jones, 2008).

Initial phase of the FHWA FPM initiative is to measure average travel rates on five freight-significant corridors (Jones et al., 2005). ATRI analyzed the severity of 30 key freight bottlenecks in the U.S. interstate system (Short et al., 2009). Freight bottlenecks occurred at highway interchanges were analyzed using a freight congestion index. Possible causes for the bottlenecks may include roadway geometry (e.g., grade, curvature, and sight distance), capacity (number of lanes), toll booths, speed limit, weather, truck volume vs. general traffic volume, and available lane of travel for trucks.

The MnDOT completed a study on truck parking analysis. The goal was to develop the information necessary to support decisions regarding future approaches to the truck parking issues in Minnesota (Maze et al., 2010). Short and Murray (2008) demonstrated the capability of utilizing FPM data for truck parking analysis. Another application is to utilize the FPM data to evaluate the travel time and delay at border crossing. FHWA conducted a study to address the need to reduce the hours of delay for commercial motor vehicles passing through ports-of-entry (FHWA, 2002). However, manually truck data collection at border crossing plaza is labor intensive and expensive.

Recently, FHWA is leading the effort to asses and validate the appropriateness of using GPS data from commercial vehicles to derive mobility and reliability performance measures and to support congestion monitoring on the highway system. Four key factors, including average daily traffic (ADT) per lane, percent of heavy vehicle, grade, and congestion level, were investigated. The preliminary findings indicated that (1) estimates of speed from FPM data are sufficiently accurate for performance measurement on most roadways in the United States, (2) FPM speed estimates show a consistent negative bias due to differences in operating characteristics of trucks and autos, and (3) grade and congestion have the greatest effect on FPM data accuracy among the four key factors evaluated (FHWA, 2012).

1.3.3 National Corridors Analysis & Speed Tool (N-CAST)

ATRI in coordination with the FHWA previously announced in October 2012 a beta release of Freight Performance Measures (FPM) tool that expands on the scope and functionality of the original FHWA-sponsored "FPMWeb" application (www.freightperformance.org/). The National Corridors Analysis & Speed Tool (N-CAST, www.atri-online.org/n-cast) provides key roadway performance and truck mobility information for the U.S. Interstate Highway System. The N-CAST database includes average speed and share of total position reads of each one-mile segment in AM peak (6-10AM), mid-day (10AM-3PM), PM peak (3PM-7PM), and off peak (7PM-6AM) periods. The N-CAST tool has the potential to be integrated with existing truck data sources to generate critical performance measures (such as delay and reliability) to provide technical guidance to stakeholders in the freight industry.

For example, the vehicle-hours of delay on Interstate and NHS corridor can be computed as,

$$Annual\ Delay = \sum_{day} \sum_{All\ Segments} \left(\frac{Segment\ Length}{Travel\ Speed} - \frac{Segment\ Length}{Threshold\ Speed} \right) \times HCAADT \tag{Eq. 1-1}$$

The Reliability Index (RI) for 80th percentile travel time can be defined as,

$$RI_{80} = \frac{80^{th}\ percentile\ Travel\ Time}{Travel\ Time\ at\ Agency{-}Specified\ Threshold\ Speed} \tag{Eq. 1-2}$$

1.4 Data Sources

Traffic data obtained from FHWA, MnDOT, and American Transportation Research Institute (ATRI) for this study.

1.4.1 ATRI Truck GPS data

Since 2002, the ATRI has partnered with FHWA and the trucking industry to continuously collect GPS data on key national corridors, using nearly 500,000 commercial trucks in North America. This massive amount of truck GPS data can provide public agencies at both the federal and regional level with tools that can increase understanding of freight activity, identify impediments along the freight network, and provide for near-real-time operations decision-making.

Aside from its official use by the U.S. DOT, ATRI's data has now been used by more than a dozen MPOs and 9 state DOTs to conduct truck- and freight-related analyses. Other "providers" of traffic data who claim to incorporate "commercial vehicles" primarily use taxis and limos to meet this definition. Those same providers do have some large trucks, but their total truck populations do not exceed 35,000 for the entire U.S. According to ATRI, "no other traffic provider in the U.S. has more than 10% of the large truck units that ATRI has". The ATRI data also includes descriptive data for their truck units at a high-level. Existing research has concluded that there are no good surrogate data for large trucks. That is, it's inadequate to use cars or taxis as a surrogate for large truck analyses.

The University of Minnesota (UMN) has established a data sharing agreement with ATRI. The data attributes to be reported for each record will include a unique vehicle number, latitude, longitude, and date/time. No two trucks will use the same identifier. Twelve months (January 2012 to December 2012) of truck GPS data in the Twin Cities metro area (TCMA) were obtained. A sample of GPS point cloud data is displayed in Figure 1-1. Example of truck GPS data is listed in Table 1-1.

Table 1-1 Sample Truck GPS Data

Truck ID	XXXXXXXXX
Date & Time String	2012-12-31 18:00:33 (UTC Time Zone)
Speed	55
Heading	W
Latitude	44.9639807
Longitude	-92.6853899

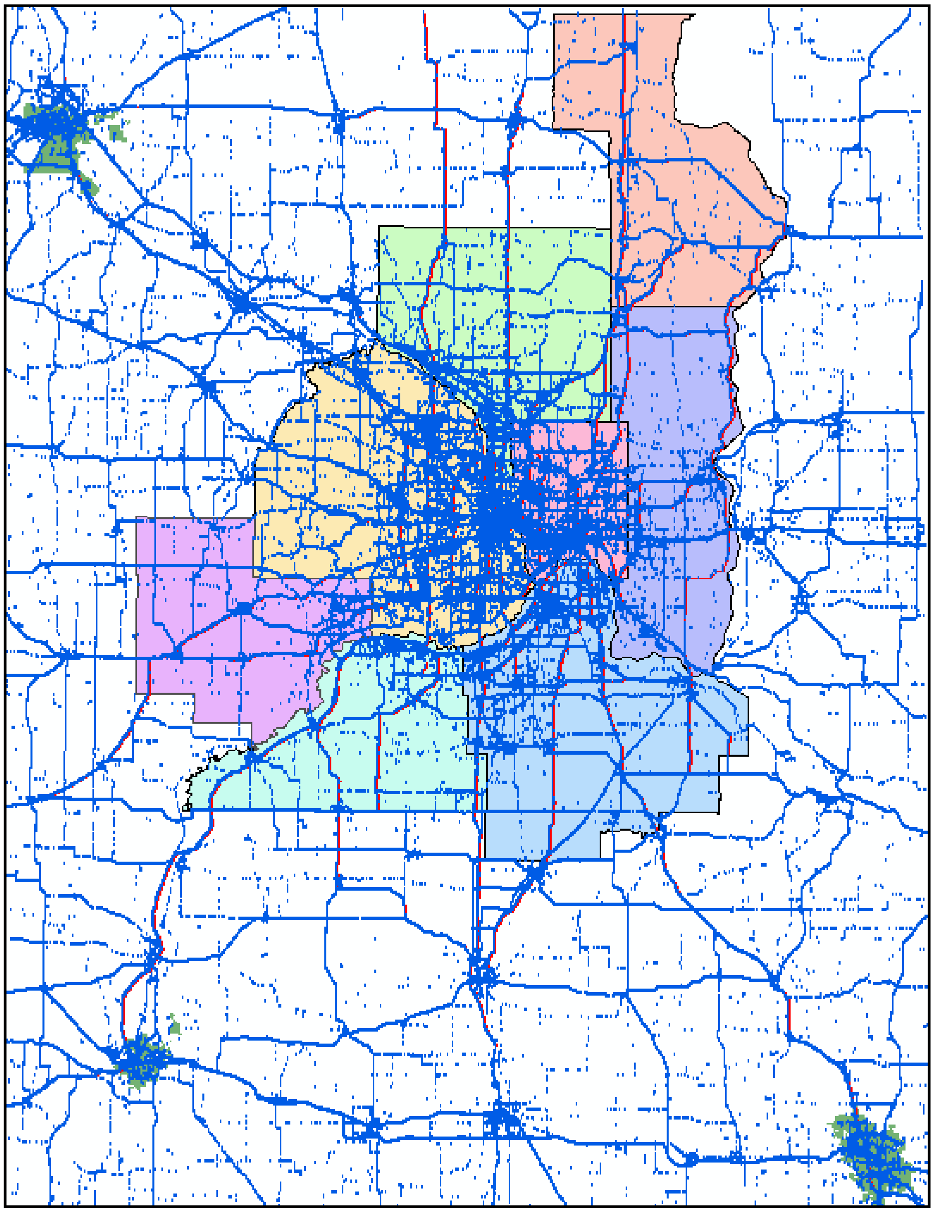


Figure 1-1 Snapshot of Truck GPS Point Cloud (Dec. 2012)

1.4.2 National Corridors Analysis & Speed Tool (N-CAST)

ATRI, in coordination with the FHWA, announced a beta release of Freight Performance Measures (FPM) tool that expands on the scope and functionality of the original FHWA-sponsored "FPMWeb" application. The National Corridors Analysis & Speed Tool (N-CAST) provides key roadway performance and truck mobility information for the U.S. Interstate Highway System. The N-CAST database includes average speed and share of total position reads of each one-mile segment in AM peak (6-10AM), mid-day (10AM-3PM), PM peak (3PM-7PM), and off peak (7PM-6AM) periods. The N-CAST tool has the potential to be integrated with existing truck data sources to generate critical performance measures (such as delay and reliability) to provide technical guidance to stakeholders in the freight industry.

1.4.3 National Performance Management Research Data Set (NPMRDS)

In July 2013, FHWA has announced a National Performance Management Research Data Set (NPMRDS) to support its FPM and Urban Congestion Report (UCR) programs. The NPMRDS includes probe vehicle based travel time data (for both passenger and freight vehicles) for all National Highway System (NHS) facilities. The NPMRDS will support transportation agencies needs by obtaining a comprehensive and reliable set of data that can be broadly deployed for use in measuring, managing and improving the US transportation system.

1.4.4 MnDOT WIM Data

The WIM data contains individual vehicle data such as number of axle, speed, vehicle class, and weight. Speed data from WIM sensors is an ideal benchmark data source to validate the speed derived from probe vehicle GPS data. There are 4 WIM stations, listed as follows, in the 8-county TCMA. The WIM data was used for both truck speed and volume comparisons at each location. Detailed descriptions of the MnDOT WIM data are included in Appendix C.

- WIM #36 in Lake Elmo (State Highway 36)
- WIM #37 in Albertville/Otsego (Interstate Highway 94)
- WIM #40 in West St. Paul (US Highway 52)
- WIM #42 in Cottage Grove (US Highway 10/61)

1.4.5 Automatic Traffic Recorder (ATR) Data

Continuous traffic counting devices (WIMs and ATRs) are installed in the TCMA (TCMA Map & Interactive Mapping Application). In the 7-county metro area, there are 18 ATR’s that collect vehicle classification (11 of which are on trunk highways) and 4 WIM’s (3 of which are on trunk highways). The WIM/ATR program is currently progressing towards the goal of converting every ATR in the state to collect vehicle classification.

Three different types of ATR devices were deployed by MnDOT in TCMA to collect traffic volume, speed, and/or classification information. Limitations of different ATR devices are summarized as follow.

- ATR volume only recorder – Collect all traffic counts. This data cannot be used for truck volume comparison.
- ATR volume/speed recorder – No vehicle classification information. This data cannot be used for truck speed comparison.
- ATR volume/speed/class - The Vehicle Classification counts can provide volumes for heavy commercial vehicles.

The HCAADT is theoretical estimate of the total number of heavy commercial vehicles using a specific segment of roadway (in both directions) on any given day of the year. This estimate represents the total number of heavy commercial vehicles per year divided by 365 and is developed by MnDOT using factors to adjust for season. The Heavy Commercial Average Daily Traffic (HCADT) a 24-hour heavy commercial traffic volume that should be qualified by stating a time period (e.g., MHCADT – monthly average daily heavy commercial traffic, or HCADT for the period 6/21/2011-6/23/2011).

Sample ATR data are listed as follows:

Table 1-2 ATR Volume by Hour of Day

Date	Oct. 30, 2012	
Hour	EB	WB
1	1	5
2	2	1
3	0	1
4	1	3
5	4	1
6	21	5
7	42	16
8	48	31
9	45	26
10	38	19
11	30	25
12	25	29
13	22	27
14	34	35
15	29	40
16	46	50
17	47	50
18	53	51
19	29	43
20	20	35
21	8	22
22	9	25
23	3	13
24	9	8
TOTAL	566	561

Table 1-3 ATR Speed Data in Different Speed Bins by Hour of Day

HOUR	40 MPH	45 MPH	50 MPH	55 MPH	60 MPH	65 MPH	70 MPH	75 MPH	80 MPH	85 MPH	100 MPH	110 MPH	>110 MPH
07:00	6	0	0	0	0	0	0	1	0	0	2	21	18
08:00	6	0	1	0	0	0	0	0	0	2	1	18	18
09:00	3	1	1	0	1	0	0	0	0	4	2	16	10
10:00	3	0	0	0	1	1	0	0	0	1	3	7	16
11:00	2	0	0	0	0	0	0	0	0	0	2	8	13
12:00	1	1	0	0	0	0	0	0	1	0	2	10	7
13:00	4	1	0	0	0	0	0	0	0	1	2	4	22
14:00	4	2	0	0	0	0	0	0	0	0	3	9	12
15:00	5	2	0	0	3	0	0	0	0	1	4	17	14
16:00	6	0	1	0	1	0	0	0	0	0	3	14	23
17:00	5	2	0	0	0	0	0	0	0	0	1	14	31
18:00	3	0	0	1	0	0	0	0	0	2	1	9	13

Table 1-4 Vehicle Counts by Class and Hour of Day

Time	Lane #	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13	Class 14
8:00	1	0	37	8	0	0	0	0	0	0	0	0	0	0	0
8:00	2	0	15	8	0	0	0	0	3	0	0	0	0	0	0
9:00	1	0	24	9	0	1	0	0	4	0	0	0	0	0	0
9:00	2	0	11	7	0	0	0	0	1	0	0	0	0	0	0
10:00	1	0	13	15	0	0	0	0	1	0	1	0	0	0	0
10:00	2	0	14	6	0	2	0	0	3	0	0	0	0	0	0
11:00	1	0	19	4	0	0	0	0	2	0	0	0	0	0	0
11:00	2	0	24	5	0	0	0	0	0	0	0	0	0	0	0
12:00	1	0	14	7	0	1	0	0	0	0	0	0	0	0	0
12:00	2	0	13	8	1	0	0	0	5	0	0	0	0	0	0
13:00	1	0	25	9	0	0	0	0	0	0	0	0	0	0	0
13:00	2	0	22	13	0	0	0	0	0	0	0	0	0	0	0
14:00	1	0	21	4	0	2	0	0	0	2	0	0	0	0	0
14:00	2	0	29	7	0	4	0	0	0	0	0	0	0	0	0
15:00	1	0	26	15	0	3	0	0	1	0	1	0	0	0	0
15:00	2	0	34	15	0	0	0	0	1	0	0	0	0	0	0
16:00	1	0	31	14	0	1	0	0	1	0	0	0	0	0	0
16:00	2	0	33	13	0	1	0	0	3	0	0	0	0	0	0
17:00	1	0	33	17	0	2	0	0	1	0	0	0	0	0	0
17:00	2	0	37	14	0	0	0	0	0	0	0	0	0	0	0
18:00	1	0	22	6	0	1	0	0	0	0	0	0	0	0	0
18:00	2	0	34	9	0	0	0	0	0	0	0	0	0	0	0

1.4.6 Other Data Links

Additional web links of other data are listed as follows.

- MnDOT Online Mapping Application, http://www.dot.state.mn.us/traffic/data/tma.html
- Metro trunk highway HCAADT map, http://www.dot.state.mn.us/traffic/data/maps/th_adt_overview/2011_HCAADT_Metro_Map.pdf
- Greater MN trunk highway HCAADT map, http://www.dot.state.mn.us/traffic/data/maps/th_adt_overview/2011_HCAADT_Gr8MN_Map.pdf
- MN Road data ftp site, ftp://ftp2.dot.state.mn.us/pub/outbound/TDA/WIM/WIM_Sites/
- Web link for the WIM Data Analyst's Manual, http://www.fhwa.dot.gov/pavement/wim/pubs/if10018/if10018.pdf
- Web link to the monthly WIM reports, http://www.dot.state.mn.us/traffic/data/html/wim_reports.html

1.5 Report Organization

The rest of this report is organized as follows. Data summary and processing mythology are discussed in Section 2. Performance measures and analysis results are included in Section 3. Brief discussion of the National Performance Measurement Research Data Set (NPMRDS) and a data analysis example using the NPMRDS data in Minnesota are presented in Section 4. Finally, conclusion and summary are included in Section 5.

2. DATA PROCESSING METHODOLOGY

A data analysis methodology was developed to process raw truck GPS data. The processed results were used to derive performance measures to better understand the mobility and reliability of trucks traveling along the key freight corridors in the Twin Cities metro area (TCMA). First, truck GPS raw data received from American Transportation Research Institute (ATRI) is summarized in the following section. Second, a list of studied corridors in TCMA, the data processing methodology and analysis results are presented. Processed probe vehicle speed and volume percentage by hour are compared to the data collected from a weigh-in-motion (WIM) station. Lastly, freight performance measures, such as truck delay, cost of delay, and travel time reliability are derived and discussed.

2.1 GPS Data Summary and Limitation

ATRI's database of GPS traces of trucks includes nearly 4 billion truck positions annually in North America. The truck GPS traces provide empirical evidence of where and when real truck activity occurs. ATRI acquires this information through several private sector data sharing partnerships and compiles it as part of the freight performance measures (FPM) initiative, an effort sponsored in part by the Federal Highway Administration (FHWA, 2002). The primary source of these data is onboard communications equipment installed on commercial trucks (e.g. tractor-trailer combinations or FHWA vehicle class 9 or above) from large trucking firms and independent truckers. The ATRI's GPS data represents a good sample of truck flows, but it does not represent all truck flows. It does not separate intra-urban commercial motor vehicles (CMV) from inter-regional freight movements. More information about ATRI's GPS data distribution by vehicle configuration and fleet size is included in Appendix D.1.

As part of the data sharing agreement between the UMN and ATRI, the research team received three different sets of truck GPS data as summarized and listed in Table 2-1. Dataset A and C contain probe vehicle spot speed and latitude-longitude location information. Dataset B does not include vehicle spot speed information. Dataset A has a positioning accuracy less than 3 meters. At 95% probability, the GPS positioning accuracy of dataset B and C is about 150 and 58 meters, respectively. Corresponding tolerance is used to merge raw GPS point to a nearest roadway. Due to data privacy concerns, the vehicle ID is masked or encrypted. In addition, the vehicle ID in dataset B rotates every 15 days and the vehicle ID in dataset C changes every 24 hours. The estimated GPS pinging rate for dataset A, B and C are about 8, 18 and 1 minute with standard deviations of 15, 26, and 5 minutes, respectively. A list of ATRI truck GPS data fields for each dataset is included in Table 2-2.

There are no Automatic Traffic Recorders (ATR) that collect vehicle classification counts located on the metropolitan freeway system within the 494/694 ring, and only 1 ATR on the ring (I-694 in Oakdale) which would be heavily influenced by through truck trips as that is the designated through route to avoid travelling through the downtowns. In addition, 1 Weigh-in-Motion (WIM) counter is on the freeway US-52 within the ring and would provide vehicle classification data. There are also 2 ATRs on County Highways within the ring that are also vehicle classification capable; however, truck movements on these highways could be very different in composition and purpose than those on the freeway system. Data for this study depended predominantly on ATR freeway counts taken outside the ring, but made inferences about truck movements on freeways inside the ring.

2.2 Key Freight Corridors

Thirty eight (38) key freight corridors in the Twin Cities metro area (TCMA), as illustrated in Figure 2-1, were selected for this study. This study also includes 4 major corridors that connect the Twin Cities metropolitan area to regional freight centers in St. Cloud, Mankato, and Rochester. List of each freight corridor ID referred in the data processing and analysis, and its corresponding route description is tabulated in Table 2-3.

Table 2-1 Summary of ATRI GPS Data

Data Set	DS-A	DS-B	DS-C
Time Zone	GMT/UTC	GMT/UTC	GMT/UTC
Spot Speed	Yes	No	Yes
Static ID	Yes	Rotates every 15 days	Rotates every 24 hours
Data Accuracy	Within <3 meters	Within 124-134 meters at 90% probability and 129-150 meters at 95% probability.	Within 13-56 meters at 90% probability and 15-58 meters at 95% probability.
Snap Tolerance Used (meter)	**50**	**150**	**50**
2013 Number of Truck Trips	**74,823**	**35,179**	**76,471**
2013 Raw Data Size	50,170,591	3,142,634	38,871,190
2013 Snapped	18,792,493	957,076	13,270,602
2013 Snapped Percentage	37.5%	30.5%	34.1%
Average Sampling Time (min)	8	18	1
SD Sampling Time (min)	15	26	5

Table 2-2 ATRI Truck GPS Dataset

Data Field	DS-A	DS-B	DS-C
1	truckid	truckid	truckid
2	readdate	readdate	readdate
3	speed	-	speed
4	heading	-	-
5	latitude	latitude	latitude
6	longitude	longitude	longitude

Table 2-3 List of Routes in TCMA

Route ID	Interstate	Highway No.	Highway Name	Length (mile)
1	N	242	State Highway 242	13.19
2	N	610	State Highway 610	6.80
3	N	252	State Highway 252	4.10
4	Y	694	Interstate 694	22.37
5	N	36	State Highway 36	21.61
6	Y	494	Interstate 494	42.78
7	N	100	State Highway 100	15.80
8	Y	394	Interstate 394	9.58
9	N	12	US Highway 12	16.49
10	N	280	State Highway 280	3.32
11	N	7	State Highway 7	34.26
12	N	62	State Highway 62	12.39
13	N	110	State Highway 110	1.38
14	N	212	US Highway 212	34.37
15	N	77	State Highway 77	11.77
16	N	32	County Road 32	1.99
17	N	101	County Road 101	2.19
18	N	42	County Road 42	21.38
19	N	316	State Highway 316	7.82
20	N	18	County Road 18	3.07
21	N	51	State Hwy 51	11.24
22	N	97	State Hwy 97	12.83
23	N	95	State Hwy 95	126.43
24	Y	94	I-94	135.45
25	N	8	US Highway 8	22.12
26	N	65	State Hwy 65	58.35
27	N	61	US Highway 61	60.91
28	N	55	State Hwy 55	55.00
29	N	52	US Hwy 52	85.12
30	N	5	State Hwy 5	85.98
31	N	10	US Hwy 10	99.87
32	N	47	State Hwy 47	58.48
33	Y	35	I-35E**	113.68
34	Y	35	I-35W	116.10
35	N	3	State Hwy 3	46.56
36	N	21	State Hwy 21	38.38
37	N	169	US Hwy 169	104.09
38	N	13	State Hwy 13	43.37

* Highlighted in light blue are the interstate corridors. Highlighted in pink are the US corridors.

** I-35E from TH-5 to I-94 is excluded from the key freight routes

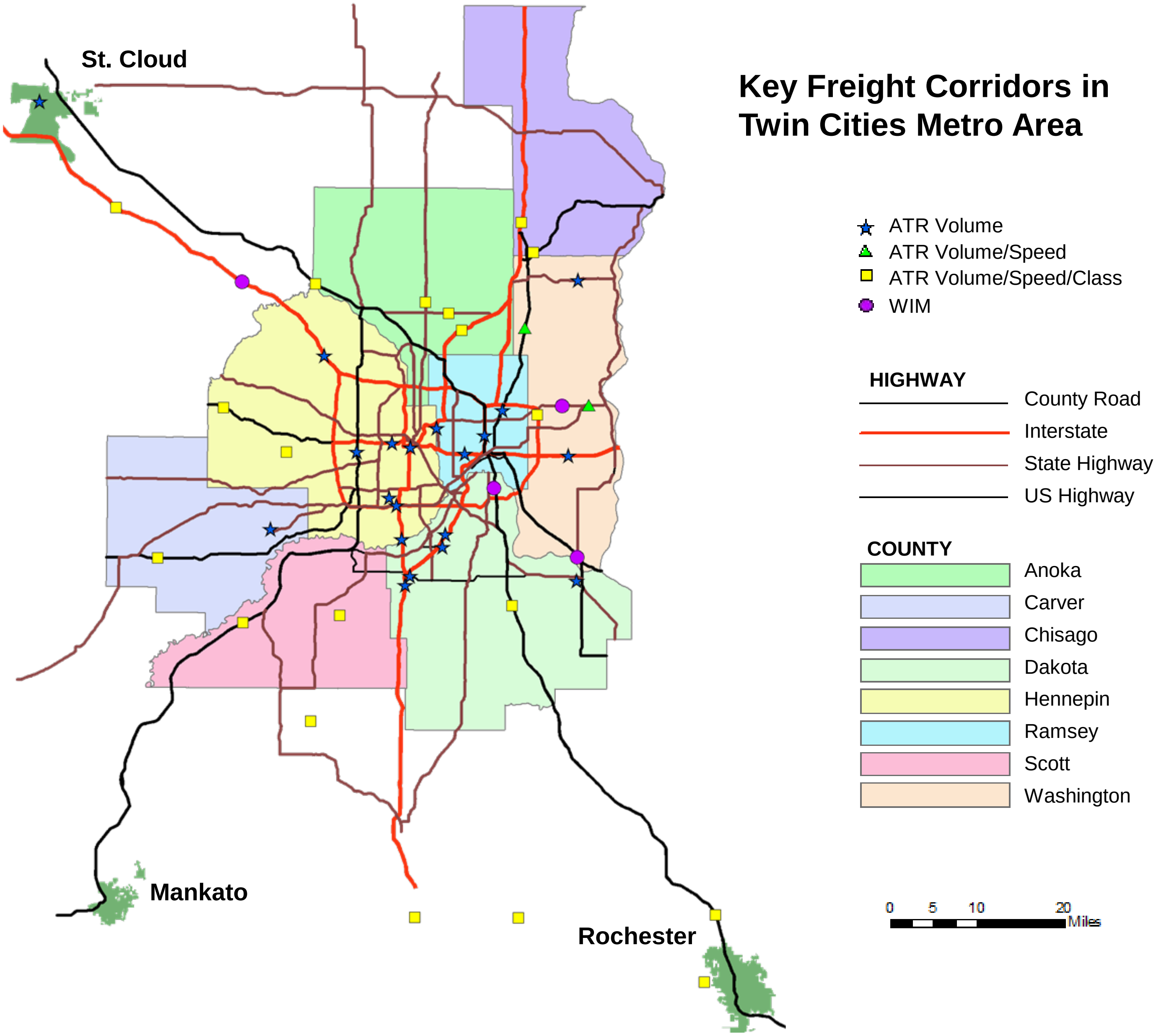


Figure 2-1 Key Freight Corridors in Twin Cities Metro Area

(Note: I-35E from TH-5 to I-94 is excluded from the key freight routes)

2.3 Data Processing Methodology

A route geo-spatial database of 38 key freight corridors in the TCMA was prepared using the ArcGIS software (http://www.esri.com/software/arcgis). The geographic information system (GIS) roadway network data was imported to an open source Structured Query Language (SQL) object-relational database, called *PosgreSQL* (http://www.postgresql.org/). In addition, a spatial database extension, call *PostGIS* (http://postgis.net/), for PostgreSQL database was included to support geographic objects analysis and allow location queries to be executed in the SQL environment.

After importing the raw truck GPS data from each dataset into the PostgreSQL database, several SQL scripts were developed to locate nearest roadway segments for all GPS latitude-longitude points and compute linear referencing measurements and distances. Individual vehicle trip speed was then computed by grouping vehicle ID and sorting the location data by time. Average vehicle space mean speed of a network segment is calculated by dividing the linear distance difference over time difference between two consecutive GPS data points within the same trip. Vehicle spot speed was also included for later data analysis. Processed data does not meet the speed filtering parameters (potential anomalies) are stored in a separate database for later truck stop location and stop duration analyses. The data processing and analysis flowchart was presented in Figure 2-2.

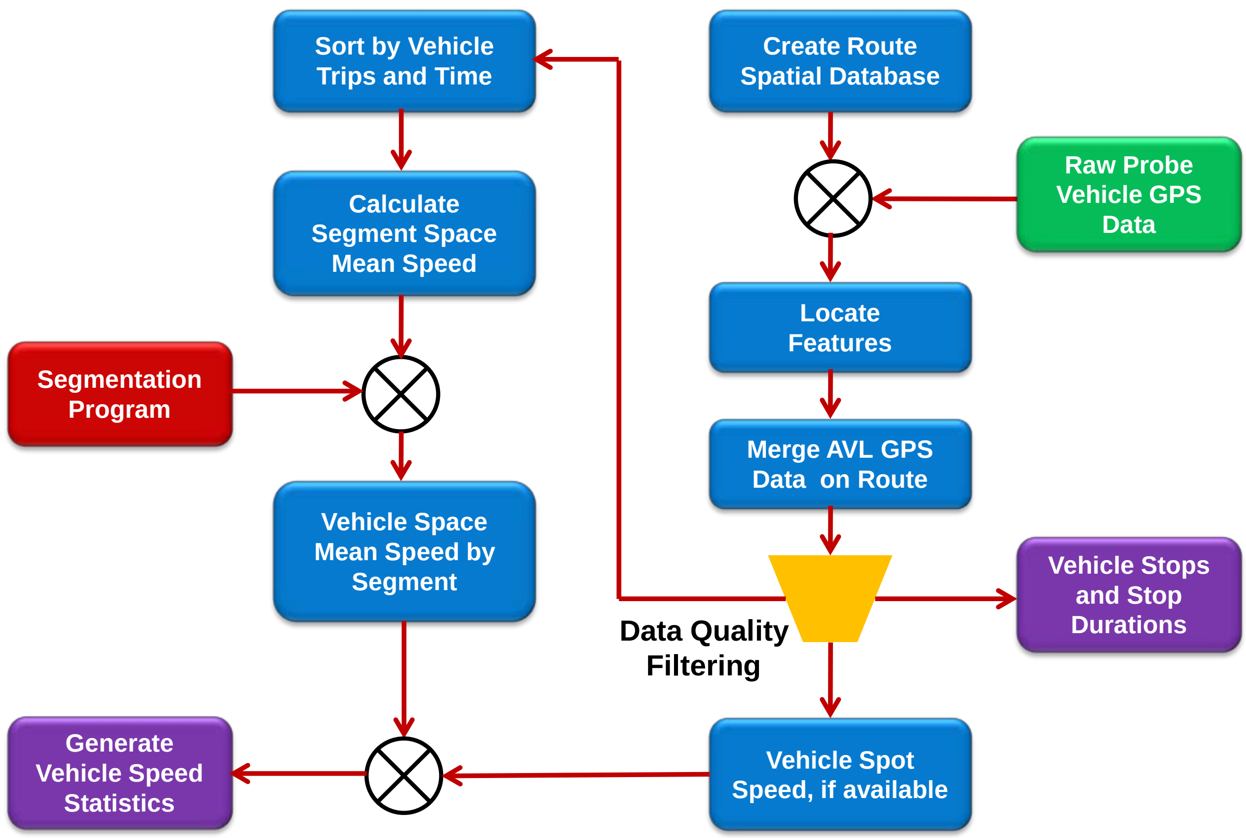


Figure 2-2 Data Processing Flowchart

Truck speed variations by location and by hour of day were analyzed. Speed and volume variations at specified mile marker were analyzed to compare the changes over the hour of day. Computed truck speed versus the general traffic speed gathered by state DOTs were compared to evaluate the speed difference between trucks and passenger vehicles. Raw truck GPS data did not pass through the data quality filter were trucks that might stop for service or rest. Public truck rest locations or facility along the key corridors in the TCMA and their stop durations were also derived to evaluate truck parking activity and service availability.

2.4 Data Analysis

Data proximity, spot vs. processed speed (or space mean speed), comparisons of speed and hourly volume percentage between probe vehicles and WIM stations were discussed and presented in this section. Positive direction is defined as the direction along a route where mile post increases. And the negative direction is the direction along a route where mile post decreases. Bar charts of number of probe vehicle data points by route in both directions are included in Appendix D.2.

2.4.1 GPS Data Proximity Analysis

Due to GPS data accuracy and the accuracy of road network GIS data, collected GPS data points distribute along a roadway as illustrated in Figure 2-3. As shown in the bar charts of data proximity by route in Appendix D.3, most of raw data from dataset A and C are, in average, 20 meters away from roadway centerline. In average, most GPS points from Dataset B are about 70 meters away from roadway.

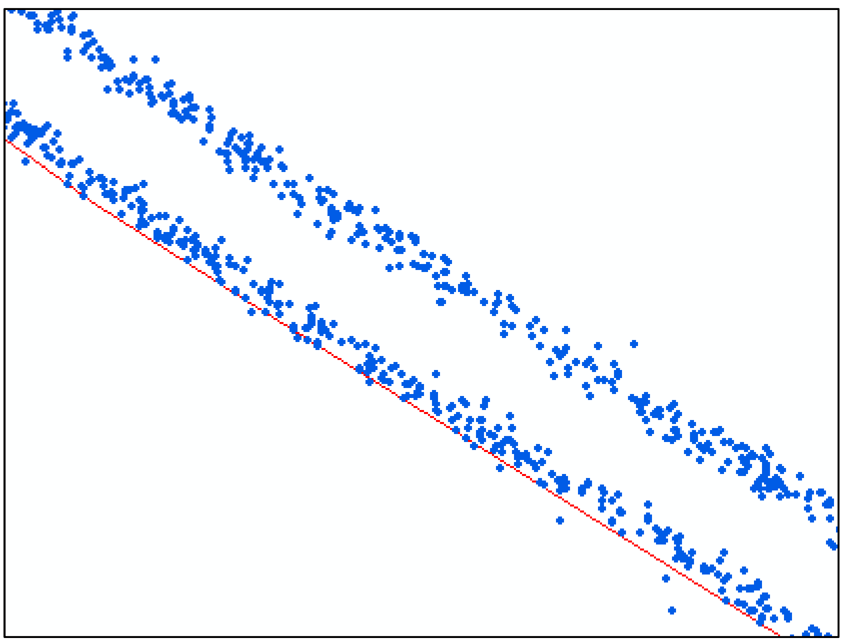


Figure 2-3 Example of GPS Data Point Cloud

2.4.2 Comparisons of Processed Probe Vehicle Results and WIM data

There are four Weigh-In-Motion (WIM) stations in the TCMA. The WIM sensor records individual vehicle speed, classification, and weight information. It's an ideal source to validate processed probe vehicle data. 12-month of WIM data from all four stations were received from MnDOT. Both passenger vehicles (class 2) and heavy commercial vehicles (class 9 and above) were analyzed and compared with processed results from probe vehicle data. Descriptions of these four WIM stations and their corresponding 2011 HCAADT counts are listed in Table 2-4 as follows. WIM station #37 is discussed in the following section. Additional data analysis results of WIM station #36, 40 and 42 are presented in Appendix D.4 ~ D.7.

Table 2-4 Description of WIM stations

WIM ID	36	37	40	42
Route Name	MN 36	I-94	US 52	US 61
County Name	Washington	Wright	Dakota	Washington
City Name	Lake Elmo	Otsego	West St Paul	Cottage Grove
Direction	EB	WB	NB	SB
Mile Post	15	200	127	119
WIM Location Description	.7 mi W of CSAH17 Lake Elmo Ave N) in Lake Elmo	1.2 mi NW of CSAH19 (La Beaux Ave) in Otsego	0.5 mi N of CSAH14 in West St. Paul	0.4 mi S of TH95 (Manning Ave S), S of Cottage Grove
WIM Type	VOLUME/SPEED/CLASS/WEIGHT			
Route ID	5	24	29	27
Roadway Segment ID	15	59	81	16
Linear Ref Direction	1	1	1	-1
2011 HCAADT	1100	6900	4400	1750

2.4.3 Spot vs. Space Mean Speed

Spot speed is the instantaneous vehicle speed captured by the GPS unit. Processed speed (or space mean speed) is the average vehicle speed calculated based on two consecutive vehicle GPS locations. Dataset A and C have spot speed information while dataset B does not have spot speed information. Spot speed at mile post 200 on I-94 is analyzed and compared with space mean speed as an example.

The histogram of probe vehicle spot speed and space mean speed are displayed in Figure 2-4(a) and 2-4(b) in both directions. In the increasing mile post direction (positive direction), the median of spot speed and space mean speed are 64.0 and 64.2 MPH, respectively. The distribution of average spot speed in positive direction is 61.3 MPH; 2.4 MPH lower than the average space mean speed at the same location. Similarly, the median of spot speed and space mean speed in the decreasing mile post direction (negative direction) are 64.0 and 64.5 MPH, respectively. The distribution of average spot speed in negative direction is 62.7 MPH, 1.7 MPH lower than the average space mean speed at the same location. In general, the standard deviation of spot speed is about twice as large as the processed speed in both directions.

Figure 2-5(a) illustrates the hourly comparison of average spot speed with space mean speed at a segment on I-694 WB before the Highway 51 exit ramp. The average spot speed, displayed by the red curve with green diamond marker, is about 14 MPH lower than the space mean speed displayed in blue curve with triangle marker after 7AM. The gap is significantly larger from 9-11PM. The hourly spot speed average has larger standard deviation as compared to the average space mean speed. The standard deviation of the spot speed is as high as 20 MPH after 7AM. The standard deviation of the space mean speed exceeds 10 MPH during the AM and PM peak hours as shown in Figure 2-5(a).

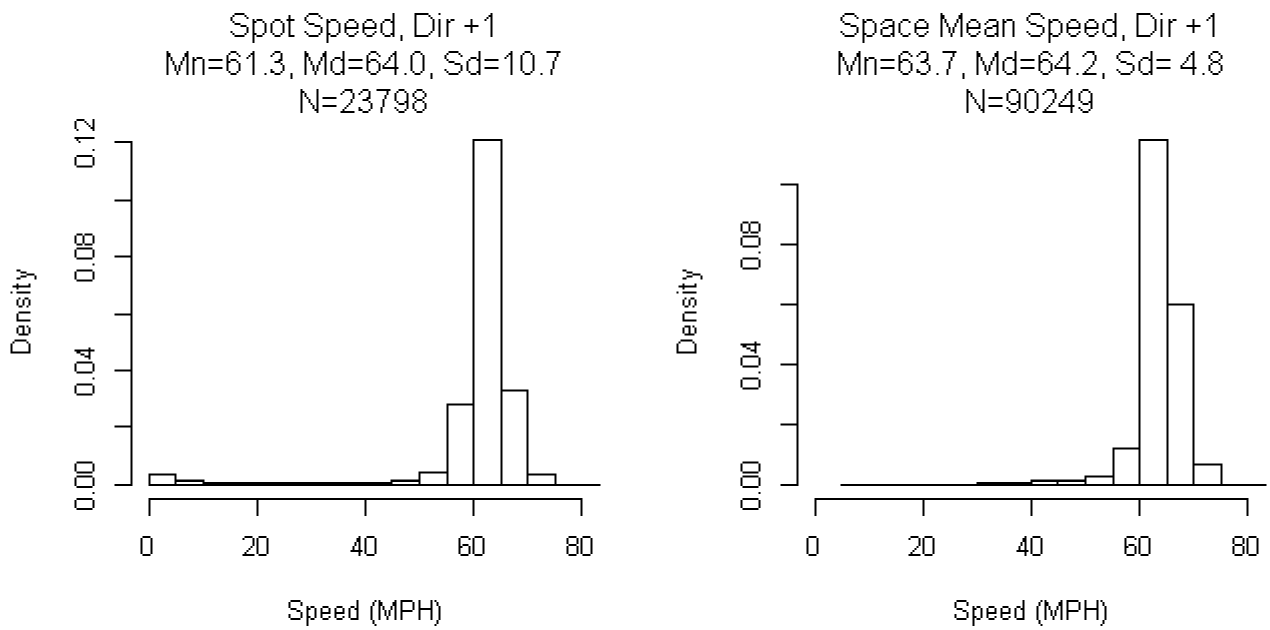


Figure 2-4(a) Spot vs. Space Mean Speed on Route I-94 at Mile Post 200
(In Increasing Mile Post Direction)

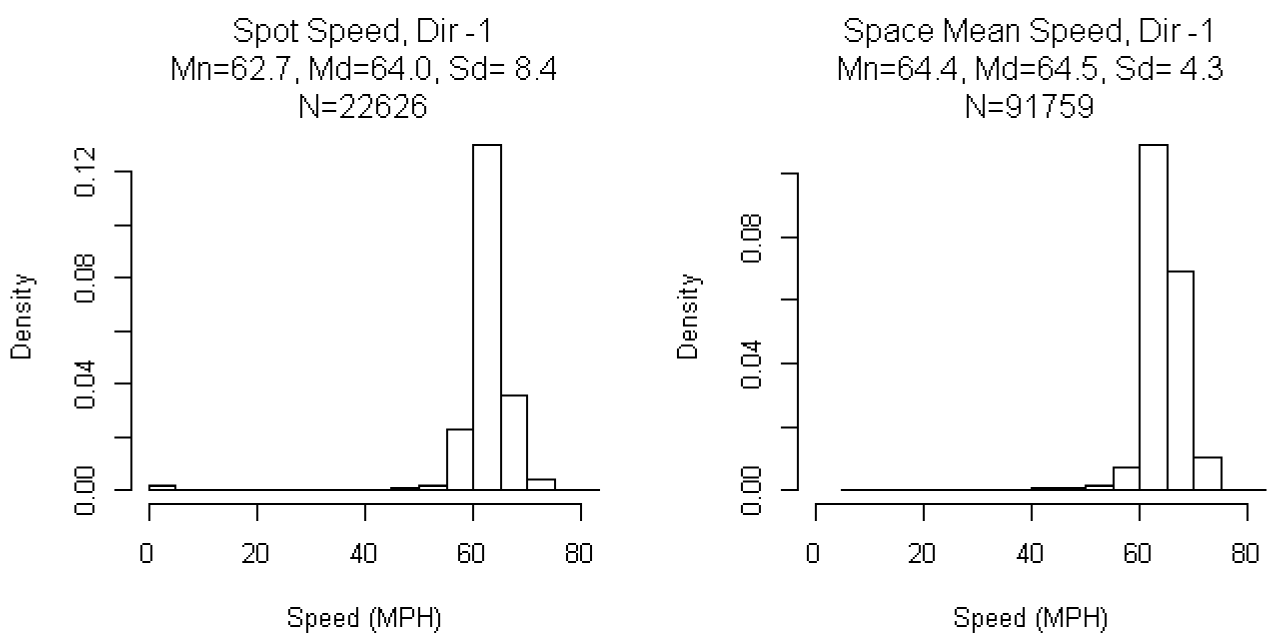


Figure 2-4(b) Spot vs. Space Mean Speed on Route I-94 at Mile Post 200

(In Decreasing Mile Post Direction)

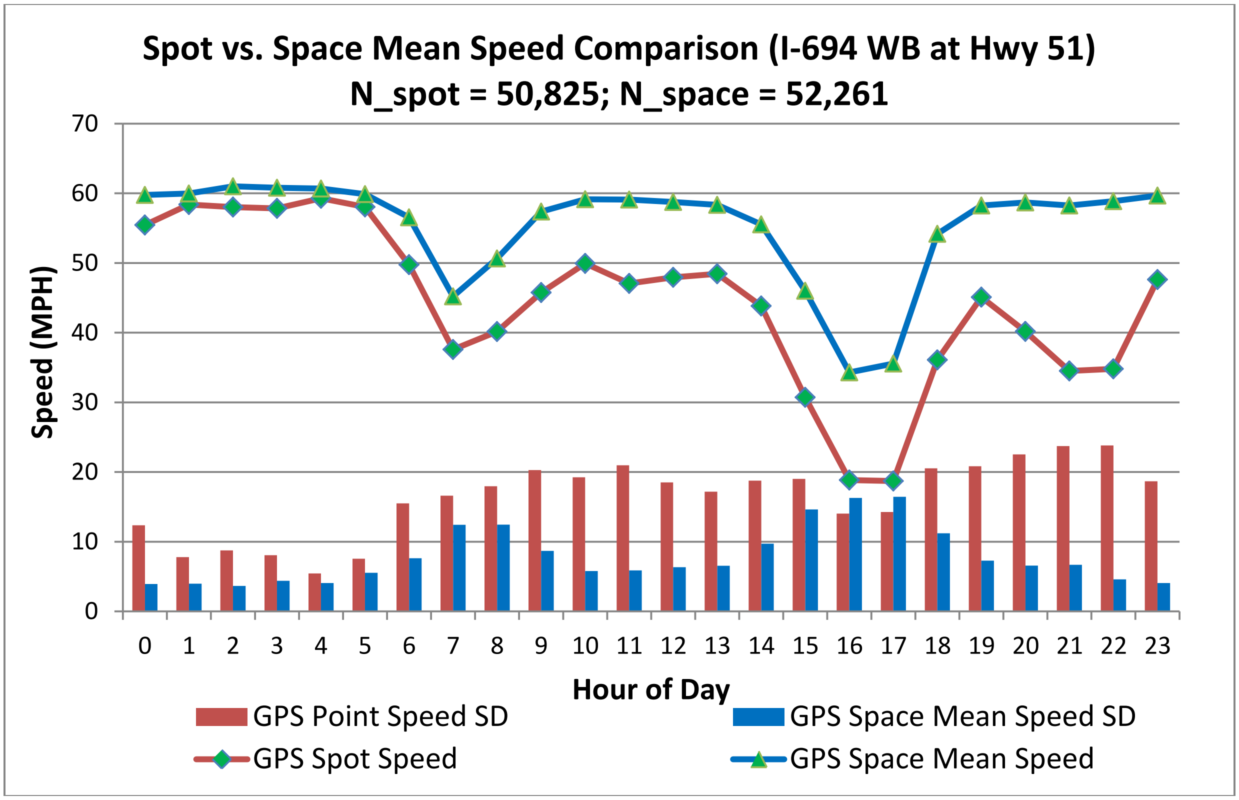


Figure 2-5(a) Spot Speed vs. Space Mean Speed on Route I-694 WB near State Highway 51

Figure 2-5(b) illustrates the hourly comparison of average spot speed with space mean speed at a segment on I-394 EB after the Highway 100 interchange. The average spot speed, displayed by the red curve with green diamond marker, is about 10 MPH lower than the space mean speed displayed in blue curve with triangle marker after 8AM. The gap is significantly larger from 7-11PM. The hourly spot speed average has larger standard deviation as compared to the average space mean speed. The standard deviation of the spot speed is as high as 20 MPH after 7AM. The standard deviation of the space mean speed exceeds 10 MPH during the AM and PM peak hours as shown in Figure 2-5(b).

Figure 2-5(c) illustrates the hourly comparison of average spot speed with space mean speed at a segment on I-494 EB after the Highway 100 interchange. The average spot speed, displayed by the red curve with green diamond marker, is about 16.5 MPH lower than the space mean speed displayed in blue curve with triangle marker after 9AM. The gap is significantly larger from 7-11PM. The hourly spot speed average has larger standard deviation as compared to the average space mean speed. The standard deviation of the spot speed is as high as 20 MPH after 7AM. The standard deviation of the space mean speed exceeds 10 MPH during the AM and PM peak hours as shown in Figure 2-5(c).

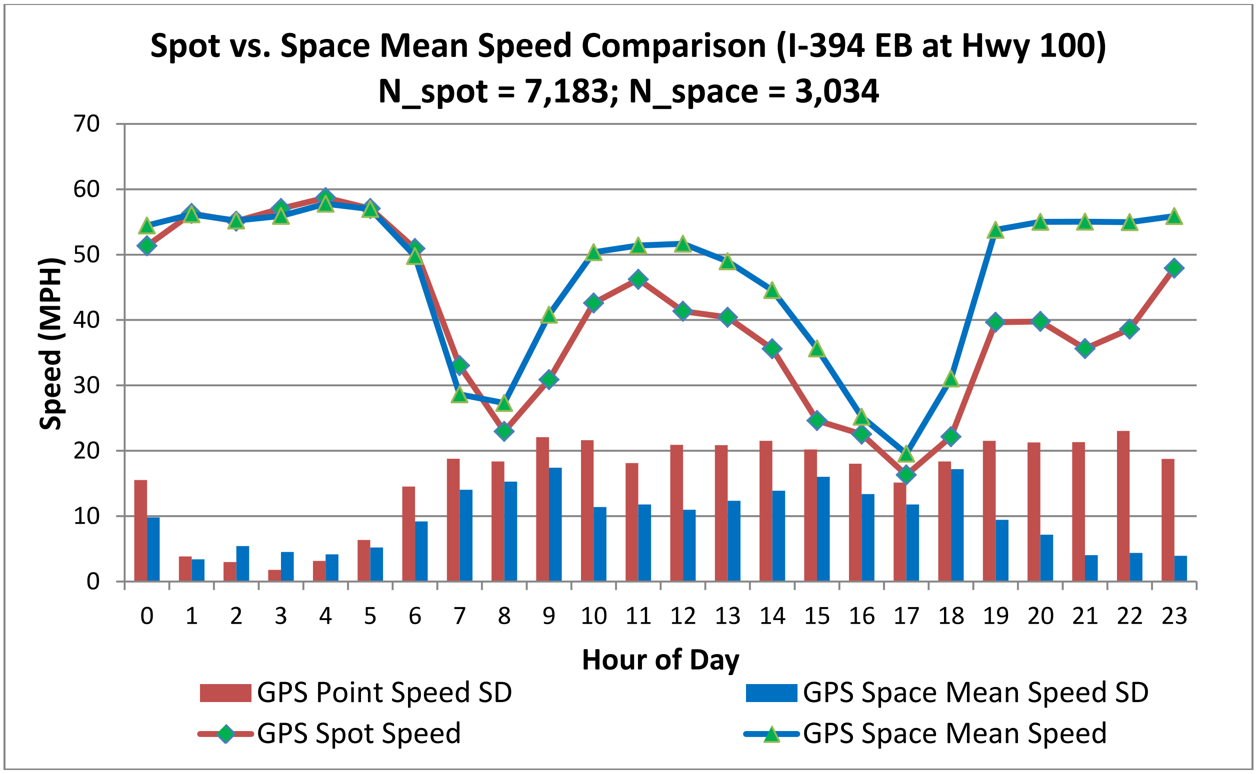


Figure 2-5(b) Spot Speed vs. Space Mean Speed on Route I-394 EB after Highway 100

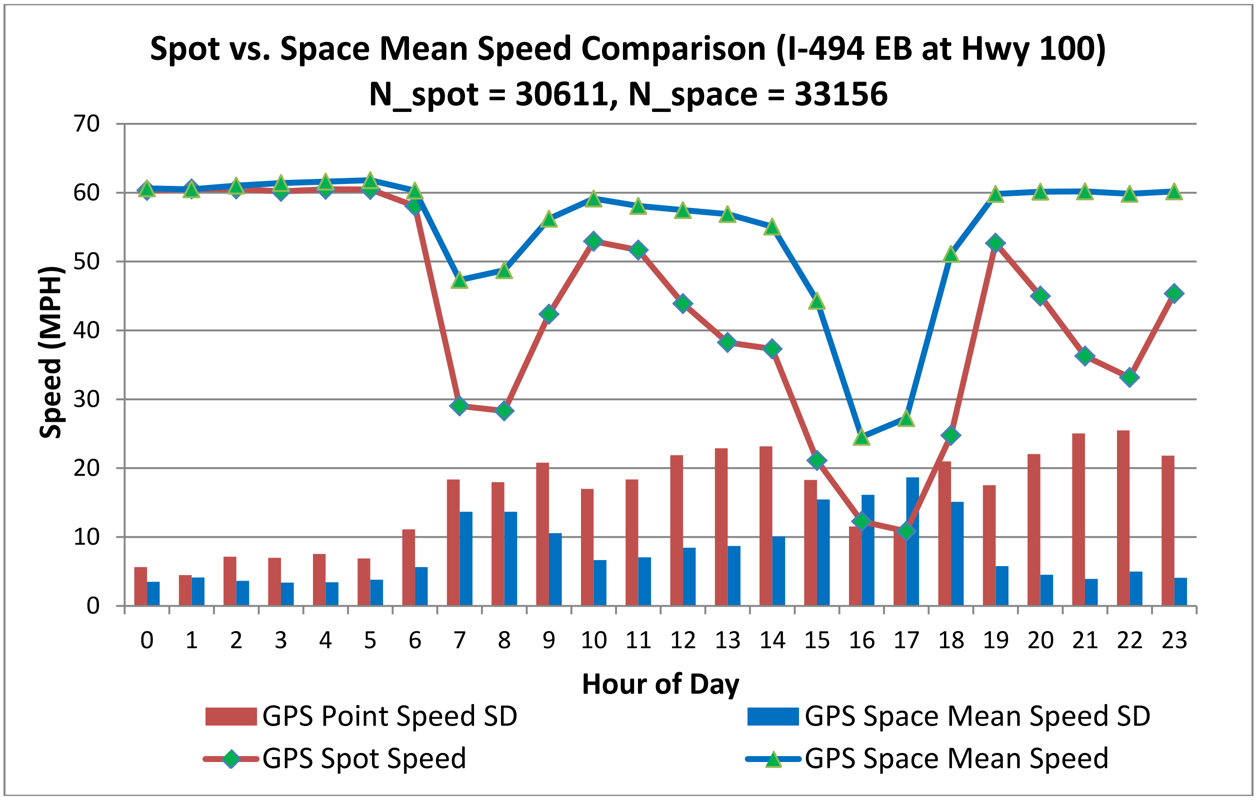


Figure 2-5(c) Spot Speed vs. Space Mean Speed on Route I-494 EB at Highway 100

2.5 Speed and Volume Comparisons

A one mile segment (I-94 WB Otsego, route ID 24, segment ID 59, mile post 200) where WIM station #37 is located is presented and discussed in this section. Additional analyses and comparisons at WIM #36, #40, and #42 are included in Appendix D.

2.5.1 Probe Vehicle vs. WIM Speed Comparisons

Probe vehicle speed at mile post 200 on I-94, where the WIM station #37 is located, are compared with speed collected by WIM #37 in 2012. The histogram of probe vehicle speed and WIM speed are displayed in Figure 2-6. The average probe vehicle speed at WIM37 location is 63.2 MPH while the WIM station recorded an average heavy commercial vehicle speed is 65.7 MPH. Similarly, the median speed of probe vehicles at WIM37 location is 64 MPH, 1 MPH lower than median speed from WIM37 station. The distribution of probe vehicle speed has a slightly larger standard deviation (6.5 MPH) than the speed (5.8 MPH) from WIM. The probe vehicle spot and median speeds by hour on weekdays are compared with WIM speeds as plotted in Figure 2-7.

Figure 2-8 displays the hourly comparison of probe vehicle speed with the speed from passenger vehicles and heavy commercial vehicles collected by WIM #37 in 2012. Average speed of passenger vehicles is about 70 MPH at this roadway segment. The average truck speeds measured from WIM and probe vehicles are about 65 and 63 MPH, respectively. The average standard deviation of speed measured from WIM for both passenger and trucks are pretty close (6.1 and 5.6 MPH, respectively) while the average standard deviation of probe vehicle speed is about 7.6 MPH, slightly higher than the WIM speeds.

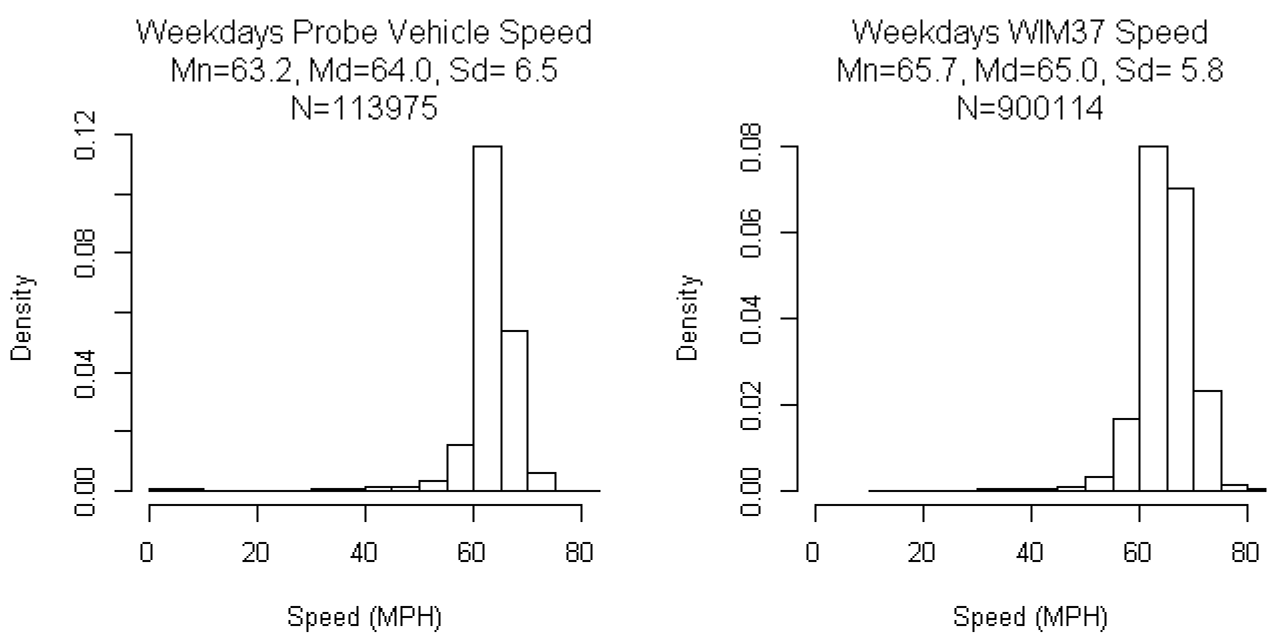


Figure 2-6 Probe Vehicle Speed vs. WIM Speed at WIM#37

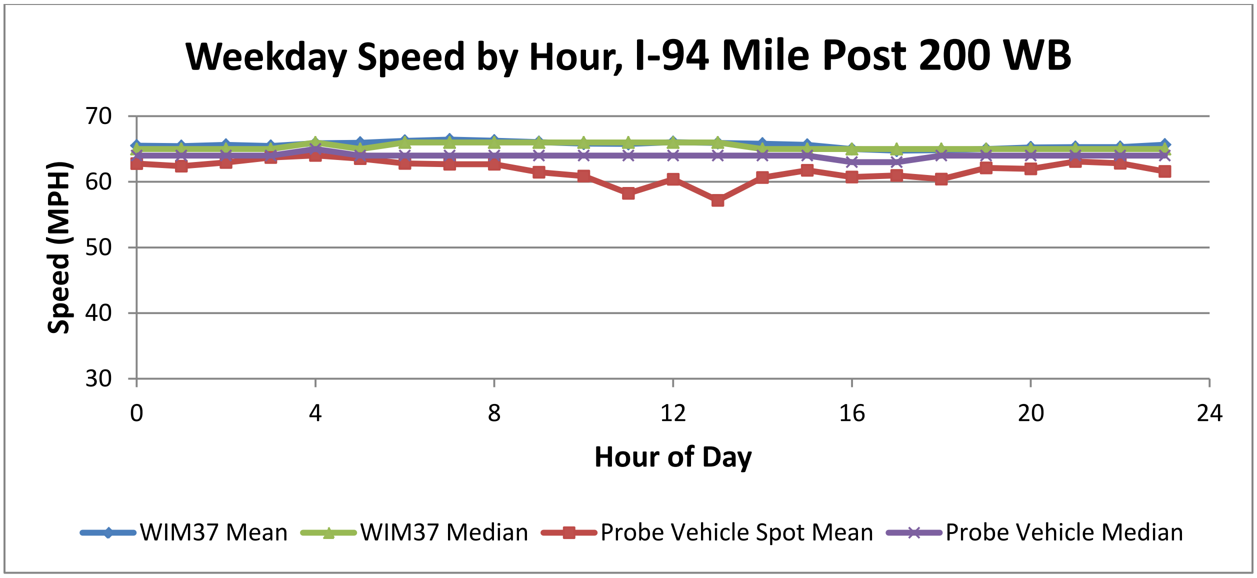


Figure 2-7 Probe Vehicle Median Speed vs. WIM Speed by Hour at WIM#37

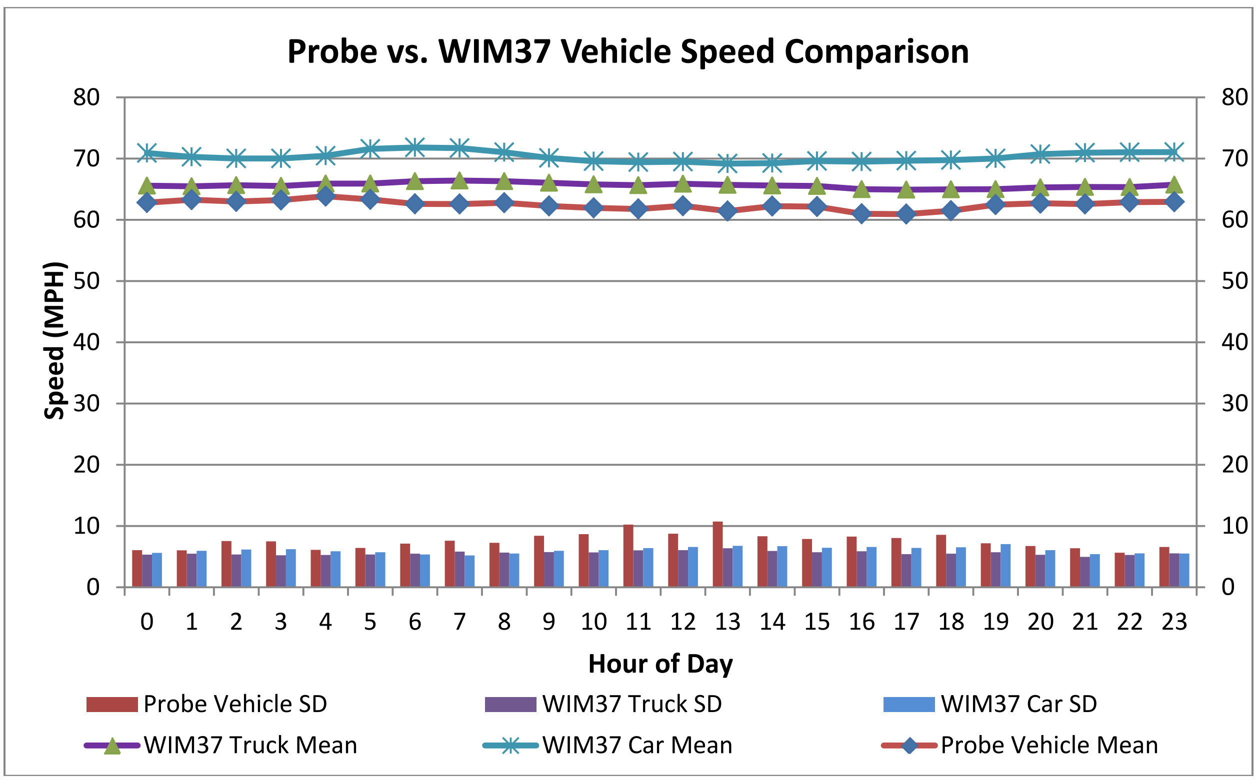


Figure 2-8 Probe Vehicle Speed vs. WIM Speed by Hour at WIM#37

2.5.2 Speed Comparison by Month and Hour

Figure 2-9 displays the average hourly and monthly speed variation from WIM station #37 in 2012. The average speed decreases slightly in the PM peak hours.

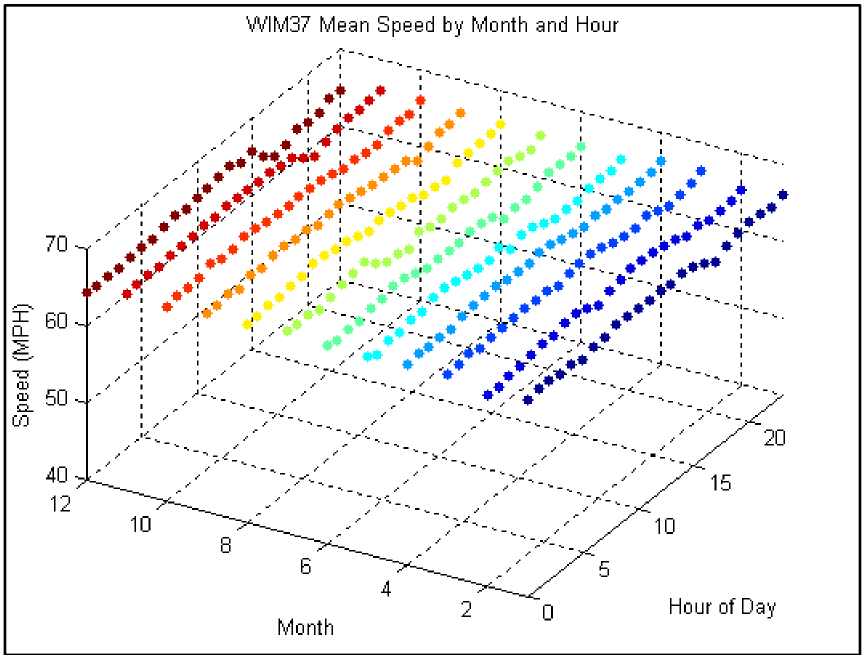


Figure 2-9 WIM37 Heavy Vehicle Mean Speed by Month and Hour

Figure 2-10 displays the average hourly speed variation from probe vehicle data at WIM station #37 in 2012. The average speed computed from probe vehicle has larger variations than those from WIM data.

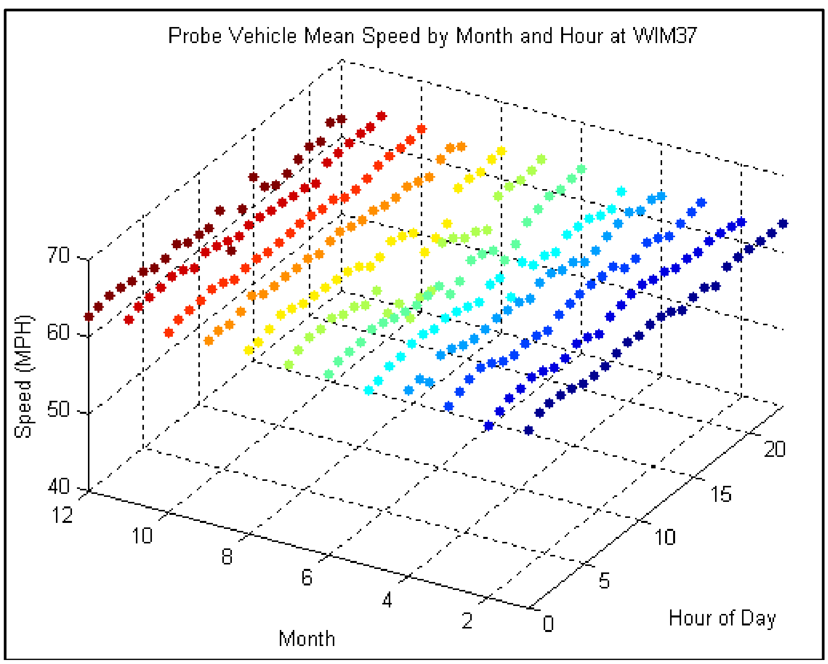


Figure 2-10 Probe Vehicle Mean Speed by Month and Hour at WIM37

2.5.3 Probe Vehicle vs. WIM Volume Percentage Comparisons

Hourly volume percentage is selected to verify the truck volume variations in a weekday. Figure 2-11 illustrates the volume variations from probe vehicle and WIM37 data. The probe vehicle spot volume percentage uses only the vehicle counts from spot speed data excluding the derived space mean speed data points. The hourly volume variation of probe vehicles follows closely to the curve from WIM37 station as shown in Figure 2-11.

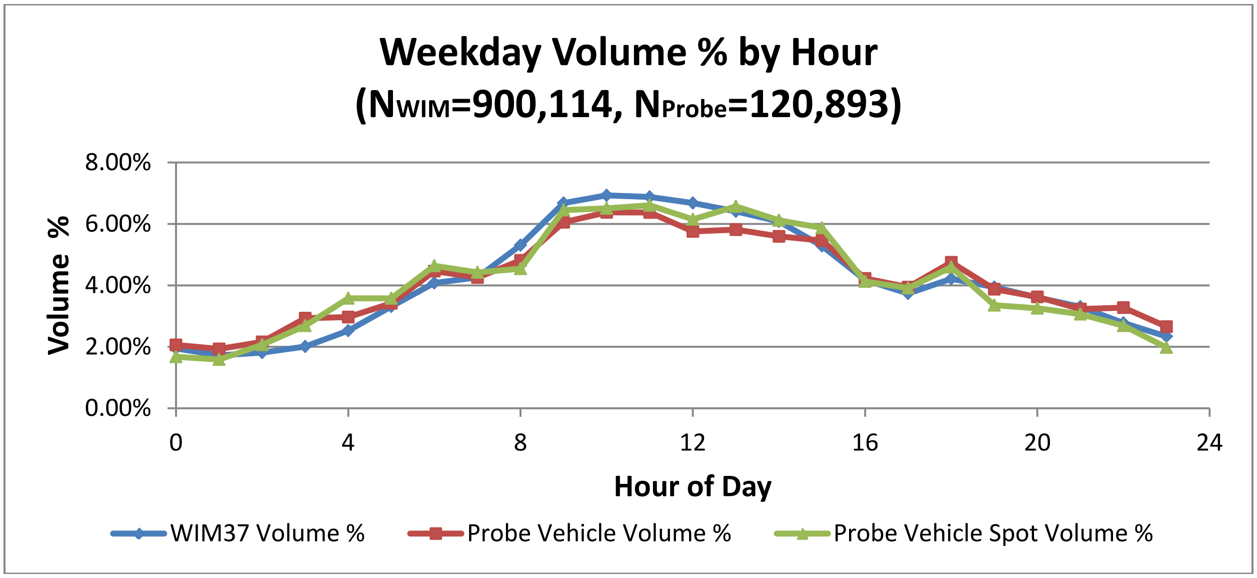


Figure 2-11 Probe Vehicles vs. WIM Volume Percentage by Hour at WIM#37

2.6 Automatic Traffic Recorder (ATR) Data

A list of automatic traffic recorder (ATR) stations on key freight corridors in the Twin Cities metro area were identified for data analysis and comparison (See Table 2-5). The ATR units collect binned vehicle counts by hour, class, and speed instead of speed and classification of each vehicle.

Table 2-5 List of ATR Stations in TCMA

ATR_ID	Route Name	Milepost	True Mile	Direction	Route ID	Segment ID	Direction Sign
188	US 52	061+00.860	62.245	N	29	19	1
191	I-35	137+00.500	137.519	N	33 (34)	88 (90)	1
200	I-94	182+00.200	183.084	N	24	77	1
335	I-35W	033+00.752	33.787	N	34	74	1
341	I-694	053+00.290	53.237	N	4	18	-1
351	US 12	142+00.839	142.285	E	9	15	-1
352	US 10	218+00.450	220.364	E	31	55	-1
353	US 169	096+00.670	96.198	N	37	49	1
365	MN 65	016+00.720	18.577	N	26	31	1
381	US 212	133+00.500	133.195	E	14	7	1
382	US 52	111+00.966	112.328	N	29	67	1
388	US 8	002+00.330	2.282	N	25	3	1
400	CSAH 92	010+00.330	10.33	N	9	15	1
422	CSAH 14	010+00.100	10.1	E	1	8	1

2.6.1 ATR Volume Processing and Analysis

ATR volume data in 2012 by vehicle classification were obtained from MnDOT. Aggregated volume for vehicle class 9 and higher were grouped by hour to compute hourly truck volume percentage. Hourly volume variation of trucks at ATR station #188 on US52 near Rochester, MN is displayed in Figure 2-12 along with the volume percentage computed from truck GPS data. The difference of the two curves indicated that probe trucks have a slightly higher representation in the AM peak hours (5-10AM) than the general hourly volume distribution from ATR.

Additional volume comparisons for the other ATR stations are listed in Appendix E.1. The hourly truck volume correlation between GPS and ATR data was computed and listed in Table 2-5 for all the ATR stations in TCMA. The hourly volume percentages from GPS and ATR data are highly correlated except at ATR station #341 and #365. ATR #341 is located on I-694 in northbound in Oakdale, MN. There was construction on I-694 in 2012. The discrepancy of hourly volume distribution was probably caused by the roadway construction last year. ATR station #365 is located on state highway 65 in Ham Lake, MN. As illustrated in Figure 2-12, the truck GPS data has a higher volume distribution in the AM peak hours while the ATR data has a higher volume distribution in the PM peak hours.

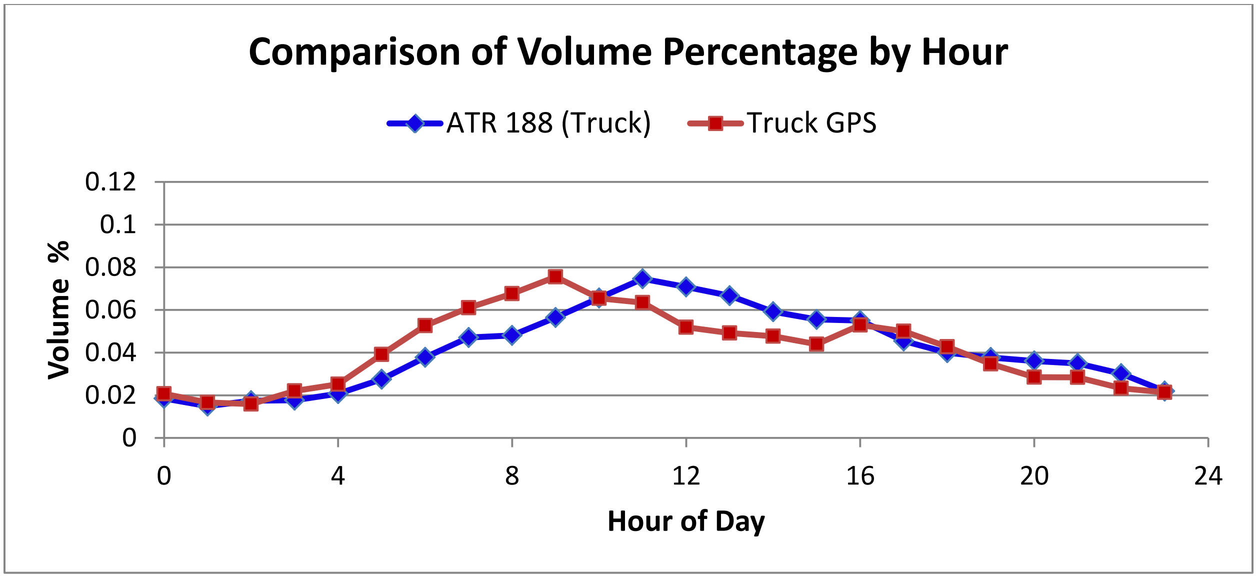


Figure 2-12 Comparison of Truck Volume Percentage by Hour (ATR Station #188)

Table 2-6 Hourly Truck Volume Correlation between GPS and ATR Data

ATR Data		Truck GPS Data			Correlation Coefficient
ID	HCAADT	Route ID	Segment ID	Count	
188	2600	29	19	43199	**0.83**
191	2150	33	88	11961	**0.94**
200	7900	24	77	129595	**0.87**
335	3450	34	74	19741	**0.93**
341	5100	4	18	70873	**0.61**
351	1600	9	15	4107	**0.93**
352	1600	31	55	11686	**0.86**
353	1750	37	49	26821	**0.96**
365	1700	26	31	4933	**0.51**
381	1350	14	7	22530	**0.99**
382	2700	29	67	42469	**0.97**
388	830	25	3	2576	**0.84**
400	1600	9	15	2841	**0.81**
422	NA	1	8	433	**0.96**

2.6.2 ATR Speed Estimation and Analysis

Vehicle counts in 13 or 20 ATR speed bins were collected hourly at each station. A sample of ATR vehicle count data by 13 speed bin is listed in Table 2-7. The ATR hourly speed can be estimated using equation (2-1) assuming normal speed distribution. The hourly comparisons of vehicle speed for both the truck GPS and the ATR station 191 data are plotted in Figure 2-13. The computed ATR speed includes speeds from all vehicles is slightly higher than the truck GPS speed. The average standard deviation of speed from ATR191 is about 9.5 MPH and the average standard deviation of the truck GPS speed is about 4.6 MPH. Additional speed comparisons for the other ATR stations are displayed in Appendix E.2.

$$Speed_j = \frac{\sum v_i \times n_i}{\sum n_i} \qquad \text{Eq. (2-1)}$$

Where,

$Speed_j$ is the hourly average speed in hour j,
v_i is the speed of bin i, and
n_i is the vehicle counts in speed bin i.

Table 2-7 List of Sample ATR Data in Speed Bins

Date	Hour	40 MPH	45 MPH	50 MPH	55 MPH	60 MPH	65 MPH	70 MPH	75 MPH	80 MPH	85 MPH	100 MPH	110 MPH	>110 MPH
1/1/2012	05:00	3	3	1	12	12	34	38	41	22	10	1	0	0
1/1/2012	06:00	16	1	3	10	18	49	54	43	23	7	1	0	0
1/1/2012	07:00	0	0	1	7	17	48	71	107	58	18	4	0	0
1/1/2012	08:00	0	0	0	1	10	32	91	196	157	44	12	1	0
1/1/2012	09:00	0	0	0	2	12	33	129	313	321	110	29	1	0
1/1/2012	10:00	0	0	0	0	14	38	176	486	570	183	43	1	0
1/1/2012	11:00	1	0	0	0	10	33	252	613	801	263	44	1	0
1/1/2012	12:00	3	0	1	0	4	50	247	735	947	315	62	0	0

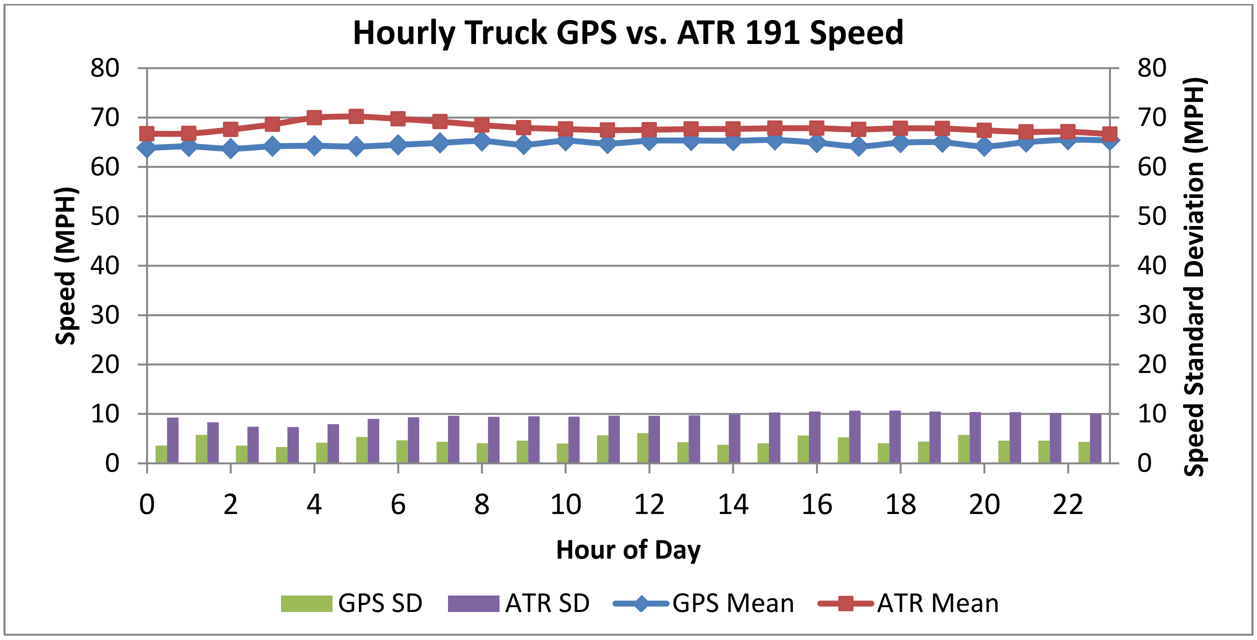


Figure 2-13 Weekday Hourly Truck GPS vs. ATR 191 Speed Comparisons

2.7 Loop Detector Data

A list of loop detectors, as displayed in Table 2-8, nearby the WIM and ATR stations in the Twin Cities metro area were identified for data analysis. Loop detector data were processed and grouped by hour of day for comparisons with WIM and ATR data.

Table 2-8 List of Loop Detectors nearby WIM and ATR Stations

Detector Station	Detector ID	Direction	Lane #	Nearby WIM/ATR Station
1222	6314	WB	1	WIM 37
1222	6315	WB	2	WIM 37
1171	5634	NB	1	WIM 40
1171	5635	NB	2	WIM 40
1172	5638	NB	1	WIM 40
1172	5639	NB	2	WIM 40
1232	7219	WB	1	ATR 200
1232	7220	WB	2	ATR 200
1555	6451	NB	1	ATR 335
1555	6452	NB	2	ATR 335
1418	6244	NB	1	ATR 341
1418	6245	NB	2	ATR 341

2.7.1 Loop Detector Speed Analysis

Vehicle data in 2012 from the identified loop detectors were obtained from MnDOT. A sample of processed loop detector data is listed in Table 2-9.

Table 2-9 Sample Loop Detector Data

year	month	day	time	station	L_v	volume	occupancy	speed
2012	1	26	1921	S1171	32.5	10	9.222222	80.0931
2012	1	26	1922	S1171	32.5	4	4.8333335	61.12853
2012	1	26	1923	S1171	32.5	6	5	88.63636
2012	1	26	1924	S1171	32.5	4	3.2777777	90.13868
2012	1	26	1925	S1171	32.5	6	4.888889	90.65083
2012	1	26	1926	S1171	32.5	7	5.888889	87.80017

Raw loop detector data from MnDOT contains volume and occupancy information in 30 seconds aggregation. The following equation was used to compute the speed of traffic flow.

$$\boldsymbol{Speed\ (MPH)} = \frac{\boldsymbol{Volume \times L_v}}{\boldsymbol{Occupancy \times \frac{30}{100}}} \times \frac{\boldsymbol{3600\ sec\ in\ an\ hour}}{\boldsymbol{5280\ ft\ in\ a\ mile}}$$

Eq. (2-2)

Where,

Volume is the number of vehicle counts in 30 seconds,
L_v is the effective vehicle length in feet, and
Occupancy is the percentage of time a detector is occupied by vehicles in 30 seconds.

As shown in equation (2-2), the accuracy of speed calculation from a loop detector depends on the effective vehicle length. The effective vehicle length needs to be calibrated frequently by the traffic engineer due to the dynamic mixture of vehicle classes. The speed of longer vehicles (for example, semi-trucks) is usually underestimated. On the other hand, the speed of a shorter vehicle (for example, motorcycles or compact cars) is usually overestimated.

Figure 2-14 displays the hourly speed average from loop detector station *1222* nearby WIM station 37 on I-94 in WB direction. Detector *d6314* is located in lane 1 (outer or right lane) and detector *d6315* is located in lane 2 (inner or left lane). The average speed difference confirms that the speed in the right lane (blue line with circle marker) is about 15 MPH lower than the average speed in the left lane (red line with diamond marker). This is probably caused by more trucks traveling in the right lane and the loop detector tends to underestimate the speed of trucks.

In addition to the speed difference, the pattern of hourly average speed variation looks abnormal. The lowest average speed occurs at 4AM. And higher traffic speed occurs in PM peak and around 9PM. This is a different pattern from our expectation that the AM and PM peak periods usually have lower average traveling speed than mid-day and mid-night off-peak periods. This speed pattern was further verified with processed data from MnDOT online tool using the “Data Plot application” as shown in Appendix F.1.

The average traffic speed derived from loop detector is less reliable because it heavily relies on the estimated effective vehicle length, traffic volume, and mixture of trucks and cars. Loop detector speed data will not be compared with the WIM speed due to the unreliable nature of the loop data.

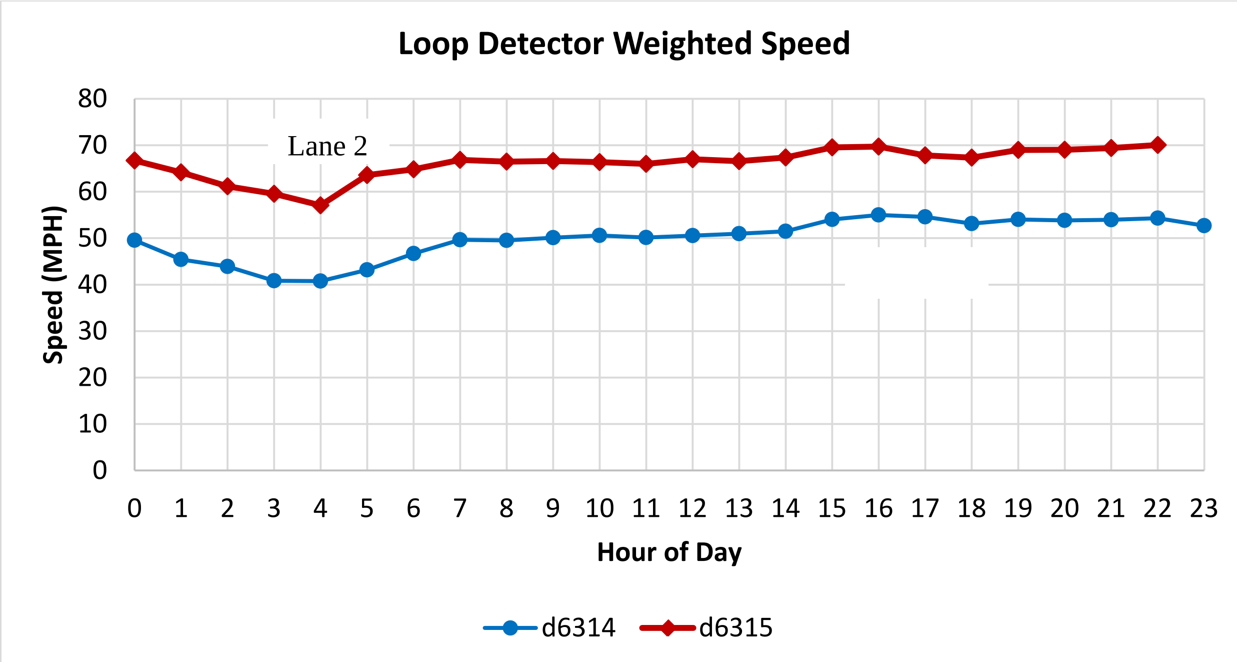


Figure 2-14 Hourly Speed Variations by Lane at Loop Detector Station #1222

Loop detector speeds from two urban locations in TCMA are compared with the processed GPS data. Figure 2-15 illustrates the comparison of truck GPS speed and the loop detector speed by hour on weekdays in I-394 EB east of highway 100 where the traffic is usually congested during rush hours. The pattern of speed curves from loop detector and GPS is similar. The top green curve with black square marker represents the hourly average speed of all traffic from the loop detectors. In general, the standard deviation of loop detector speed is closer to the standard deviation from the space mean speed.

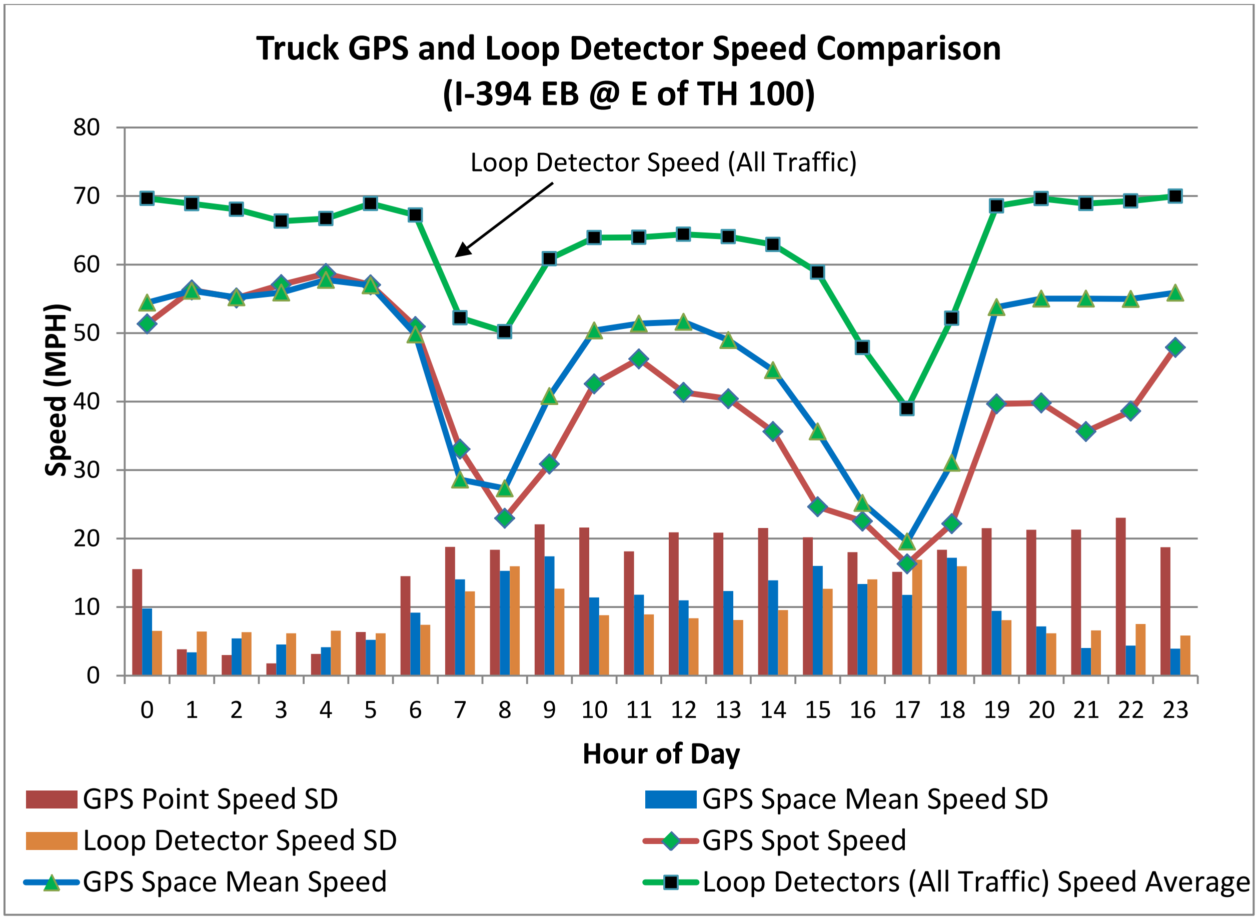


Figure 2-15 Truck GPS and Loop Detector Speed Comparison (I-394 at Highway 100)

Figure 2-16 displays the comparison of truck GPS speed and the loop detector speed by hour on weekdays in I-494 EB at France Avenue where the traffic is usually congested during rush hours. The pattern of speed curves from loop detector and GPS is similar. In fact, average speed from loop detector is almost the same as the speed derived from GPS space mean speed in the afternoon peak hours. The top green curve with black square marker represents the hourly average speed of all traffic from the loop detectors. Overall, the standard deviation of loop detector speed is between the standard deviations from the spot and space mean speed.

One month of loop detector speed and truck GPS speed was analyzed to compare the speed differences during AM and PM period (Appendix F.5). In average, the truck GPS speed is about 11 to 12 MPH lower than the general traffic speed derived from loop detector sensors.

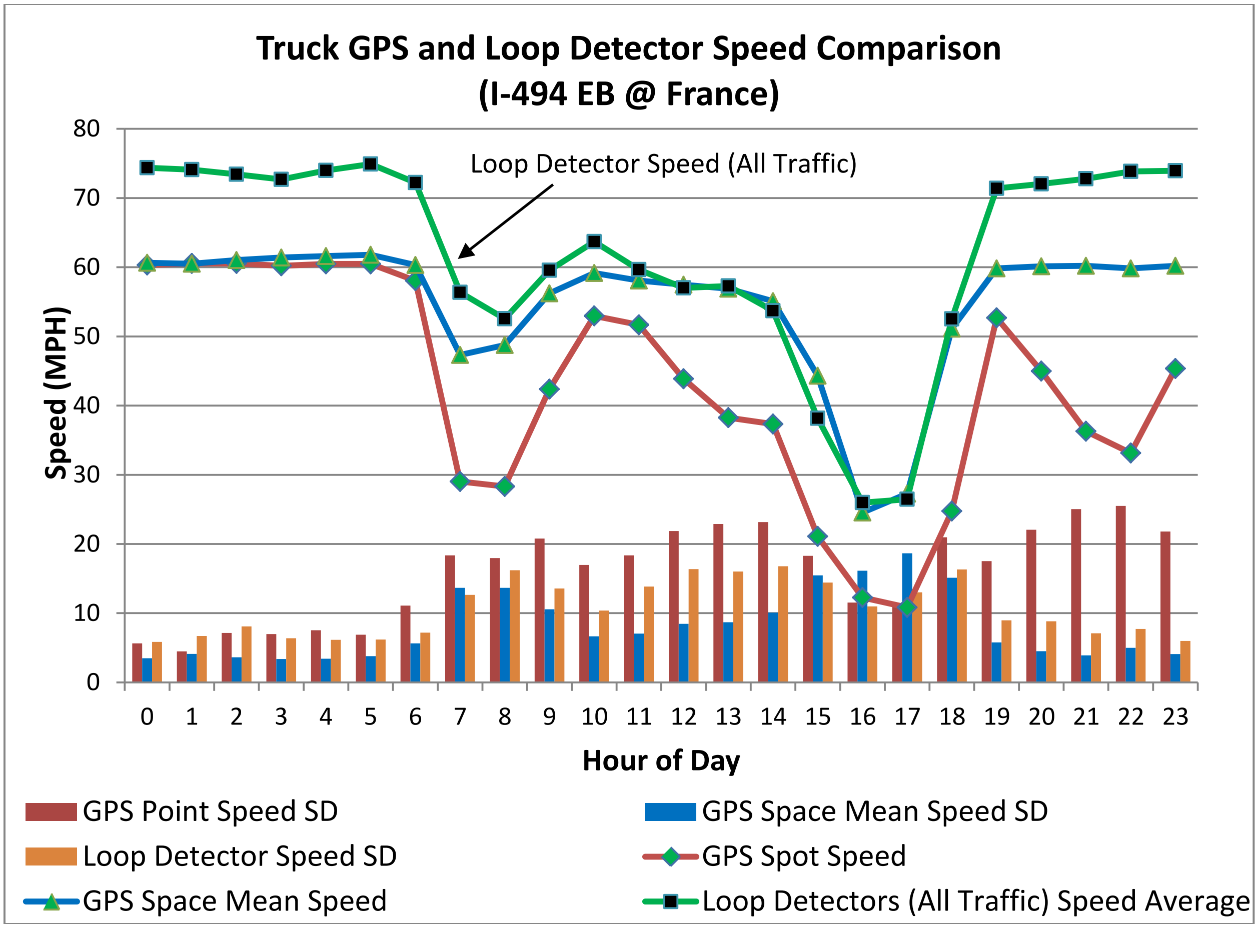


Figure 2-16 Truck GPS and Loop Detector Speed Comparison (I-494 at France)

2.7.2 Loop Detector Volume Analysis

The hourly volume percentages for both detectors at station #1222 were plotted in Figure 2-17. Lane 2 (left lane, in red color) has relatively higher volume percentage than the volume percentage in lane 1(right lane, blue color) during the day (10AM to 6PM). More vehicles travel in the right lane after 7PM and before 9AM as Figure 2-17 illustrated. The hourly volume percentage of loop detector station 1222 (both lanes combined) is compared with the volume percentage from the nearby WIM station 37. As displayed in Figure 2-18, the volume distribution from the loop detector in the mid-day period (9AM to 2 PM) is higher than the distribution from the WIM data. The volume distribution from the WIM data in the AM and PM peak is slightly higher than the distribution from the loop detector data as illustrated in Figure 2-17. Additional plots of loop detectors compared with data from WIM40 are displayed in Appendix F.2. More plots of loop detector data compared with ATR data (station 200, 335 & 341) are displayed in Appendix F.3 & F.4.

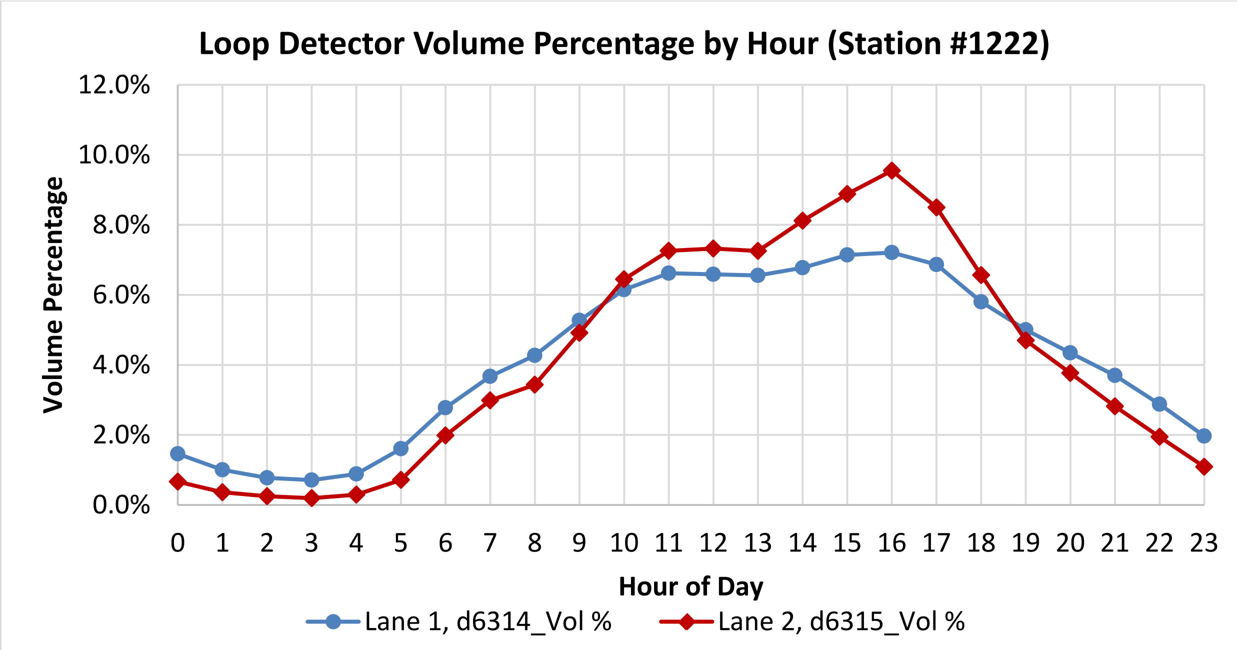


Figure 2-17 Hourly Volume Percentages by Lane at Loop Detector Station #1222

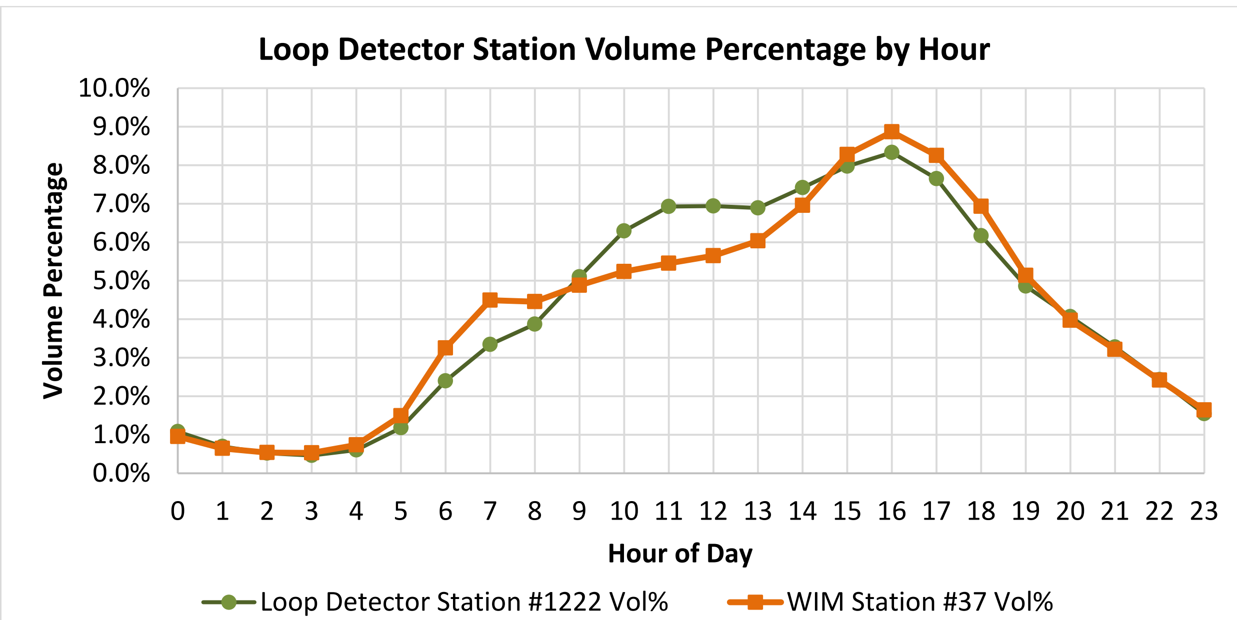


Figure 2-18 Hourly Volume Percentage Comparisons (Loop Detector Station 1222 vs. WIM 37)

Data from loop detectors, Automatic Traffic Recorder (ATR) stations, and Weigh-In-Motion (WIM) sensors in 2012 were obtained from MnDOT. The data were processed, analyzed and compared with speed and volume data processed from truck GPS data. The purpose is to validate the results from processed truck GPS data with WIM, ATR, and loop detector data. A comparison of different traffic data sources is listed in Table 2-10.

The loop detector does not provide vehicle classification information and vehicle speed derived from occupancy data relies heavily on calibrated vehicle length by location and time of day. Many ATR devices can collect vehicle volume, speed, and classification data. However, many of them were designed to collect counts in a pre-configured speed or vehicle class bins and thus make it difficult to compare with truck GPS data. The WIM data source, containing all volume, speed and classification information, presents an ideal benchmark source for truck GPS data validation. However, most of the WIM stations were instrumented in rural area for vehicle weight monitoring and pavement maintenance.

Table 2-10 Comparison of Different Traffic Data Sources

Data Source	Vehicle Class	Volume	Speed or Travel Time
Truck GPS	9 and higher	Sample	Yes
Loop Detector	No	Yes	Calc. from occupancy
ATR	Yes	Yes	Yes
WIM	Yes	Yes	Yes

3. PERFORMANCE MEASURES

Truck mobility, delay and reliability measures are identified and discussed in this section. Truck delay and reliability measures are computed based on the target speed used by MnDOT for performance measures.

3.1 Corridor Target Speed

Threshold speed for each corridor is selected using the target speed provided by MnDOT as illustrated in Figure 3-1. In general, 45 MPH threshold speed is used in the core of the TCMA and 55 MPH or higher is used for corridors outside the metropolitan area. Interregional corridor (IRC) targets are 65 mph for interstates, 60 mph for High Priority IRCs and 55 mph for Medium Priority IRCs. In some cases when a corridor contains both some high priority and medium priority segments; the corridor target is a time-weighted average. Target speed on non-freeways is usually less than freeways. There is no target for IRCs in urban areas, connectors or freight routes. The exact target speeds are likely to evolve and be refined as MnDOT and partner agencies gain experience in performance monitoring on arterial streets (Turner & Qu, 2013).

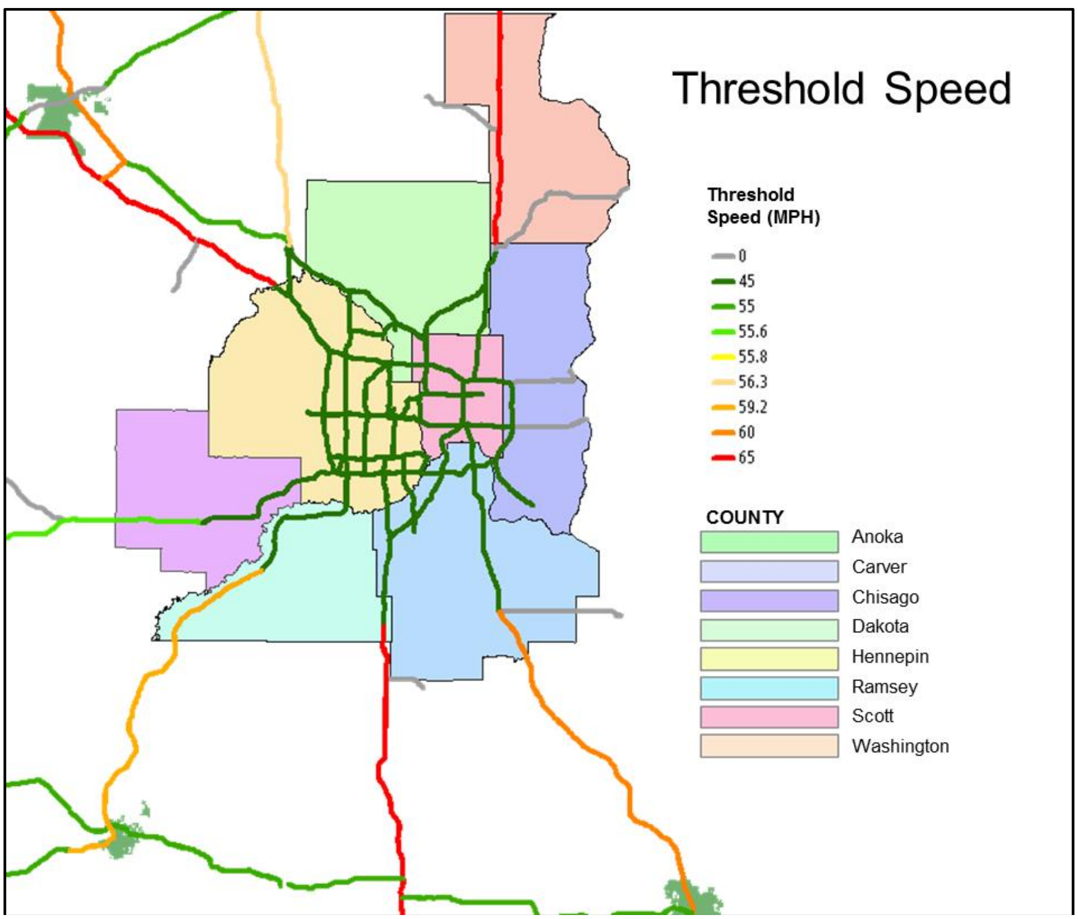


Figure 3-1 Threshold Speed in TCMA (Source: MnDOT RTMC)

The performance measures were analyzed in the following three periods. These time periods are chosen in consistent with the annual transportation results scorecard published by MnDOT (2011). Percent of freight corridor miles with average speed below 45 MPH in AM or PM Peak is measured as listed in Table 3-1. Figure 3-2 and 3-3 illustrate the location and direction of segments with speed less than 45 MPH during AM and PM peak hours, respectively. Figure 3-4 and 3-5 display the GIS map of average truck speed in AM and PM peak hours.

- AM Peak: 5 - 10AM
- Morning Off-Peak: 10AM - 2PM
- PM Peak: 2 - 7PM

Table 3-1 Percent of Miles in TCMA below 45 MPH during AM/PM Peak in 2012

Time Period (2012 Weekdays TCMA)	AM Peak 5-10 AM	PM Peak 2-7 PM
# of Miles with Average Speed < 45 MPH	96	147
Total Miles of RTMC Stations in TCMA	774	774
Percentage of Miles < 45 MPH	**12.4%**	**19.0%**

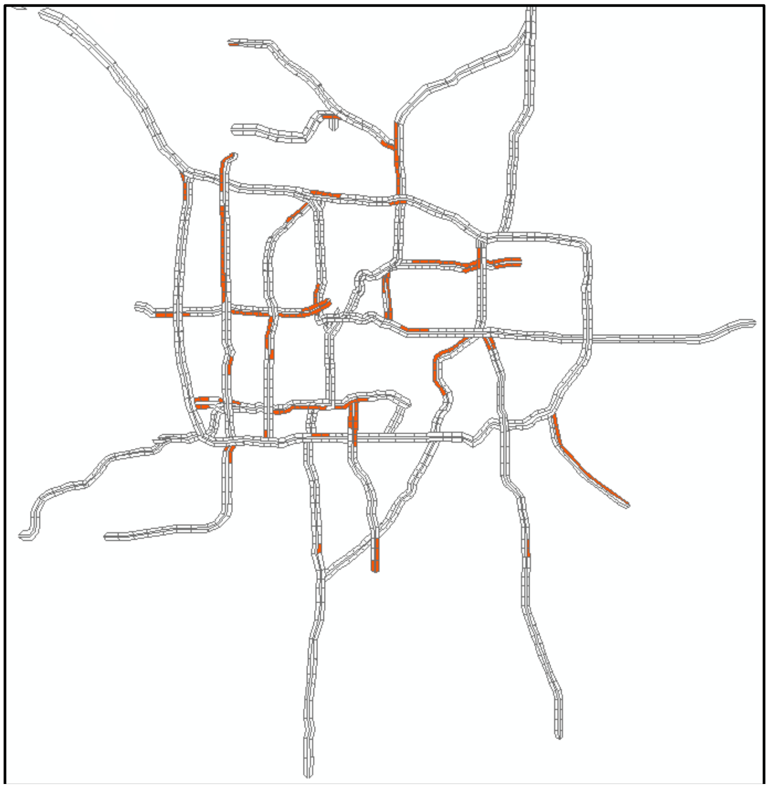


Figure 3-2 GIS Map of Truck Speed Less Than 45 MPH during AM Peak (5-10 AM) in 2012

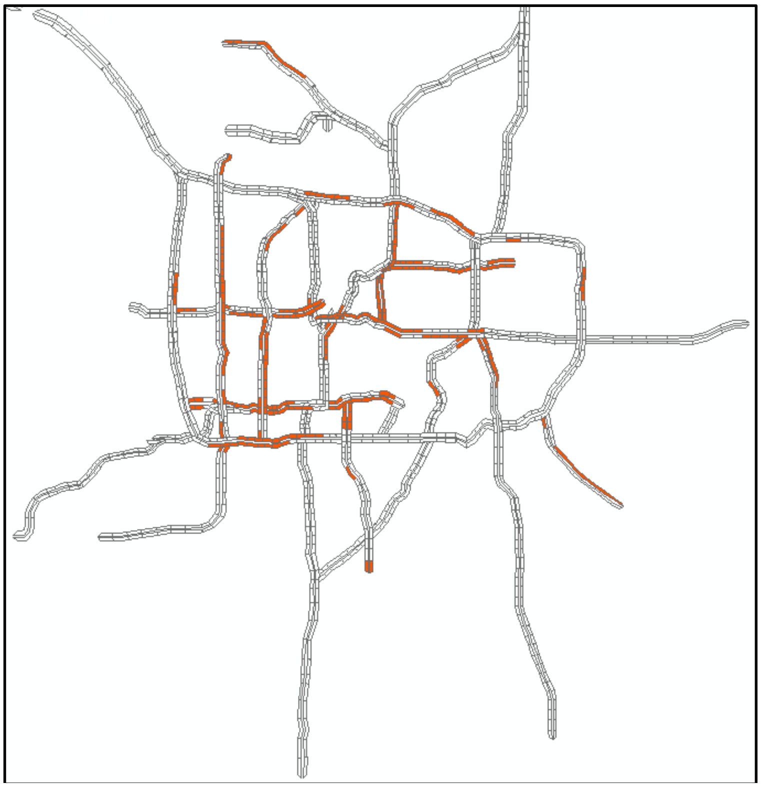


Figure 3-3 GIS Map of Truck Speed Less Than 45 MPH during PM Peak (2-7 PM) in 2012

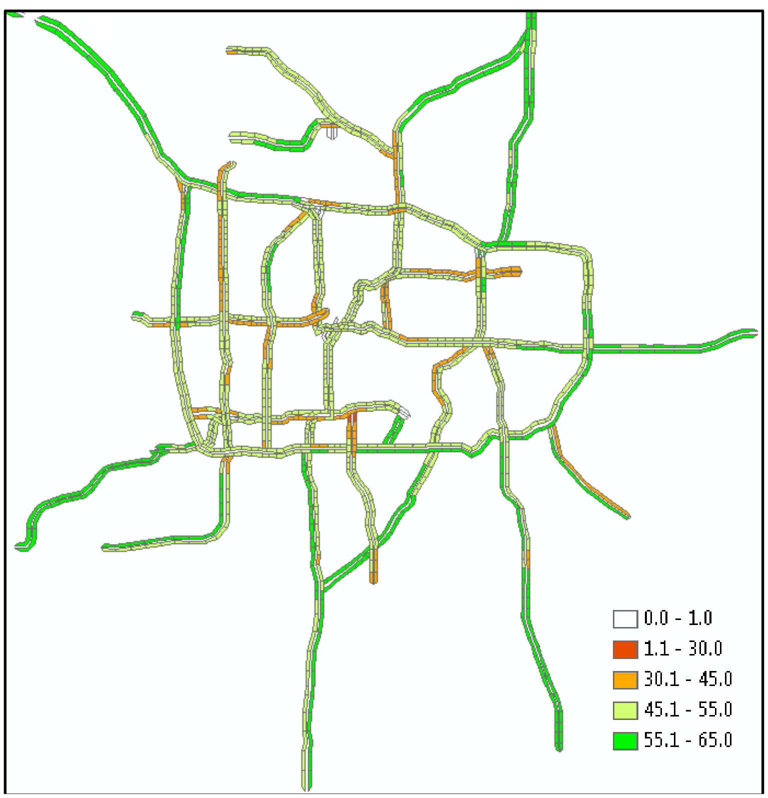


Figure 3-4 GIS Map of Truck Speed during AM Peak (5-10 AM) in 2012

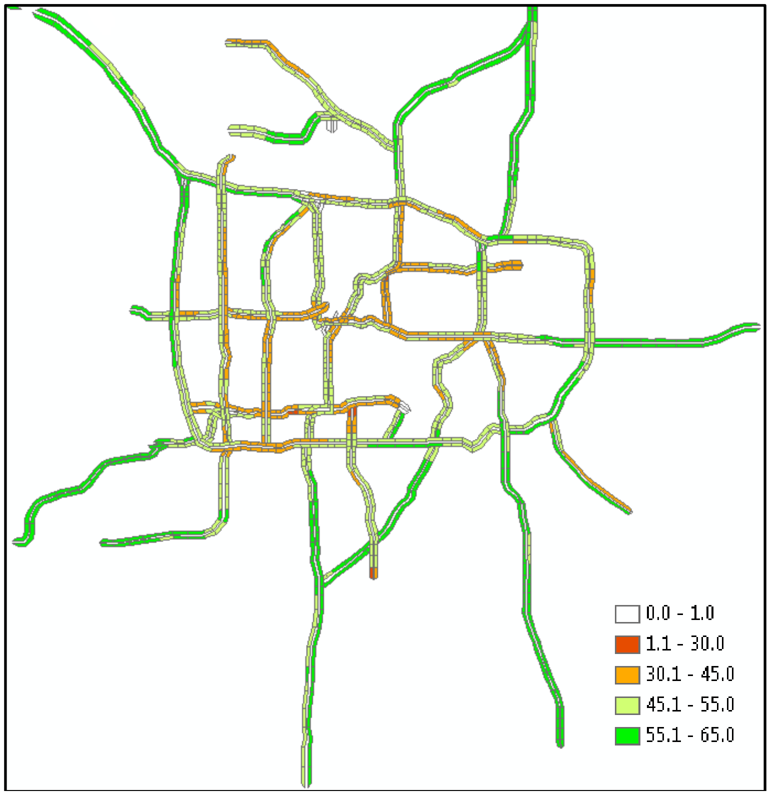


Figure 3-5 GIS Map of Truck Speed during PM Peak (2-7 PM) in 2012

3.2 Freight Node & Freight Corridor

Figure 3-6(a) displays the GIS map of Heavy Commercial Annual Average Daily Traffic (HCAADT) in TCMA. I-94, I-35W, I-494, and I-694 have the highest daily truck volume as compared to other corridors in the TCMA. Corridors in TCMA with HCAADT greater than 7500 vehicles are listed in Table 3-2(a). Note: The HCAADT is theoretical estimate of the total number of heavy commercial vehicles using a specific segment of roadway (in both directions) on any given day of the year. This estimate represents the total number of heavy commercial vehicles per year divided by 365 and is developed by MnDOT using factors to adjust for season. Different from HCAADT, the Heavy Commercial Average Daily Traffic (HCADT) a 24-hour heavy commercial traffic volume that should be qualified by stating a time period (e.g., MHCADT – monthly average daily heavy commercial traffic, or HCADT for the period 6/21/2011-6/23/2011).

Corridors in TCMA with HCAADT per lane greater than 1500 vehicles are listed in Table 3-2(b). Figure 3-6(b) illustrates the GIS map of HCAADT per lane in TCMA. I-94, I-35, I-494, State Highway 280, State Highway 65, and I-696 have higher truck activities than the other corridors in TCMA. I-94 between St. Cloud and Maple Grove, I-494 between Highway 55 and US Highway 212, I-35 in Burnsville, I-694 between State Highway 65, and I-35E near US Highway 52 and State Highway 55 have the highway daily truck volume per lane, as illustrated in Figure 3-7.

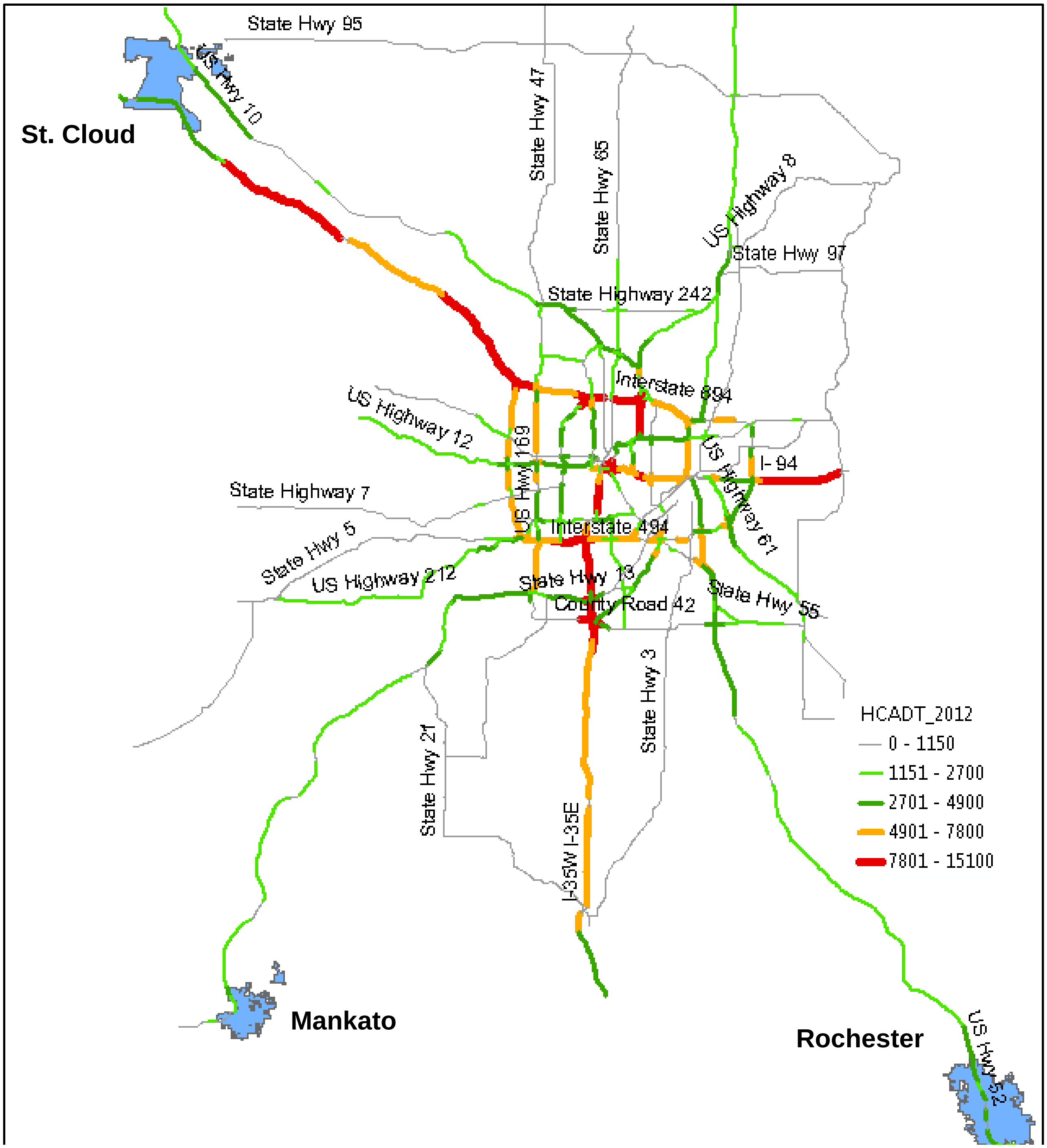


Figure 3-6(a) 2012 Heavy Commercial Annual Average Daily Traffic (HCAADT) in TCMA

Table 3-2(a) Percentage of Miles by Route with HCAADT Greater than 7500

Rank	Route	Route Name	Route ID	% of Miles with HCAADT > 7500
1	94	Interstate 94	24	36.8%
2	280	State Highway 280	10	25.0%
3	694	Interstate 694	4	17.4%
4	35	Interstate 35W	34	16.2%
5	65	State Hwy 65	26	13.6%
6	494	Interstate 494	6	9.3%
7	42	County Road 42	18	9.1%
8	51	State Hwy 51	21	8.3%
9	100	State Highway 100	7	6.3%
10	5	State Hwy 5	30	4.7%
11	13	State Hwy 13	38	2.3%
12	55	State Hwy 55	28	1.8%
13	35	Interstate 35E	33	1.8%

Table 3-2(b) Percentage of Miles by Route with HCAADT per Lane Greater than 1500

Rank	Route	Route Name	Route ID	% of Miles with HCAADT Per Lane > 1500
1	94	Interstate 94	24	28.7%
2	694	Interstate 694	4	26.1%
3	18	County Road 18	20	25.0%
4	494	Interstate 494	6	16.3%
5	35	Interstate 35W	34	15.4%
6	42	County Road 42	18	9.1%
7	35	Interstate 35E	33	8.8%
8	55	State Hwy 55	28	3.6%
9	10	US Hwy 10	31	3.0%
10	52	US Hwy 52	29	2.3%
11	13	State Hwy 13	38	2.3%
12	65	State Hwy 65	26	1.7%
13	169	US Hwy 169	37	1.0%

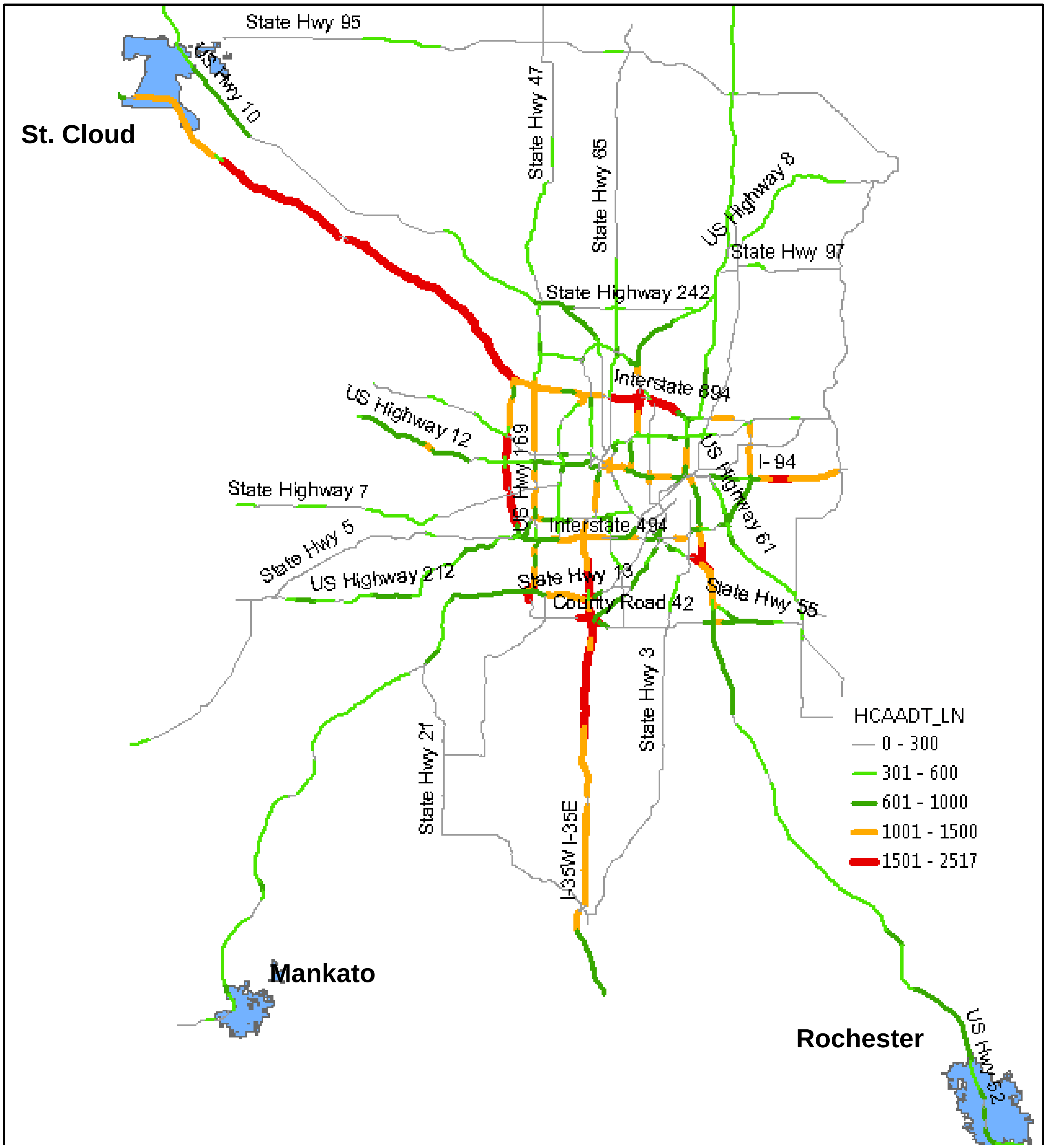


Figure 3-6(b) GIS Map of 2012 HCAADT Per Lane in TCMA

Figure 3-7 illustrates the truck volume from the GPS samples in 2012 during 7 and 8 AM period. Interstate 94, 494, 694 and 35 have higher truck GPS samples in the AM peak hours. The monthly average of truck GPS samples by route per1-mile segment is listed in Table 3-3(a). Interstate 94 has the highest truck GPS samples as listed in Table 3-3(a), highest percentage of miles with HCAADT greater than 7500 according to Table 3-2(a), and highest percentage of miles with HCAADT per lane greater than 1500 as listed in Table 3-2(b). Interstate 694 ranks the second highest in truck GPS samples as displayed in Table 3-3(a), third highest percentage of miles with HCAADT greater than 7500 according to Table 3-2(a), and second highest percentage of miles with HCAADT per lane greater than 1500 according to Table 3-2(b). Interstate 494 ranks the third highest in truck GPS samples according to Table 3-3(a), sixth highest percentage of miles with HCAADT greater than 7500 according to Table 3-2(a), and fourth highest percentage of miles with HCAADT per lane greater than 1500 as listed in Table 3-2(b).

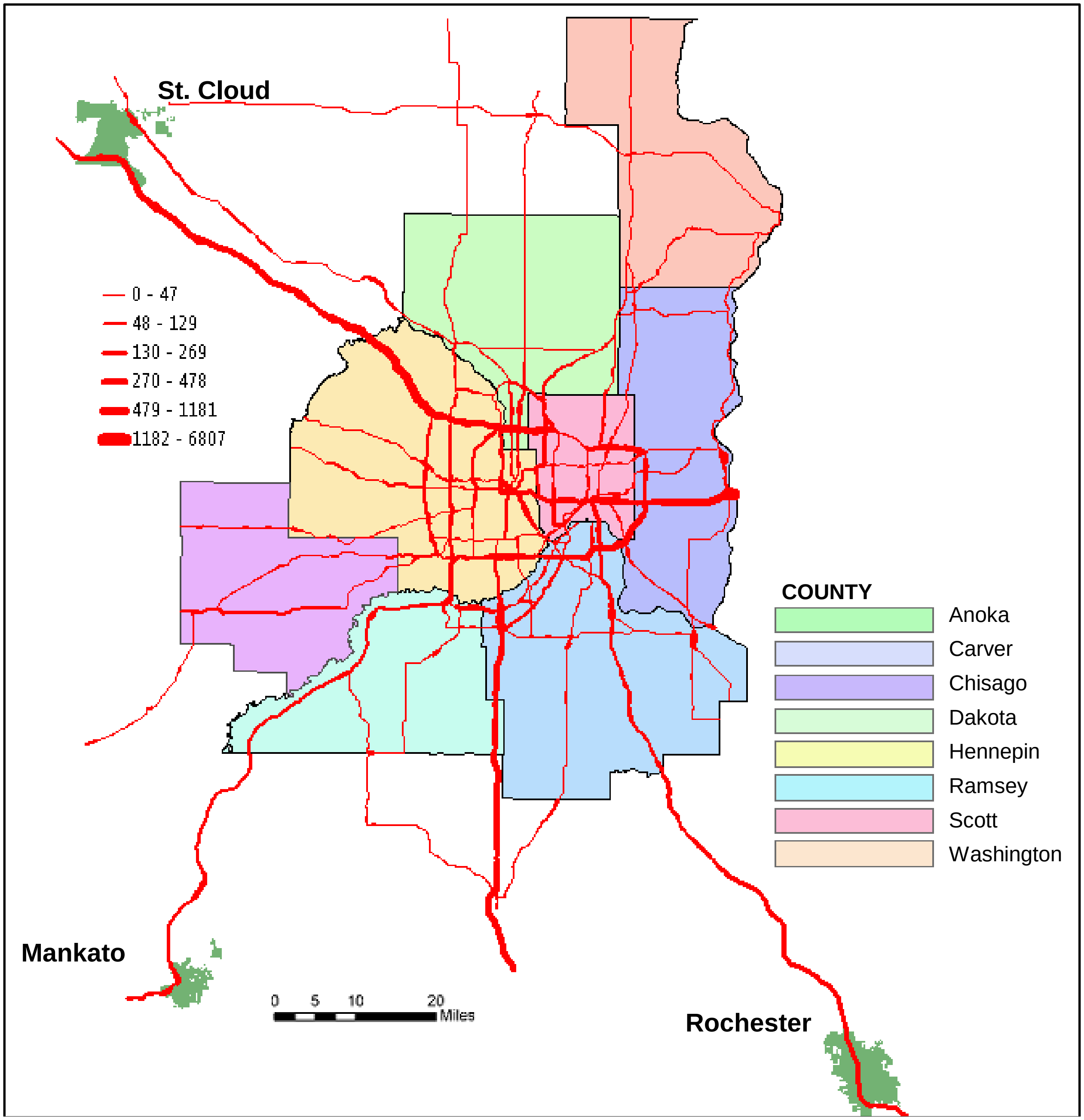


Figure 3-7 GIS Map of 2012 GPS Truck Counts in 7-8 AM

Table 3-3(a) Rank of GPS Truck Samples by Route in 2012

Rank	Route	Route Name	Route ID	Average GPS Samples Per Month Per Mile in 2012
1	94	Interstate 94	24	14,244
2	694	Interstate 694	4	7,880
3	494	Interstate 494	6	5,518
4	52	US Hwy 52	29	5,174
5	35	Interstate 35W	34	4,260
6	35	Interstate 35E	33	3,599
7	169	US Hwy 169	37	2,741
8	212	US Hwy 212	14	1,807
9	280	State Highway 280	10	1,437
10	10	US Hwy 10	31	1,359
11	65	State Hwy 65	26	1,210
12	100	State Highway 100	7	999
13	394	Interstate 394	8	945

Table 3-3(b) lists the combined ranking of truck activities using the results from Table 3-2(a) and 3-3(a). The interstate highway system in the TCMA carries the highest freight movement and activities. State highway 65 ranks as the fifth busiest trucking activities in the TCMA in 2012.

Table 3-3(b) Combined Ranking of Truck Activities by Freight Corridor in 2012

Ranks	Table 3-2(a)	Table 3-3(a)	Combined
Interstate 94	1	1	**1**
Interstate 694	3	2	**2**
Interstate 494	6	3	**3**
Interstate 35W	4	5	**4**
State Hwy 65	5	11	**5**

3.3 Truck Mobility

MnDOT uses number of hours in peak periods with average speed below threshold speed in the annual mobility scorecard to measure mobility. Figure 3-8 and 3-9 display the truck mobility or congestion intensity in terms of hours of congestion in peak period on the RTMC roadway network. Figure 3-8 displays the number of hours in AM peak period with average truck speed below threshold speed (45 MPH on RTMS network). And, Figure 3-9 illustrates the number of hours in PM peak period with average truck speed below threshold speed.

Figure 3-8 and 3-9 display the numbers of hours of truck delay (speed less than threshold speed) during the peak periods in TCMA. They are different from Figure 3-4 and 3-5 which display the average speed of each segment in TCMA. For example, a segment with 2 hours of average truck speed lower than the threshold speed in AM peak period (47, 46, 39, 37, 46 MPH) will have an average speed (43 MPH), which is lower than the threshold speed. Or, another example of a segment with 2 hours of average truck speed lower than the threshold speed in PM peak period (55, 48, 44, 43, 55 MPH) will have an average speed (49 MPH), which is high than the threshold speed.

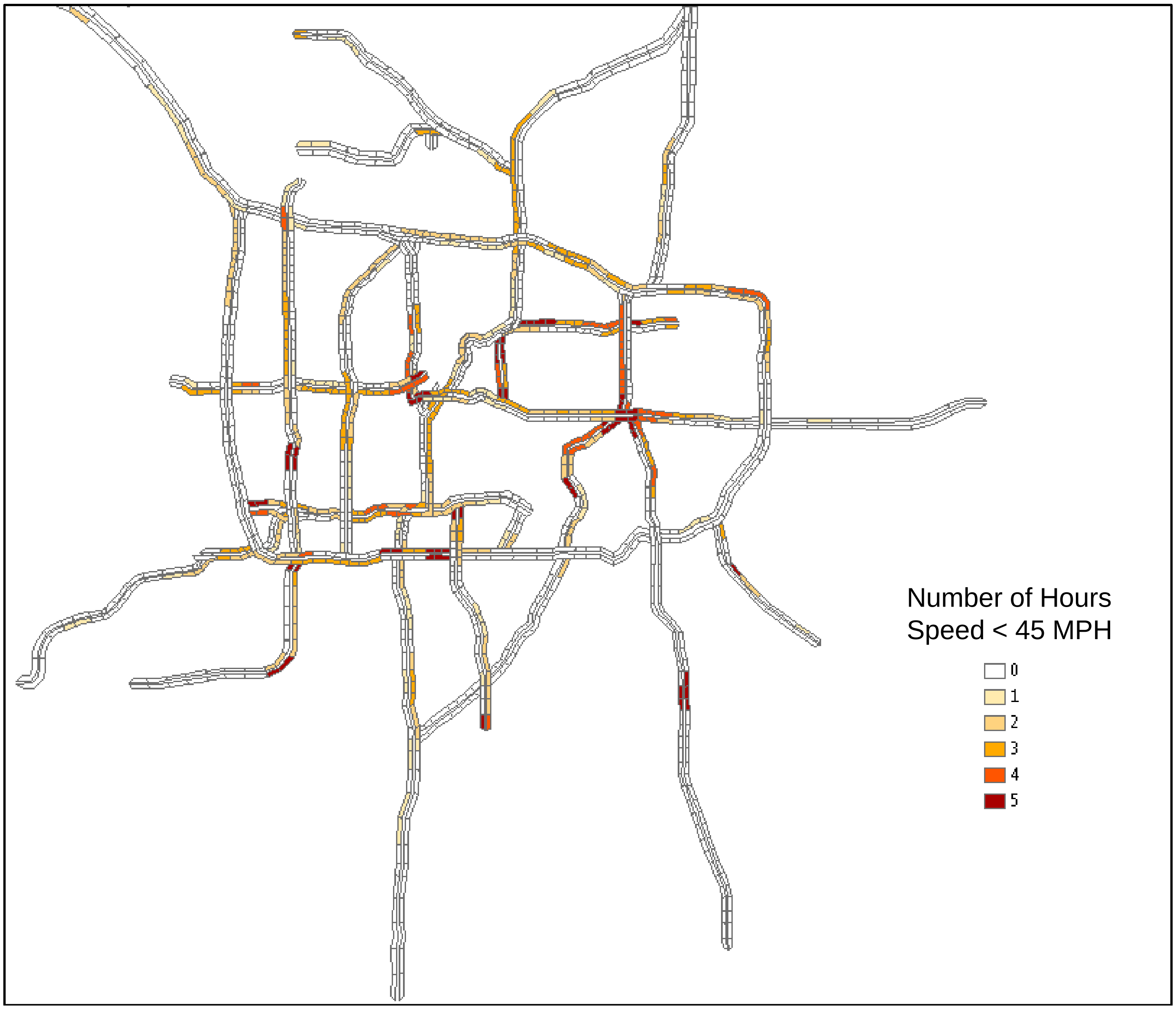


Figure 3-8 Number of AM Peak Hours with Average Speed Less than Threshold Speed

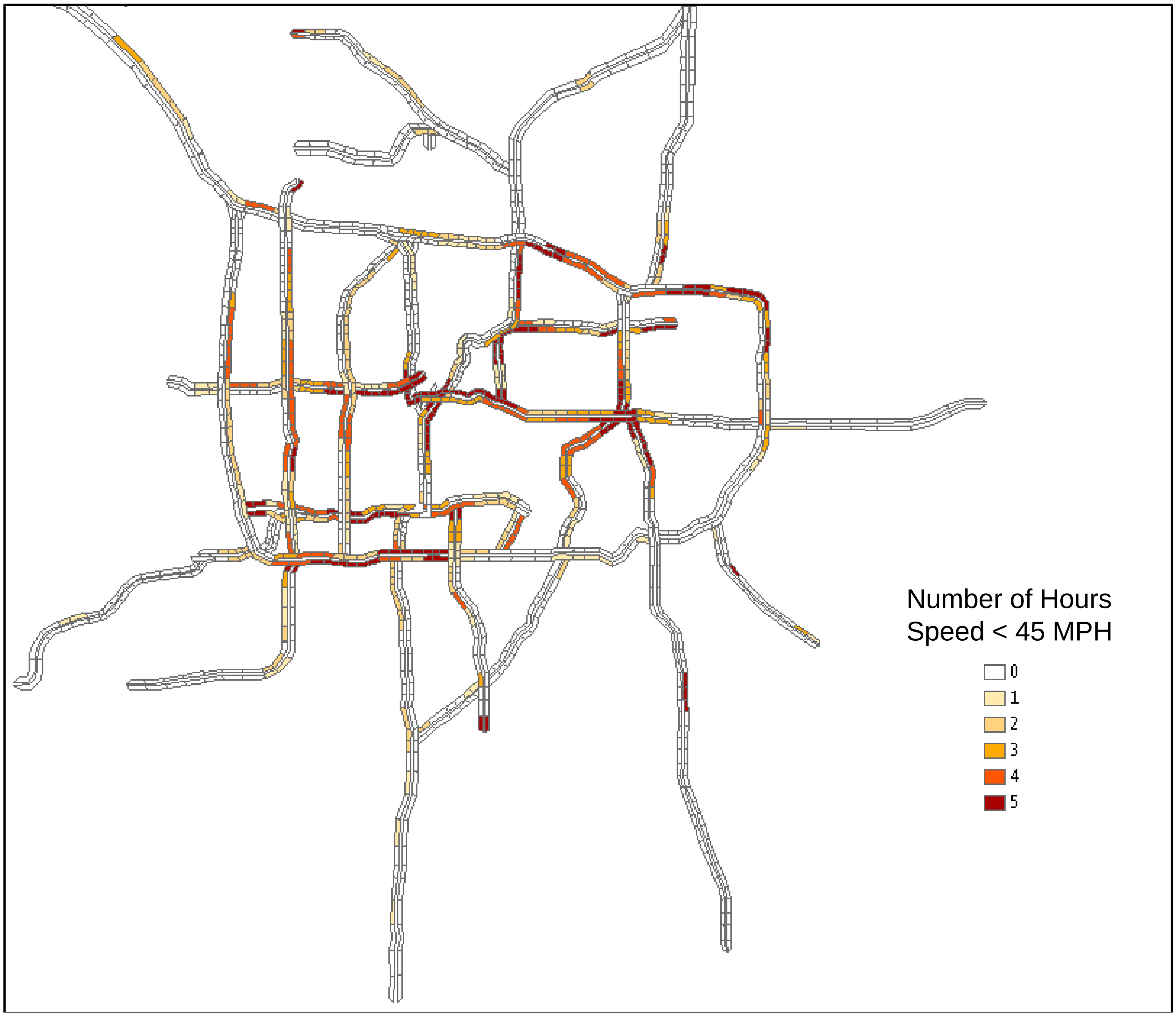


Figure 3-9 Number of PM Peak Hours with Average Speed Less than Threshold Speed

3.4 Truck Delay

Daily truck delay of each roadway link can be calculated using equation (3-1). Hourly truck volume percentage derived from truck GPS data (discussed in Chapter 2, section 2.5.3, 2.6.1, and 2.7.2) and the 2012 HCAADT data published by MnDOT is also used to calculate truck delay for each corridor. The hourly truck volume percentage will reflect the daily truck delay contributed by the truck volume variations during the peak hours.

$$Truck\ Delay_{Route} = \sum_{Segment} \sum_{Hour} \left(\frac{Segment\ Length}{Travel\ Speed} - \frac{Segment\ Length}{Threshold\ Speed} \right) \times HCAADT \times Truck\_Volume\_\%_{\ Hour,Segment} \qquad \text{Eq. (3-1)}$$

Where,

Segment length is equal to 1 mile,

$\boldsymbol{Truck\_Volume\_\%_{Hour,Segment}}$ is the hourly truck volume percentage for a segment, and $\sum_{\boldsymbol{Hour}} \boldsymbol{Truck\_Volume\_\%_{Hour}} = \mathbf{1.0}$

Table 3-4 is used as an example to demonstrate how the daily truck delay of a roadway segment S is calculated. Column (b) is the hourly average speed at segment S. Column (c) is the hourly volume percentage distribution, and column (d) is the HCAADT volume at segment S. Assume the threshold speed at segment S is 45 MPH. The hourly delay at this segment is zero when the average speed is greater than 45 MPH. At hour 8-9 and 17-19, the hourly delay is computed using [45 – value in (b)] x [column (c)] x [column (d)] = [column (e)]. Summation of column (e) is the total daily delay (3,585 hours) at segment S.

Table 3-4 Sample Truck Speed and Volume Data for Delay Calculation

Hour (a)	Average Speed (MPH) (b)	Hourly Volume % (c)	HCAADT (d)	Delay Hours (e)
0	62	2.0%	6700	0
1	60	2.0%	6700	0
2	58	3.0%	6700	0
3	56	3.0%	6700	0
4	57	3.0%	6700	0
5	58	3.5%	6700	0
6	55	3.5%	6700	0
7	52	4.0%	6700	0
8	44	4.5%	6700	301.5
9	43	4.5%	6700	603
10	49	5.5%	6700	0
11	52	6.5%	6700	0
12	57	6.5%	6700	0
13	58	6.0%	6700	0
14	60	5.5%	6700	0
15	59	5.5%	6700	0
16	52	5.0%	6700	0
17	42	4.5%	6700	904.5
18	40	4.5%	6700	1507.5
19	44	4.0%	6700	268
20	48	4.0%	6700	0
21	53	3.5%	6700	0
22	60	3.0%	6700	0
23	61	3.0%	6700	0
	Total	100.0%	Total	**3,585**

Using the procedures explained in previous exercise, the daily truck delay of a route can be computed by aggregating the delays from each segment. The average truck delay of the I-494 corridor was discussed as an example using 45 MPH threshold speed.

Figure 3-10 illustrates the daily truck delay in hours between I-94/I-494 interchange (mile post 43) in Maple Grove and interchange of I-94/I-494 (mile post 0) in Woodbury. The blue bars are the truck delay in westbound and the red bars are the delay for eastbound truck traffic. Corresponding average truck speed at each mile post is also plotted for both eastbound (red line with the diamond mark) and westbound (blue line with the square mark) directions. Majority of the daily truck delay occurs from I-94 to I-394 and from highway 212 to highway 77. Daily truck delay is about 95 hours in eastbound and 37 hours in westbound.

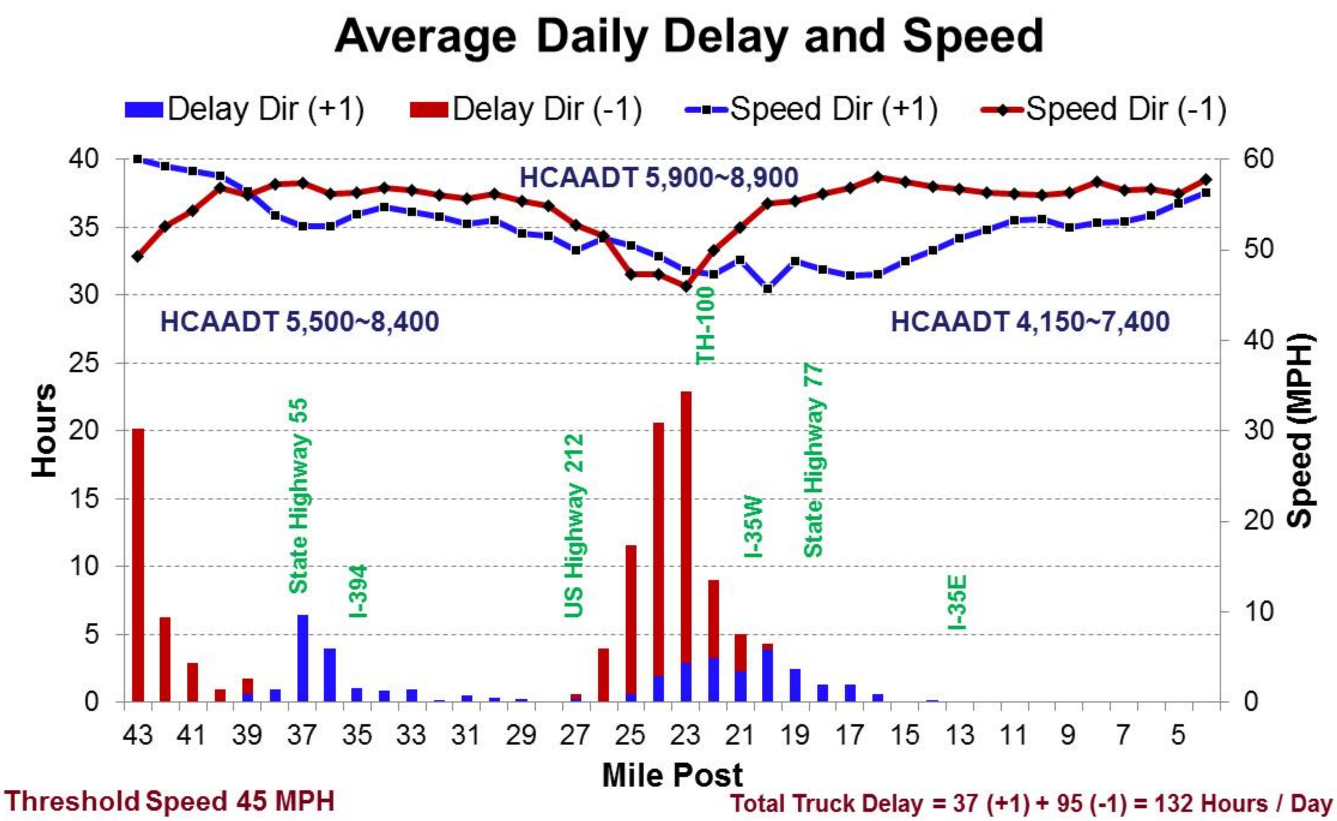


Figure 3-10 Average Daily Truck Delay and Speed on I-494 in 2012

Hours of truck delay in both AM and PM peak hours are illustrated in Figure 3-11 and 3-12, respectively.

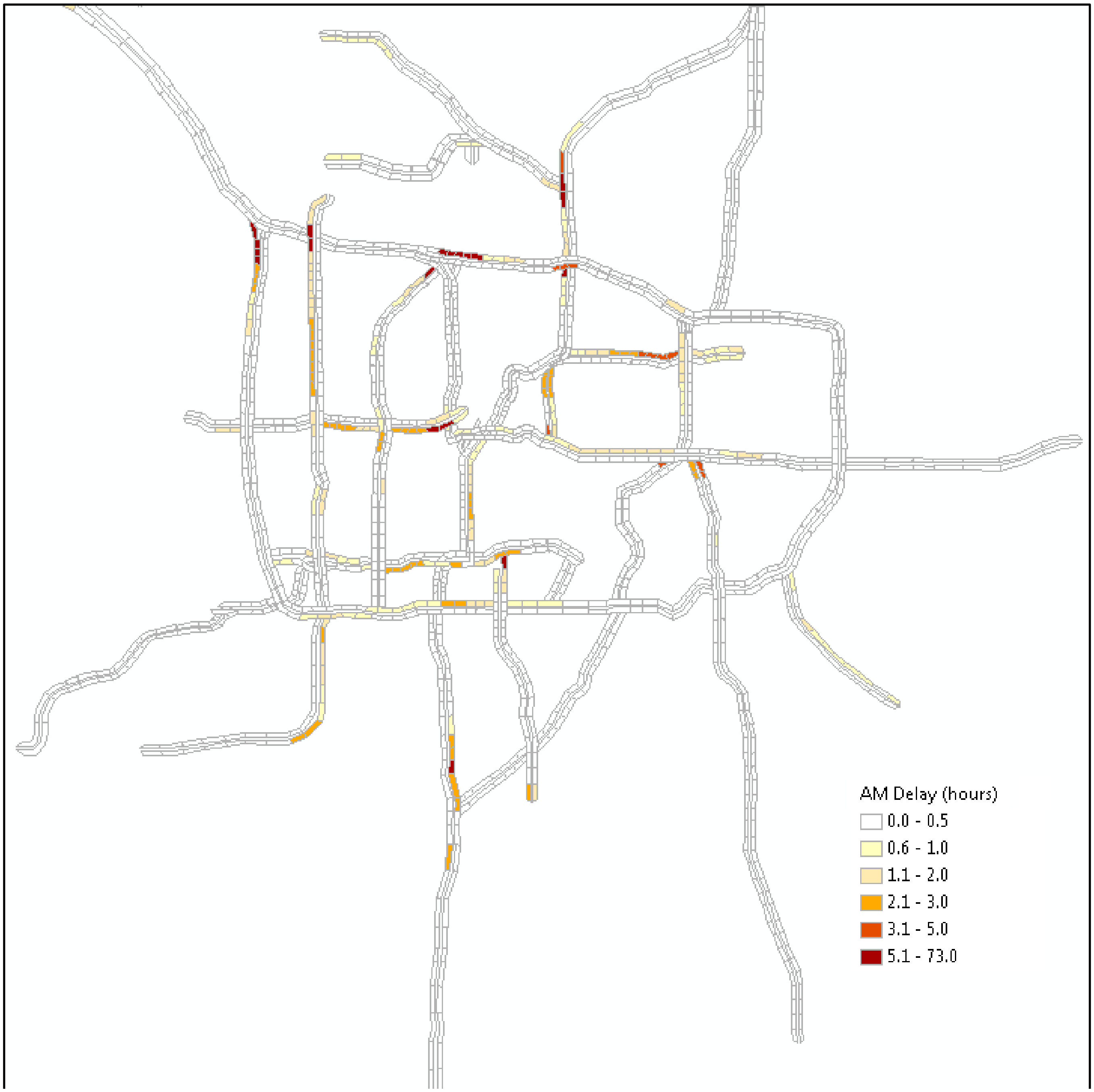


Figure 3-11 Map of Truck Delays in AM Peak

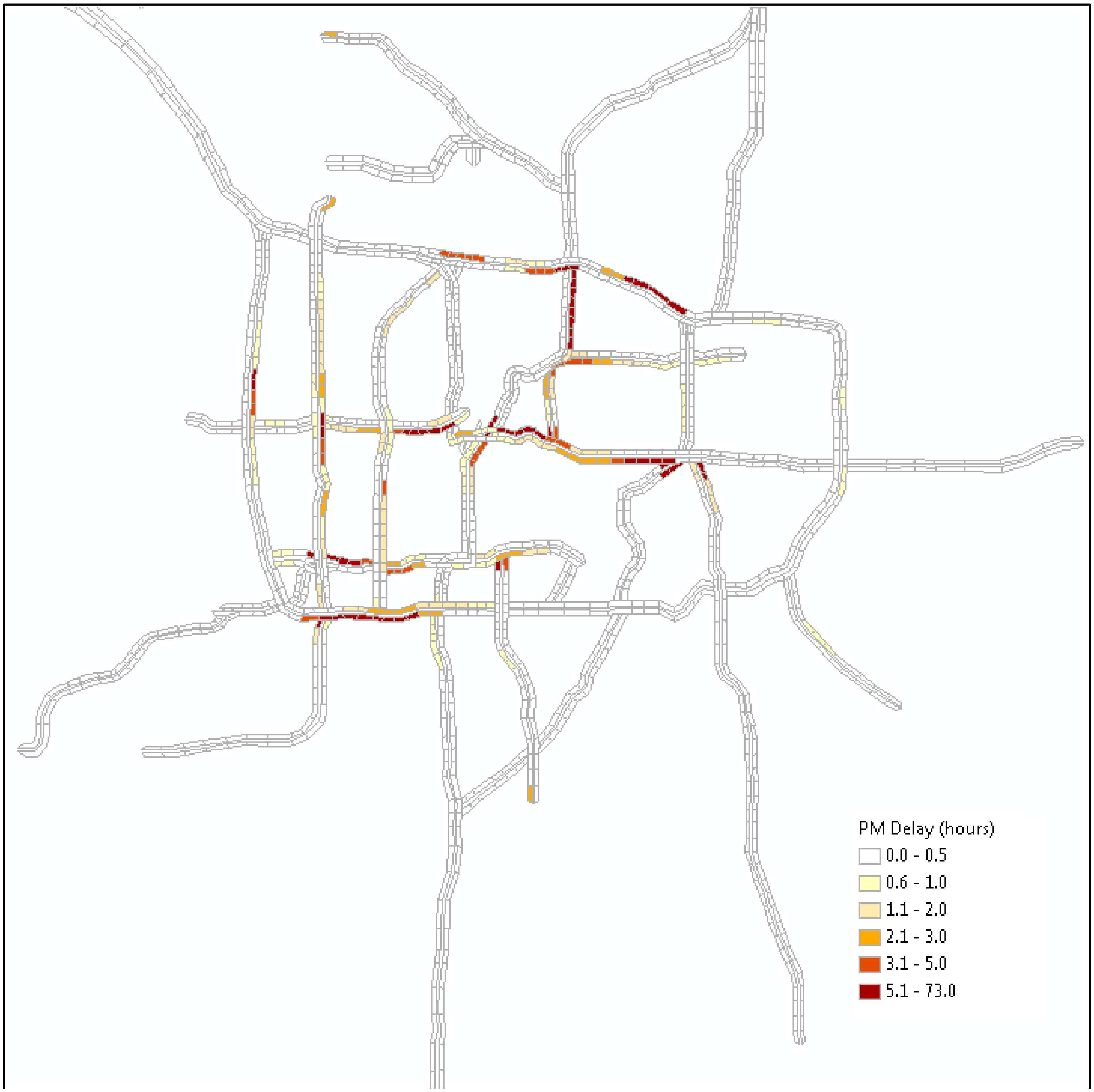


Figure 3-12 Map of Truck Delays in PM Peak

3.5 Truck Travel Time Reliability

An 80th percentile travel time reliability index, defined as equation (3-2), was used to compute the reliability of truck travel time.

$$RI_{80} = \frac{80^{th}\ percentile\ Travel\ Time}{Travel\ Time\ at\ MnDOT\ Specified\ Threshold\ Speed} \qquad \text{Eq. (3-2)}$$

The 80 percentile travel time reliability indices for all corridors in TCMA in both directions were plotted in Figure 3-13 and 3-14 for AM and PM peak hours, respectively. Travel time of a roadway segment is considered reliable, moderate reliable and unreliable using the following criteria.

- $RI_{80} < 1.5$ reliable
- $1.5 \leq RI_{80} < 2.0$ moderate reliable
- $RI_{80} \geq 2.0$ unreliable

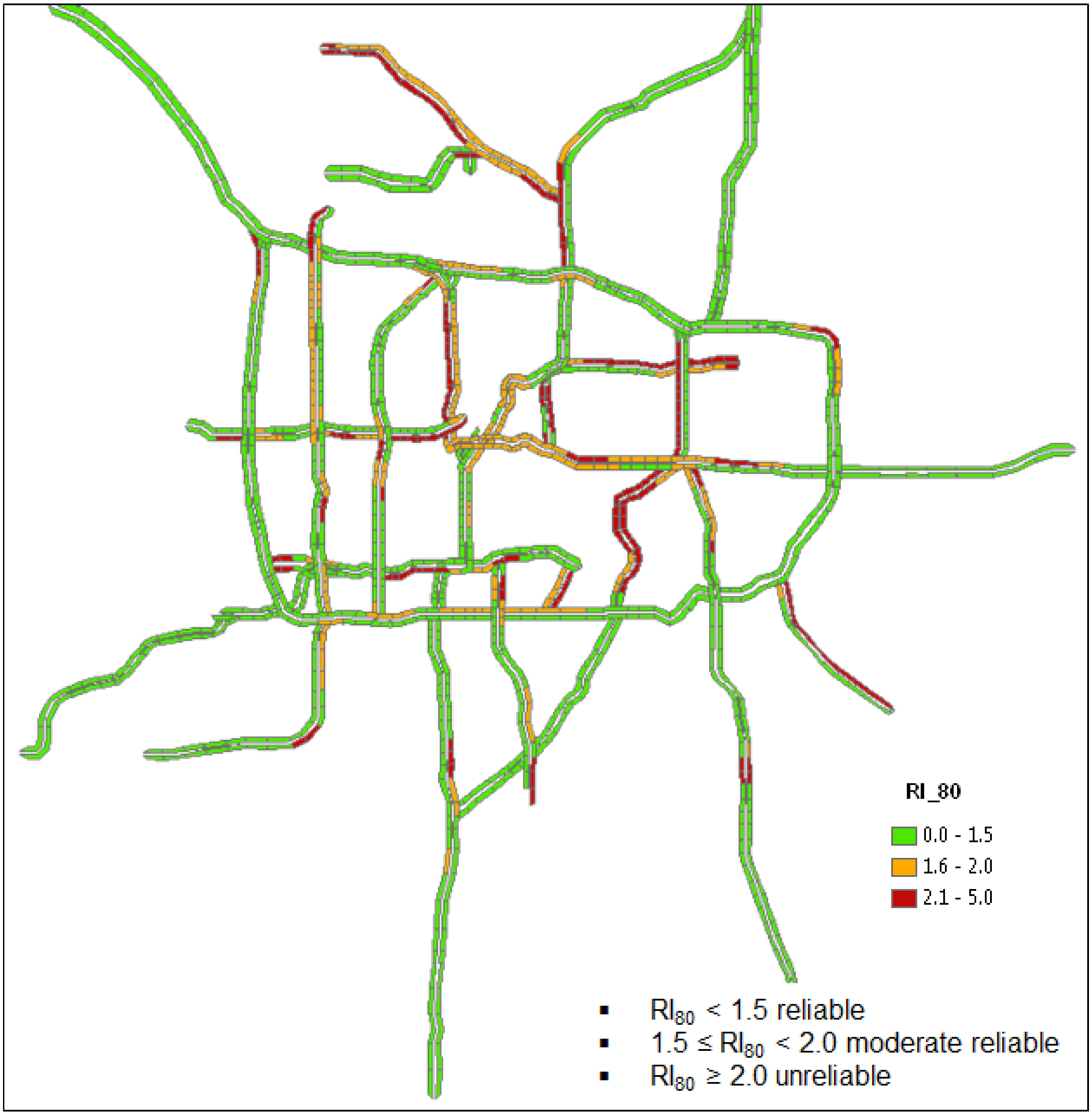
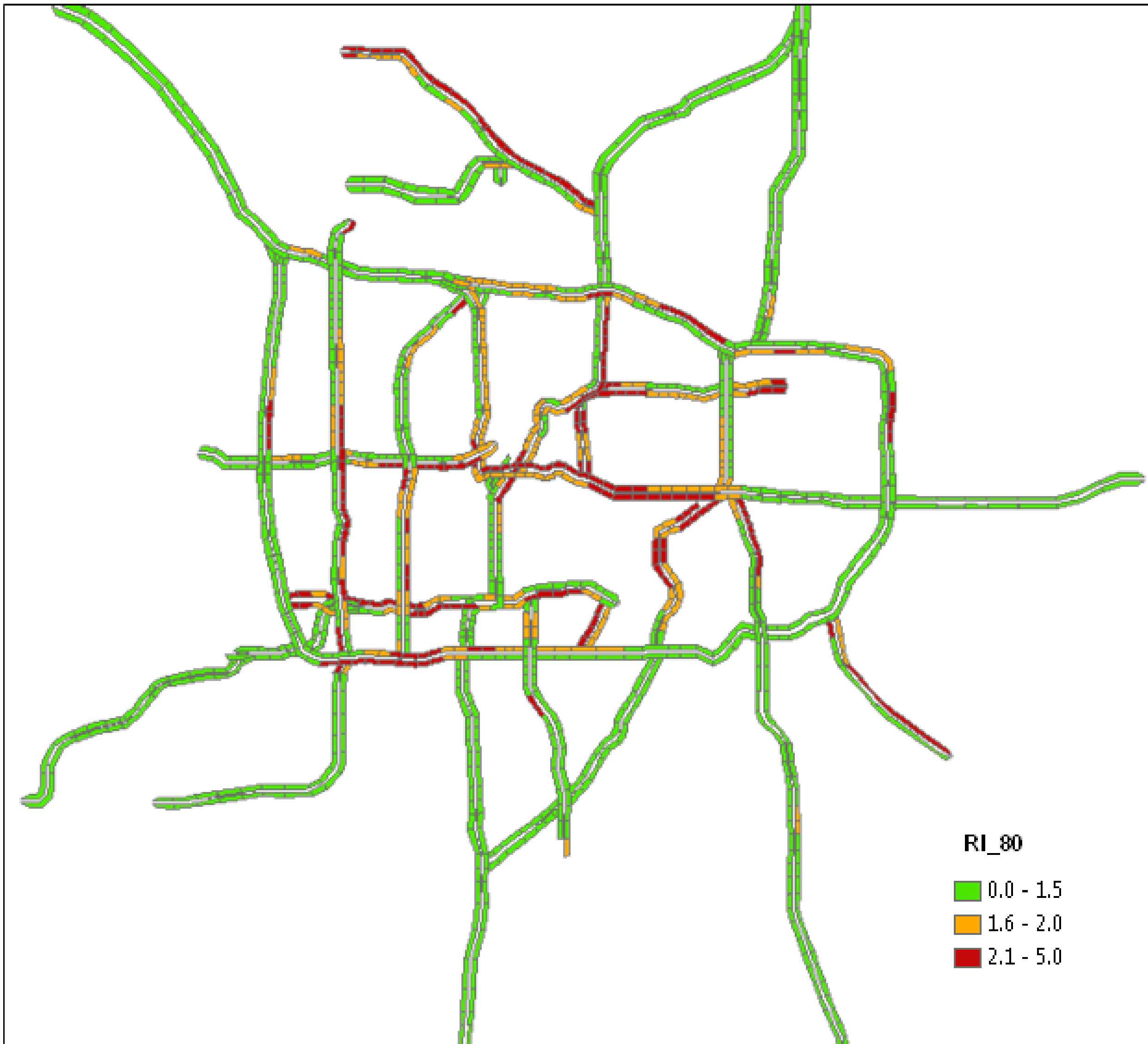


Figure 3-13 Truck Reliability Index in AM Peak

I-94 eastbound into downtown Minneapolis, TH-36 westbound after I-35E, and I-35E between I-494 & I-94 in AM have some of the least reliable congestion in TCMA as displayed in Figure 3-13. In PM peak hours, I-94 westbound before Lowry tunnel, I-94 eastbound into downtown St. Paul, I-494 eastbound before I-35W, TH62 between I-35W and TH-100, and TH-36 eastbound at TH-280 have some of the least reliable congestion in TCMA as shown in Figure 3-14.



- RI_{80} < 1.5 reliable
- 1.5 ≤ RI_{80} < 2.0 moderate reliable
- RI_{80} ≥ 2.0 unreliable

Figure 3-14 Truck Reliability Index in PM Peak

3.6 Truck Bottlenecks Identification

Truck bottlenecks delay truck freight shipment and delivery. Delays induced by bottlenecks could negatively impact a region's economy and productivity. In addition to traffic volume to capacity ratio, highway interchange, lane drop, signal, and steep grade are typical factors contribute to traffic bottlenecks. As suggested by FHWA, reducing truck bottleneck is a major solution for increasing truck freight efficiency and reliability. A few bottleneck identification techniques found in the literature are summarized as follows.

3.6.1 FHWA & Cambridge Systematics

This approach is the result of a federal program to identify freight bottlenecks (Cambridge Systematics, 2005). The methodology for locating highway truck bottlenecks is as follows:

1. Locate highway segments with a high volume of traffic in proportion to the available roadway capacity (the volume-to-capacity ratio).
2. Determine truck volumes at these locations.
3. Calculate truck hours of delay by using queuing models. The bottleneck can then be ranked by hours of delay.

This approach has some limitations related to quality of the input data. Because much of the data are derived and do not directly account for real-world truck behavior.

3.6.2 American Transportation Research Institute (ATRI)

The ATRI approach (Short et al., 2009, 2010, 2013), completed in conjunction with the Federal Highway Administration (FHWA) Office of Freight Management and Operations, uses GPS data and free flow speeds on roadway segments as a base. The truck GPS data are used to calculate the average miles per hour below free flow speed on the segment of interest. This number is multiplied on an hour-by-hour basis by the number of trucks on that section of roadway. For each hour over the course of a day, "*vehicle population by hour*" is multiplied by "*Free Flow – Average MPH*" to result in an "*hourly freight congestion value*." The sum of the 24 hourly freight congestion values is used to produce the "*total freight congestion value*." This congestion value is used to rank the severity the bottlenecks.

3.6.3 Washington State

The Washington state approach takes full advantage of the high level of GPS data and roadway information available in Washington State. The bottleneck identification and ranking process developed for Washington State includes the following tasks (Zhao et al., 2013):

1. Separate the state's entire roadway network into analysis segments based on the locations of ramps /major intersections and, in some cases, roadway length.
2. Assign to each analysis segment the appropriate roadway attributes (speed limits, classification, etc.) along with heading information to determine travel direction.
3. Assign each probe truck's GPS location reads to the appropriate segments. Account for the truck's travel direction on the segment.

4. For segments with enough truck data, use the GPS truck's travel speeds averaged over time to quantify the reliability and overall performance of each segment and identify as bottlenecks locations where trucks are performing unreliably or slowly.
5. Rank the truck bottlenecks on the basis of a range of metrics, including averaged segment travel speeds, geographic location, and the segment's Freight Goods Transportation System (FGTS) category.

3.6.4 Our Approach

This study focuses on the key freight corridors in the Twin Cities metro area (TCMA). The bottleneck identification and ranking process developed for this task involves the following steps:

1. Segment the 38 key freight corridors in TCMA into 1-mile analysis segments.
2. Associate spatial attribute to the segments using GIS software. Assign to each analysis segment the appropriate roadway attributes (type of road, threshold speed, number of lanes, AADT, heading, etc.).
3. Geo-locate truck GPS point data and assign each probe truck's GPS location point to an appropriate roadway segment and corresponding travel direction.
4. Process the truck GPS data and generate performance measures through statistical analyses.
5. Quantify mobility and reliability performance measures of each roadway segment.
6. Identify segments as bottleneck locations where average truck speed is below target speed, unreliably or having significant delays.
7. Rank the truck bottlenecks on the basis of a range of metrics, including averaged segment travel speeds, delays, reliability, and geographic location.

Previous tasks (task #1 to #4) of this project focused on step 1 to 5 as described above. The rest of this report will focus on identifying and ranking truck bottlenecks in the TCMA.

The research team first identifies truck bottlenecks by comparing the average truck delay per mile in the studied network. Table 3-5 listed 12 locations in TCMA with significant truck delays during the AM peak. A GIS map illustrating these locations (highlighted in aqua color) in AM peak period is displayed in Figure 3-15. Table 3-6 listed 18 locations in TCMA with significant truck delays during the PM peak. A GIS map illustrating these locations (highlighted in aqua color) in PM peak period is displayed in Figure 3-16. Most of the bottleneck locations are nearby an interchange.

Table 3-5 List of Truck Bottleneck in AM Peak (Based on Delay)

Rank	Location	Dir.	AM Peak Delay (hours) / Mile	AM Peak Reliability RI80	HCAADT	Number of Lanes	Length (miles)
1	I-494 S of I-94 (Maple Grove)	SB	13.18	2.5 - 4.36	5300	2	1.91
2	I-35W at Burnsville Pkwy	NB	10.67	3.46	10200	2	0.56
3	TH 169 at I-94	SB	8.76	2.65	3750	2	1.10
4	TH 100 at I-94	SB	8.34	2.05	2400	2	0.56
5	I-694 at I-94	WB	7.59	1.80	9000	3	1.83
6	I-394 at I-94	EB	6.43	3.15	4900	3	1.18
7	I-35W at US10	SB	5.74	2.5 - 2.68	5700	3	2.32
8	I-694 at I-35W	EB	3.92	1.80	12300	2	1.02
9	US52 at I-94	NB	3.8	2.93	5200	2	0.77
10	TH 280 at I94	SB	3.53	2.25	3250	2	0.43
11	TH 36 at I-35E	EB	3.37	2.65 - 3.01	2600	2	1.73
12	I-35E at I-94	SB	3.15	3.08	740	3	0.33

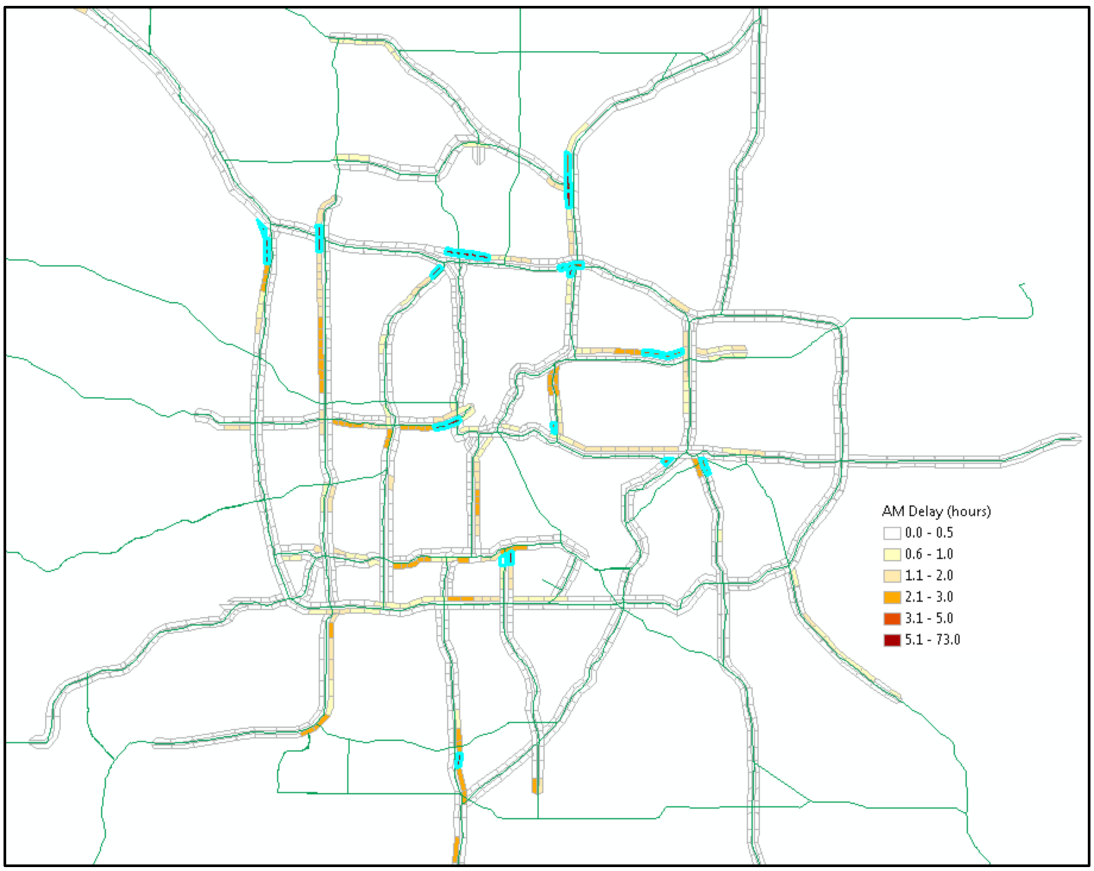


Figure 3-15 Map of Truck Bottleneck (Highlighted) with Delay ≥ 3 Hours in AM Peak

Table 3-6 List of Truck Bottleneck in PM Peak (Based on Delay)

Rank	Location	Dir.	PM Peak Delay (hours) / Mile	PM Peak Reliability RI80	HCAADT	Number of Lanes	Length (miles)
1	I-35W at I-694	NB	14.08	1.94 - 3.75	7700 - 8500	3	3.30
2	I-35W at I-94	SB	12.94	5.00	3250 - 8300	3	1.01
3	I-494 between I-35W & 169	EB	11.31	2.05 - 4.09	6900 - 9100	2	4.88
4	I-394 between TH 100 & I-94	EB	7.14	2.59 - 3.75	400	3	2.61
5	I-694 between I-35E & I-35W	WB	6.85	2.37 - 3.04	6700 - 7800	2	3.02
6	I-694 at I-35W	EB	6.81	1.58 - 2.18	9000 - 12300	2	2.25
7	TH 62 at TH 169	WB	6.41	2.81 - 5	2450	2	2.26
8	US52 at I-94	NB	6.40	4.33	4800 - 5200	3	0.75
9	I-94 at I-35W	WB	5.95	2.6 - 3.25	6600 - 6800	3	3.27
10	I-94 at I-35E	EB	5.88	2.84 - 3.21	6600 - 7100	4	2.67
11	I-494 at TH 55	NB	5.20	2.04 - 2.54	6300	2	1.93
12	I-35E at I-94	NB	5.15	3.27	740 - 810	3	0.96
13	TH 169 at I-394	NB	5.10	2.39 - 3	5000	2	2.20
14	I-696 at TH 100	WB	5.00	1.88	9000	3	1.83
15	I-35W at I-94	NB	4.07	2.45	3250 - 8300	4	1.25
16	TH 100 at TH 7	NB	4.00	3.55	3500	2	0.60
17	TH 36 at I-35W	EB	3.76	2.77	2550	2	1.69
18	TH 62 at TH 169	EB	3.26	3.23	2750	2	1.11

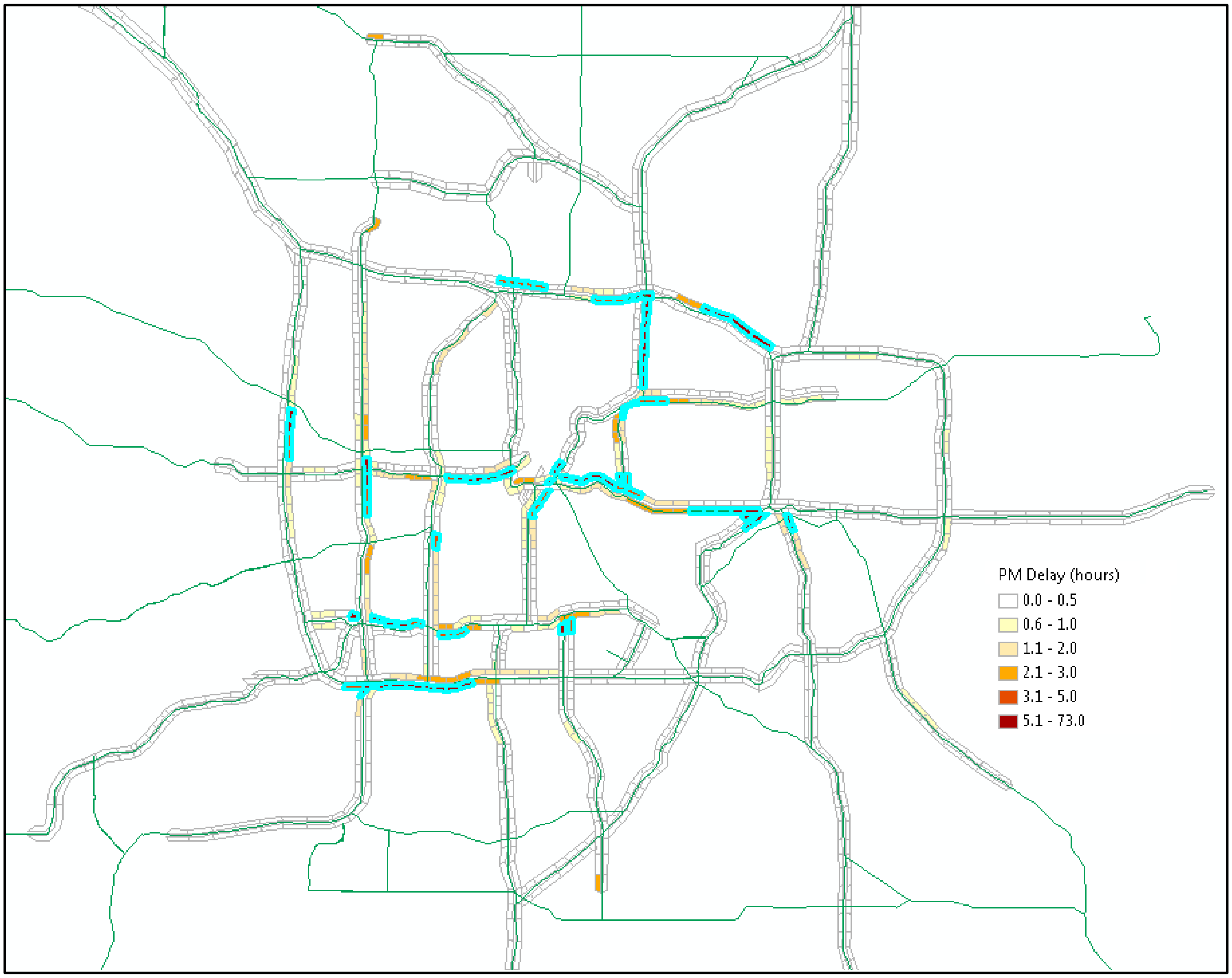


Figure 3-16 Map of Truck Bottleneck (Highlighted) with Delay ≥ 3 Hours in PM Peak

In addition to delay based approach, the research team also evaluated truck bottlenecks based on number of hours in peak period with speed less than threshold speed. Table 3-7 listed 15 locations in TCMA with significant truck delays during the AM peak. A GIS map illustrating these locations (highlighted in aqua color) in AM peak period is displayed in Figure 3-17. Table 3-8 listed 25 locations in TCMA with significant truck delays during the PM peak. A GIS map illustrating these locations (highlighted in aqua color) in PM peak period is displayed in Figure 3-18. Most of the bottleneck locations are nearby an interchange.

Table 3-7 List of Truck Bottleneck in AM Peak (Based on # of Hours below 45 MPH)

Rank	Location	Dir.	AM Peak Delay (hours) / Mile	AM Peak Reliability RI80	HCAADT	# of Lanes	Length (miles)	AM Peak Delay (hours)
1	TH 169 at I-94	SB	8.76	2.65	4150	2	1.09	9.55
2	I-394 at I-94	EB	4.55	2.35 3.15	1750 - 4750	3	1.92	8.74
3	TH 36 at I-35E	WB	3.01	2.49 - 3.08	2800	2	2.72	8.19
4	TH 280 at I-35W	NB	2.86	4.17	2700 - 3250	2	1.28	3.66
5	I-94 and I-35E common	WB / SB	1.77	1.79 - 3.08	6800	3	1.92	3.40
6	TH 280 at I-35W	SB	2.87	2.95	2700 - 3250	2	1.08	3.10
7	TH 36 at I-35W	WB	1.12	1.73 - 2.05	2950	2	1.63	1.83
8	I-494 at TH 77	WB	1.60	1.78	5800 - 6400	3	1.12	1.79
9	I-94 near Lowry Tunnel	WB	0.83	1.62 - 1.76	4000 - 6300	3	1.78	1.47
10	TH 169 S. of TH 7	NB	1.16	2.13	4850	2	1.11	1.29
11	TH 61 2.5 Mile S I-494	NB	1.65	2.41	3700	2	0.67	1.11
12	TH 62 at I-35W	EB	0.79	3.53	2250	2	1.14	0.90
13	I-494 at I-35W	WB	0.83	1.39	8800	3	1.06	0.88
14	TH 169 S. of TH 7	SB	0.68	1.45	4850	2	1.27	0.86
15	I-94 near Lowry Tunnel	EB	0.28	1.97 - 2.14	4000 - 6300	3	2.88	0.80

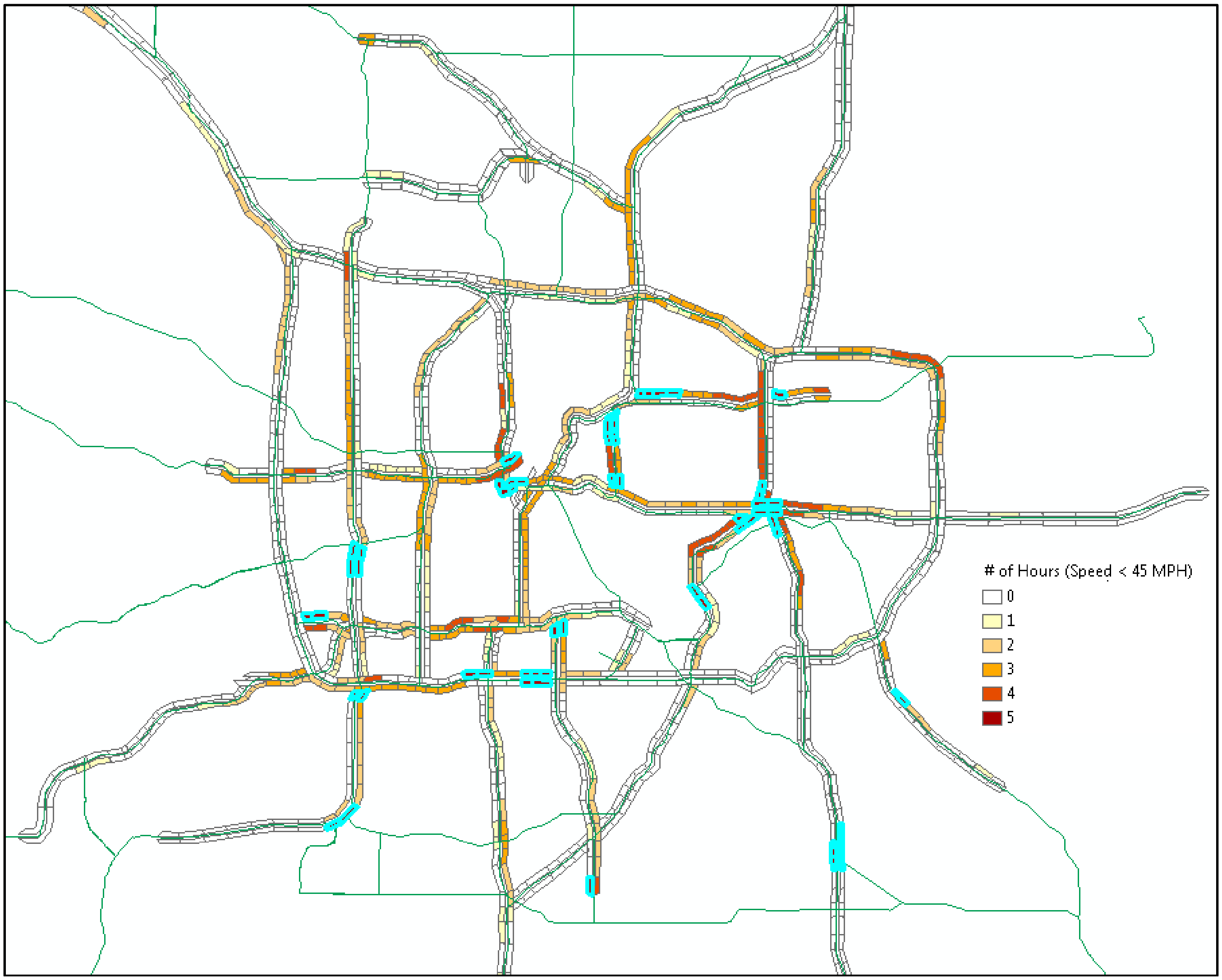


Figure 3-17 Map of Truck Bottleneck (Highlighted) with Average Speed ≤ 45 MPH for Over 5 Hours in AM Peak

Truck bottlenecks delay truck freight shipment and delivery. Delays induced by bottlenecks could negatively impact a region's economy and productivity. A few bottleneck identification techniques were briefly discussed. Highway interchange, lane drop, signal, and steep grade are typical factors contribute to traffic bottlenecks

This report generated truck performance measures, including mobility, delay and reliability, using the results from truck GPS data analysis. The performance measures can be used to identify key freight corridors and truck bottlenecks in the TCMA. The research team first identified truck bottlenecks by comparing the average truck delay per mile in the studied network. In addition to delay based approach, the research team also evaluated truck bottlenecks based on number of hours in peak period with speed less than threshold speed. Both approaches listed over 12 locations in both AM and PM peak periods in the TCMA that cause truck delays.

Table 3-8 List of truck bottleneck in PM Peak (Based on # of Hours below 45 MPH)

Rank	Location	Dir.	PM Peak Delay (hours) / Mile	PM Peak Reliability RI80	HCAADT	# of Lanes	Length (miles)	PM Peak Delay (hours)
1	I-494 between I-35W & 169	EB	14.45	2.05 - 4.50	6800 - 9100	3	3.14	45.34
2	I-35W at I-694	NB	17.79	3 - 3.75	7200 - 8500	3	2.05	36.47
3	I-394 between downtown and TH 100	EB	4.96	1.93 - 3.75	2100 - 4200	3	4.78	23.69
4	I-94 between Lowry tunnel and TH 280	WB	4.51	2.35 - 3.25	4000 - 6300	3	5.02	22.63
5	I-35E at I-94	SB	5.32	1.50 - 22.5	6200 - 7900	3	2.4	12.76
6	I-35W at I-94	SB	6.79	1.98 - 5	3700 - 7100	3	1.84	12.48
7	I-694 at I-35W	WB	5.22	1.64	7300 - 11000	2	2.13	11.11
8	US52 at I-94	NB	3.94	2.42 - 4.33	4750 - 5200	3	2.18	8.59
9	I-35W at I-94	NB	3.04	1.61 - 2.45	8300	4	2.38	7.22
10	TH 36 at I-35W	EB	3.86	2.77	2550	3	1.78	6.87
11	I-94 at I-35E common	EB	2.98	1.87 - 2.84	6800	3	2.2	6.55
12	TH 62 between I-35W & TH 100	EB	2.01	3.00 - 3.28	2250 - 5200	2	2.81	5.65
13	TH 62 at TH 100	WB	3.40	2.04 - 2.81	2250 - 2450	2	1.65	5.62
14	I-35E at I-94	NB	2.63	1.56 - 3.27	6200 - 7900	3	1.89	4.97
15	I-494 between I-35W & 77	WB	1.41	1.55 - 2.14	6000 - 9000	3	3.25	4.60
16	TH 280 at I-35W	NB	2.75	3.30	2700 - 3250	2	1.28	3.52
17	TH 169 S. of TH 7	NB	2.75	2.5	4850	2	1.11	3.05
18	TH 280 at I-35W	SB	2.53	2.10 - 3.00	2700 - 3250	2	1.08	2.74
19	TH 77 at TH 62	NB	4.72	0	2000	2	0.53	2.50
20	TH 169 S. of I-494	SB	6.72	3.24	6000	2	0.34	2.29
21	TH 77 at TH 62	SB	5.38	0	2000	2	0.39	2.10
22	I-94 near Lowry Tunnel	EB	0.57	1.54 - 2.25	4000 - 6300	3	2.88	1.63
23	US52 at I-94	SB	1.76	1.73	4750 - 5200	2	0.92	1.62
24	I-694 at I-35W	EB	0.36	1.24 - 1.87	7300 - 11000	2	1.89	0.68
25	TH 169 S. of I-494	NB	0.86	1.67	6000	2	0.41	0.35

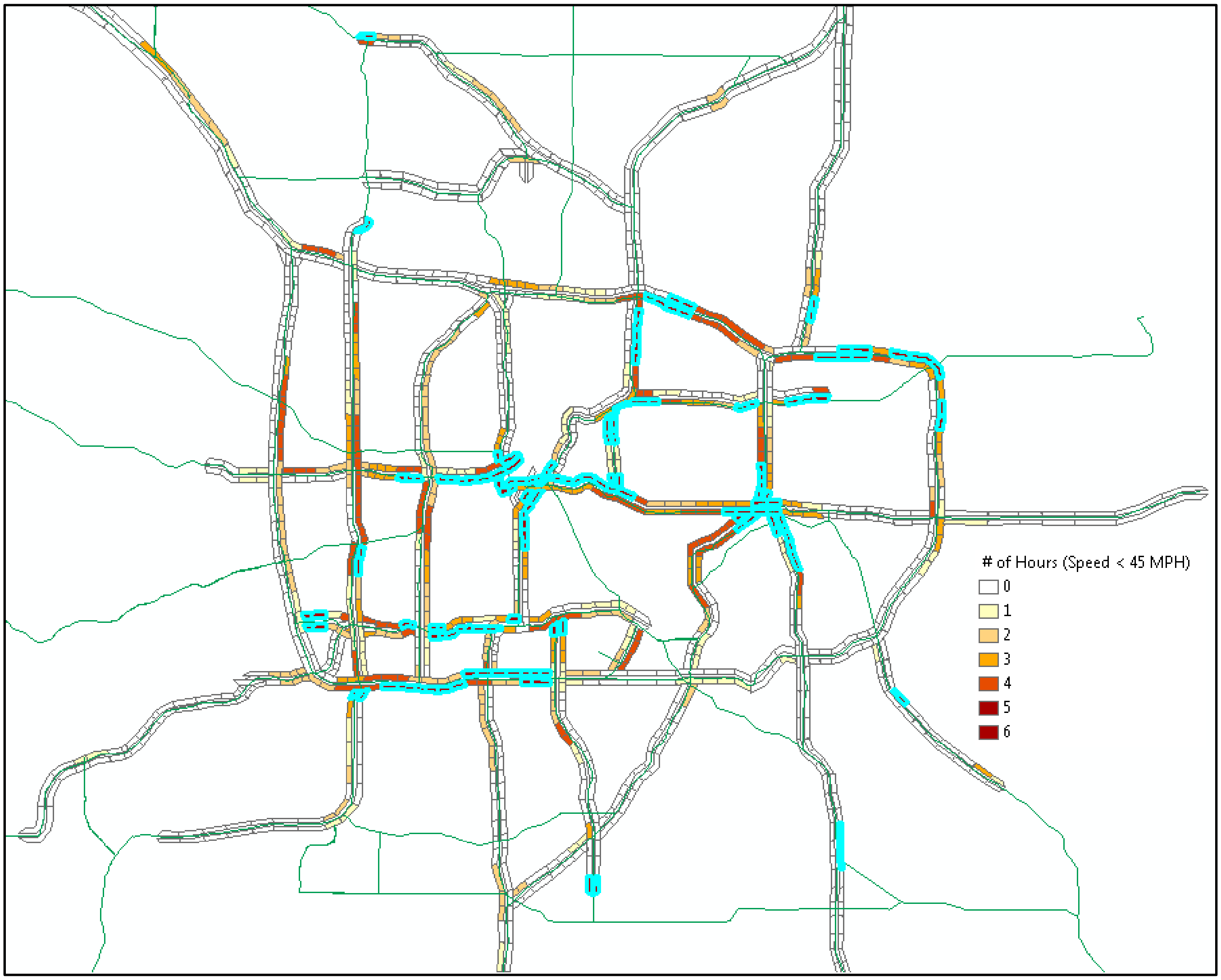


Figure 3-18 Map of Truck Bottleneck (Highlighted) with Average Speed ≤ 45 MPH for Over 5 Hours in PM Peak

Table 3-9 listed 12 locations in TCMA with significant truck delays during the combined AM and PM peak periods. A GIS map illustrating these locations (highlighted in aqua color) in combined AM and PM peak periods is displayed in Figure 3-19. Most of the bottleneck locations are nearby an interchange.

Table 3-9 List of truck bottleneck in AM and PM Peak Combined

Rank	Location	Dir.	AM Peak Delay (hours)	PM Peak Delay (hours)	AM & PM Peak Delay (hours)
1	I-494 between I-35W & 169	EB	0.7	55.2	55.9
2	I-394 at I-94	EB	7.6	18.6	26.2
3	I-494 S of I-94 (Maple Grove)	SB	25.2	0.0	25.2
4	I-694 at I-35W	EB	4.0	15.3	19.3
5	I-694 at I-94	WB	13.9	5.0	18.9
6	TH 62 at TH 169	WB	1.6	14.5	16.1
7	I-35W at I-694	NB	0.0	15.7	15.7
8	TH 280 at I94	SB	1.5	12.6	14.1
9	I-35W at I-94	SB	0.4	10.0	10.4
10	US52 at I-94	NB	2.9	4.8	7.7
11	I-35W at Burnsville Pkwy	NB	6.0	0.0	6.0
12	I-35E at I-94	SB	1.0	2.8	3.8

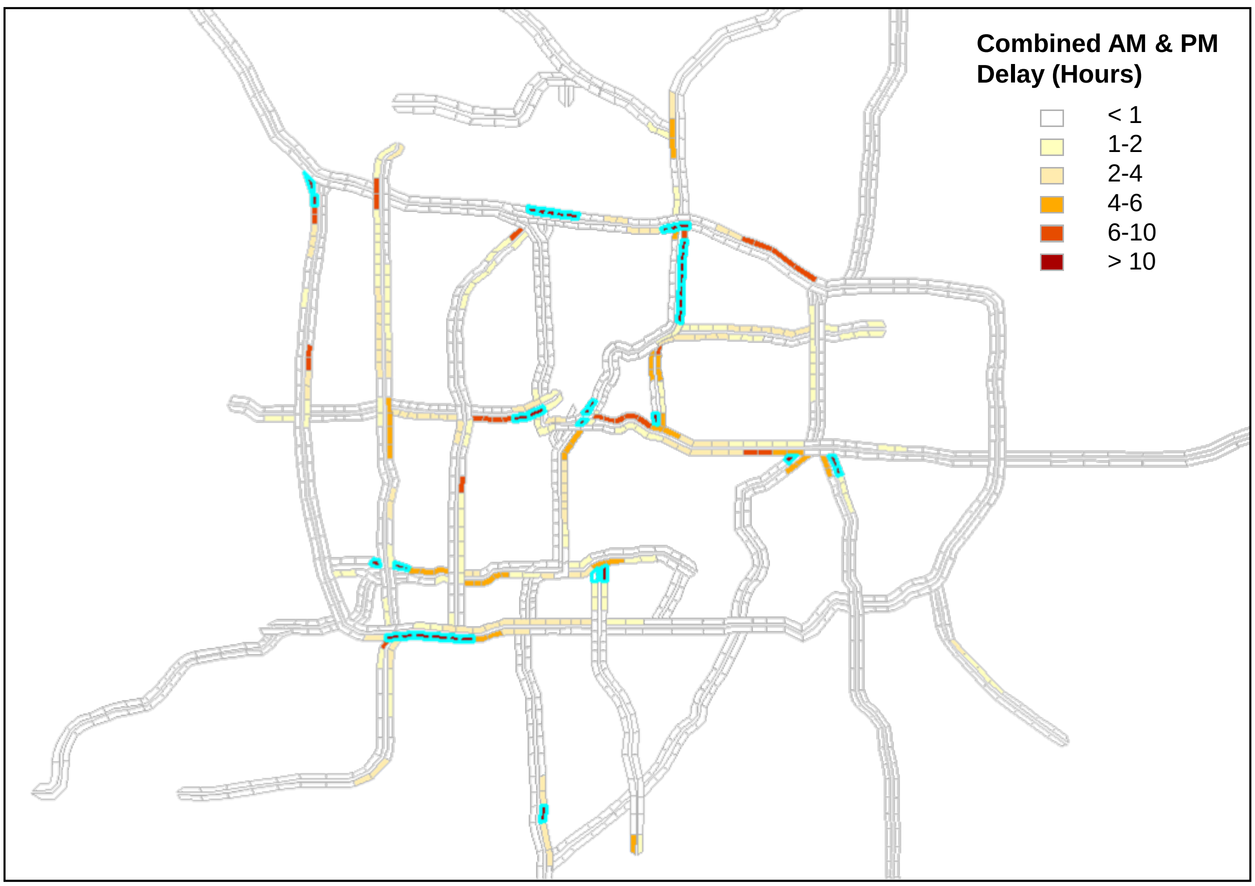


Figure 3-19 Map of Truck Bottleneck (Highlighted) with Delay Over 10 Hours in Combined AM and PM Peak Period

3.7 Truck Congestion Cost

In addition to performance measures, transportation data analysts have estimated the cost of traffic mobility deficiencies as a means of expressing the financial impact of congestion. These congestion cost measures can have utility to both transportation decision-makers and system users if they accurately reflect the tangible costs of transportation use on congested facilities. Short et al. (2010) estimated the annual cost of freight bottlenecks to the trucking industry by including truck travel time measures and operational cost data.

The annual Urban Mobility Report (UMR) produced by Texas Transportation Institute (TTI) measures the costs of congestion at both the national and the local levels. However, it does not focus exclusively on trucks. The 2012 report (Schrank et al., 2012) estimated that the overall cost of congestion in the United States was $121 billion in 2011 based on wasted fuel and lost productivity. In Minneapolis-St. Paul, MN area, annual truck congestion cost was $232 million and the total congestion cost was $1.26 billion in 2011. Cost of truck congestion used in the 2012 UMR was $88 per hour.

In 2008, the American Transportation Research Institute (ATRI), conducted a study to assess the operational costs of truck delays, defined as the full marginal cost of operating a truck for one mile or one hour in typical operating conditions (Trego, 2008). A recent update of the report in 2013 (Fender & Peirce, 2013), total marginal costs for the industry across all sectors, fleet sizes and regions were $1.63 per mile and $65.29 per hour in 2012.

Truck delay on an average weekday for each roadway segment was computed using equation (3-1) as discussed in section 3.4. By aggregating truck delays of all segments in each corridor, the total truck delays in both directions by corridor were computed as listed in the 'Total Delay' column in Table 3-10. Truck congestion cost of each corridor using the ATRI's truck operation cost ($65.29/hour) and the TTI's truck congestion cost ($88/hour) were calculated in the 'Congestion Cost (ATRI)' and 'Congestion Cost (TTI)' column in Table 3-10, respectively.

Of the 38 corridors studied in this project, several of them are county roads or state highways with traffic signals. Total truck congestion cost in the TCMA was about 0.8 million per weekday using the ATRI's operation cost per hour. The corresponding annual congestion cost was $212 million (assuming no delays on weekends). When using the TTI's congestion cost rate, the total truck congestion cost in the TCMA was about 1.1 million per weekday and the corresponding annual truck congestion cost was around $286 million (assuming no delays on weekends).

Using the simple cost calculation methodology, daily or annual truck congestion cost measures can be derived by applying industry operating cost rate to truck delays derived from empirical truck speed/time data at a corridor level or in a region.

Table 3-10 Daily Truck Congestion by Route

Route ID	Route Name	Segment Count	Total Delay (Hour)	Congestion Cost (ATRI)	Congestion Cost (TTI)
1	State Highway 242	14	657	$42,896	$57,816
2	State Highway 610	7	0.1	$7	$9
3	State Highway 252	5	44	$2,873	$3,872
4	Interstate 694	23	53	$3,460	$4,664
5	State Highway 36	22	120	$7,835	$10,560
6	Interstate 494	43	111	$7,247	$9,768
7	State Highway 100	16	29	$1,893	$2,552
8	Interstate 394	10	54	$3,526	$4,752
9	US Highway 12	17	22	$1,436	$1,936
10	State Highway 280	4	24	$1,567	$2,112
11	State Highway 7	35	145	$9,467	$12,760
12	State Highway 62	13	62	$4,048	$5,456
13	State Highway 110	2	23	$1,502	$2,024
14	US Highway 212	35	12	$783	$1,056
15	State Highway 77	12	23	$1,502	$2,024
16	County Road 32	2	102	$6,660	$8,976
17	County Road 101	3	0.2	$13	$18
18	County Road 42	22	1243	$81,155	$109,384
19	State Highway 316	8	0.4	$26	$35
20	County Road 18	4	99	$6,464	$8,712
21	State Hwy 51	12	870	$56,802	$76,560
22	State Hwy 97	13	24	$1,567	$2,112
23	State Hwy 95	127	361	$23,570	$31,768
24	I- 94	96	331	$21,611	$29,128
25	US Highway 8	23	88	$5,746	$7,744
26	State Hwy 65	59	464	$30,295	$40,832
27	US Highway 61	61	795	$51,906	$69,960
28	State Hwy 55	56	2800	$182,812	$246,400
29	US Hwy 52	86	51	$3,330	$4,488
30	State Hwy 5	86	350	$22,852	$30,800
31	US Hwy 10	100	496	$32,384	$43,648
32	State Hwy 47	59	433	$28,271	$38,104
33	I-35E	35	18	$1,175	$1,584
34	I-35W	41	129	$8,422	$11,352
34	I-35	77	610	$39,827	$53,680
35	State Hwy 3	47	590	$38,521	$51,920
36	State Hwy 21	39	90	$5,876	$7,920
37	US Hwy 169	105	563	$36,758	$49,544
38	State Hwy 13	44	622	$40,610	$54,736
Total		**1463**	**12,509**	**$816,693**	**$1,100,766**

Note: MnDOT does not have target speed specified for the highlighted corridors. 45 MPH was used for delay calculation for all corridors.

4. National Performance Measurement Research Data Set

FHWA is taking proactive steps to support transportation agencies needs by obtaining a comprehensive and reliable set of data that can be broadly deployed for use in measuring, managing and improving the US transportation system. FHWA selected HERE North America, LLC (formerly known as Nokia/NAVTEQ) to provide the National Performance Management Research Data Set (NPMRDS). The NPMRDS dataset is derived based on passenger vehicle data from HERE probe sources and American Transportation Research Institute (ATRI) truck data.

In July 2013, FHWA has announced the NPMRDS to support its FPM and Urban Congestion Report (UCR) programs. The NPMRDS includes probe vehicle based travel time data (for both passenger and freight vehicles) for all National Highway System (NHS) facilities. The NPMRDS aims to support transportation agencies needs by obtaining a comprehensive and reliable set of data that can be broadly deployed for use in measuring, managing and improving the transportation system in US.

4.1 NPMRDS Data Format

The TMC Static data file includes the following information. Sample TMC static data is listed in Table 4-1.

- TMC code
- Country (ADMIN level 1)
- State (ADMIN level 2)
- County (ADMIN level 3)
- Distance (length of TMC in miles)
- Road Number
- Road Name
- Latitude
- Longitude
- Road direction (Northbound, Southbound, Westbound, Eastbound)

Table 4-1 Sample TMC Static Data

TMC	118N04174
ADMIN level 1	USA
ADMIN level 2	Minnesota
ADMIN level 3	Washington
Distance	1.98209
Road Number	I-94
Road Name	
Latitude	44.94881
Longitude	-92.85602
Road direction	Eastbound

The travel time data file includes the following information with sample travel time data listed in Table 4-2.

- TMC code
- Date (MMDDYYYY)
- Epoch (5 minute increment, in the range 0-287). Epochs are referenced to local time.
- Travel Time – all vehicles (seconds)
- Travel Time – Passenger vehicles (seconds)
- Travel Time – Freight vehicles (seconds)

Table 4-2 Sample Travel Time Data

TMC	Date	Epoch	travel_time_all_vehicles	travel_time_passenger_vehicles	travel_time_freight_truckstmc
118N04174	11132013	180	113	115	113
118N04174	11132013	181	108	105	115
118N04174	11132013	182	110		110
118N04174	11132013	183	113	110	113
118N04174	11132013	184	117	115	122
118N04174	11132013	185	113	112	114
118N04174	11132013	186	109	108	110
118N04174	11132013	187	111	111	113

4.2 NPMRDS Data Processing

Three data joins are needed to connect the monthly travel time data to the National Highway System (NHS) roadway shapefile. The steps to join the data are illustrated in Figure 4-1. Snapshots of corresponding tables required for the joining process are displayed in Figure 4-2 to 4-4.

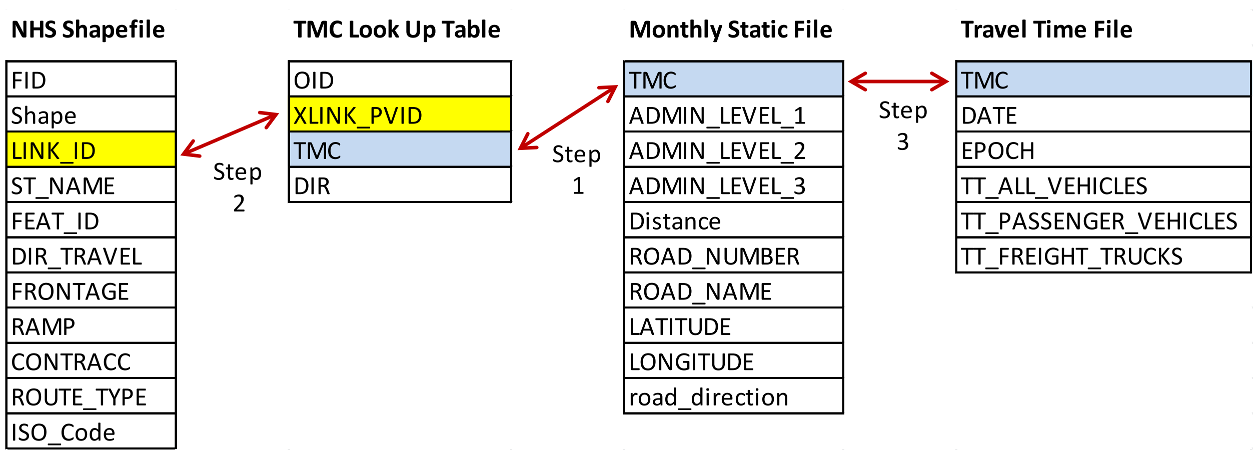


Figure 4-1 Join Travel Time File with NHS Shapefile

1. The first join will connect the TMC column of TMC look up table (LUT) with the TMC column of the static file
2. The second join will connect the LINK_ID of the shapefile with the XLINK_PVID in the result of the first join
3. The third join will connect the TMC of the Travel Time file with the TMC in the result of the second join

Table

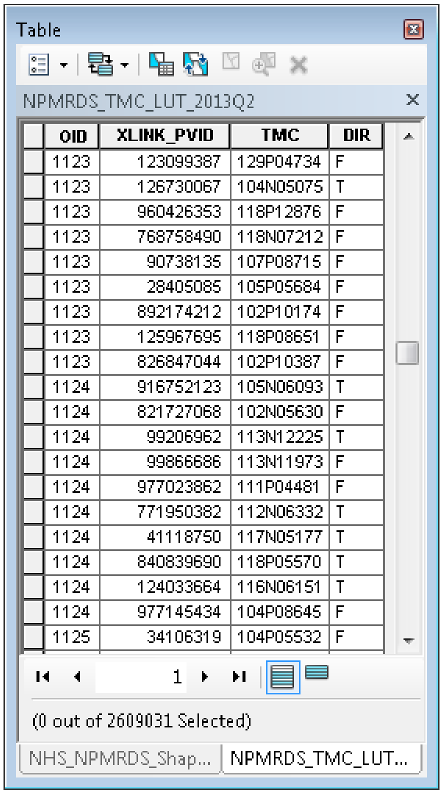
NHS_NPMRDS_Shape_file_HERE_Q2_2013

FID	Shape *	LINK_ID	ST_NAME	FEAT_ID	DIR_TRAVEL	FRONTAGE	RAMP	CONTRACC	ROUTE_T	ISO_Co
3064	Polyline	125957400	MN-100	717374575	T	N	N	Y	3	USA
3064	Polyline	125957458	I-94	717374771	F	N	N	Y	1	USA
3064	Polyline	125957459	I-94	717374771	F	N	N	Y	1	USA
3064	Polyline	125957462	I-94	717374771	F	N	N	Y	1	USA
3065	Polyline	706596371	I-35W	717374573	T	N	N	Y	1	USA
3065	Polyline	706596372	I-35W	717374573	T	N	N	Y	1	USA
3065	Polyline	706596373	I-35W	717374573	F	N	N	Y	1	USA
3065	Polyline	706596375	I-35W	717374573	T	N	N	Y	1	USA
3065	Polyline	706596377	I-35W	717374573	F	N	N	Y	1	USA
3065	Polyline	706596378	I-35W	717374573	F	N	N	Y	1	USA
3065	Polyline	707593783	COURTHOUSE BLV	717385111	T	N	N	N		USA
3067	Polyline	710281666	US-169	717374583	F	N	N	Y	2	USA
3067	Polyline	710295415	DODD RD	717378373	F	N	N	N		USA
3067	Polyline	710295416	DODD RD	717378373	F	N	N	N		USA
3067	Polyline	710295426	DODD RD	717378373	T	N	N	N		USA
3067	Polyline	710295428	DODD RD	717378373	F	N	N	N		USA
3068	Polyline	711355201	I-494	717369084	T	N	N	Y	1	USA
3068	Polyline	711355202	I-494	717369084	T	N	N	Y	1	USA
3068	Polyline	711355205	I-694	717374574	F	N	N	Y	1	USA
3068	Polyline	711355206	I-694	717374574	F	N	N	Y	1	USA
3069	Polyline	711443476	US-52	717374772	T	N	N	Y	2	USA
3069	Polyline	711443477	US-52	717374772	T	N	N	Y	2	USA
3071	Polyline	711637439	MN-610	717368520	T	N	N	Y	3	USA
3071	Polyline	711637440	MN-610	717368520	T	N	N	Y	3	USA
3071	Polyline	711642854	US-10	717374582	F	N	N	Y	2	USA
3071	Polyline	711642855	US-10	717374582	F	N	N	Y	2	USA
3071	Polyline	711642856	US-10	717374582	T	N	N	Y	2	USA
3071	Polyline	711642857	US-10	717374582	T	N	N	Y	2	USA
3075	Polyline	717073589	I-394	717374560	F	N	N	Y	1	USA
3075	Polyline	717073590	I-394	717374560	F	N	N	Y	1	USA
3075	Polyline	717073591	I-394	717374560	F	N	N	Y	1	USA
3075	Polyline	717073592	I-394	717374560	F	N	N	Y	1	USA
3075	Polyline	717073593	I-394	717374560	T	N	N	Y	1	USA

0 (6900 out of 1792650 Selected)

NHS_NPMRDS_Shape_file_HERE_Q2_2013

Figure 4-2 Snapshot of NHS Roadway Data



Table

NPMRDS_TMC_LUT_2013Q2

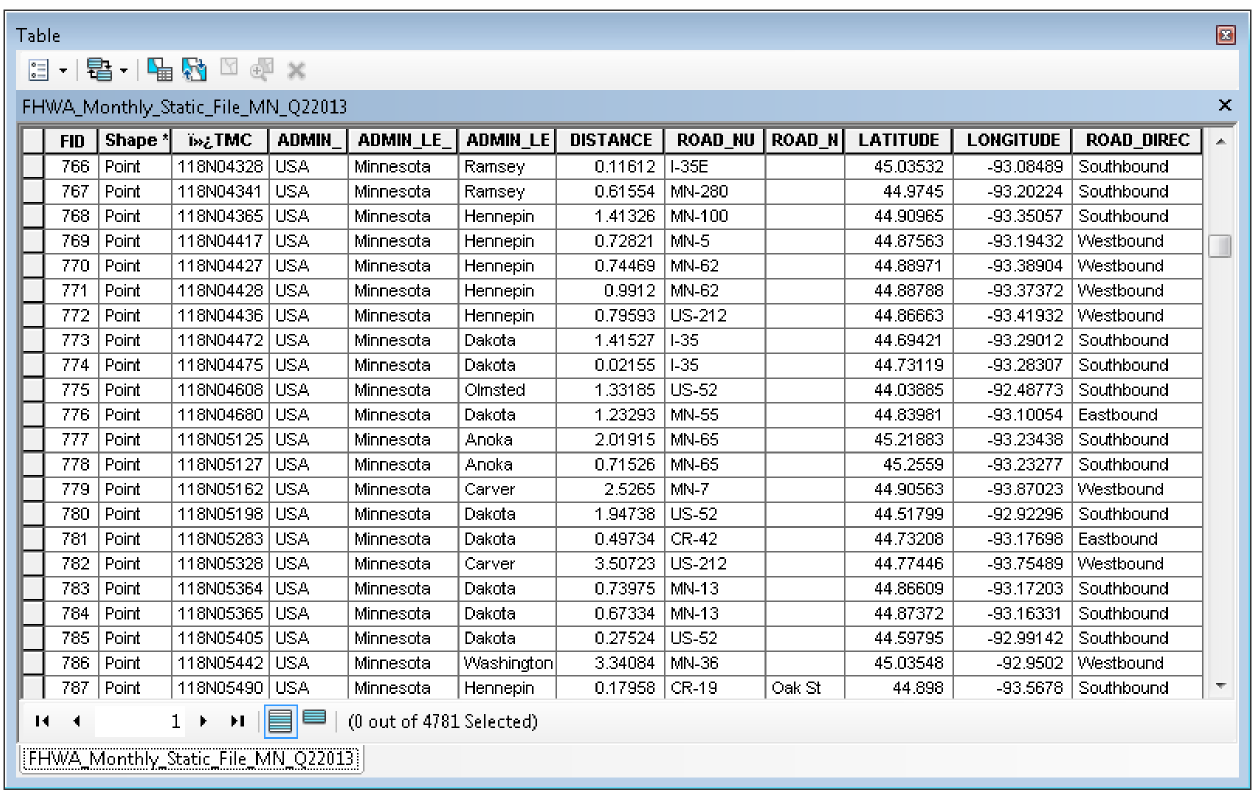
OID	XLINK_PVID	TMC	DIR
1123	123099387	129P04734	F
1123	126730067	104N05075	T
1123	960426353	118P12876	F
1123	768758490	118N07212	F
1123	90738135	107P08715	F
1123	28405085	105P05684	F
1123	892174212	102P10174	F
1123	125967695	118P08651	F
1123	826847044	102P10387	F
1124	916752123	105N06093	T
1124	821727068	102N05630	F
1124	99206962	113N12225	T
1124	99866686	113N11973	F
1124	977023862	111P04481	F
1124	771950382	112N06332	T
1124	41118750	117N05177	T
1124	840839690	118P05570	T
1124	124033664	116N06151	T
1124	977145434	104P08645	F
1125	34106319	104P05532	F

1

(0 out of 2609031 Selected)

NHS_NPMRDS_Shap... NPMRDS_TMC_LUT...

Figure 4-3 Snapshot of TMC Loop Up Table (LUT)



Table

FHWA_Monthly_Static_File_MN_Q22013

FID	Shape *	ï»¿TMC	ADMIN_	ADMIN_LE_	ADMIN_LE	DISTANCE	ROAD_NU	ROAD_N	LATITUDE	LONGITUDE	ROAD_DIREC
766	Point	118N04328	USA	Minnesota	Ramsey	0.11612	I-35E		45.03532	-93.08489	Southbound
767	Point	118N04341	USA	Minnesota	Ramsey	0.61554	MN-280		44.9745	-93.20224	Southbound
768	Point	118N04365	USA	Minnesota	Hennepin	1.41326	MN-100		44.90965	-93.35057	Southbound
769	Point	118N04417	USA	Minnesota	Hennepin	0.72821	MN-5		44.87563	-93.19432	Westbound
770	Point	118N04427	USA	Minnesota	Hennepin	0.74469	MN-62		44.88971	-93.38904	Westbound
771	Point	118N04428	USA	Minnesota	Hennepin	0.9912	MN-62		44.88788	-93.37372	Westbound
772	Point	118N04436	USA	Minnesota	Hennepin	0.79593	US-212		44.86663	-93.41932	Westbound
773	Point	118N04472	USA	Minnesota	Dakota	1.41527	I-35		44.69421	-93.29012	Southbound
774	Point	118N04475	USA	Minnesota	Dakota	0.02155	I-35		44.73119	-93.28307	Southbound
775	Point	118N04608	USA	Minnesota	Olmsted	1.33185	US-52		44.03885	-92.48773	Southbound
776	Point	118N04680	USA	Minnesota	Dakota	1.23293	MN-55		44.83981	-93.10054	Eastbound
777	Point	118N05125	USA	Minnesota	Anoka	2.01915	MN-65		45.21883	-93.23438	Southbound
778	Point	118N05127	USA	Minnesota	Anoka	0.71526	MN-65		45.2559	-93.23277	Southbound
779	Point	118N05162	USA	Minnesota	Carver	2.5265	MN-7		44.90563	-93.87023	Westbound
780	Point	118N05198	USA	Minnesota	Dakota	1.94738	US-52		44.51799	-92.92296	Southbound
781	Point	118N05283	USA	Minnesota	Dakota	0.49734	CR-42		44.73208	-93.17698	Eastbound
782	Point	118N05328	USA	Minnesota	Carver	3.50723	US-212		44.77446	-93.75489	Westbound
783	Point	118N05364	USA	Minnesota	Dakota	0.73975	MN-13		44.86609	-93.17203	Southbound
784	Point	118N05365	USA	Minnesota	Dakota	0.67334	MN-13		44.87372	-93.16331	Southbound
785	Point	118N05405	USA	Minnesota	Dakota	0.27524	US-52		44.59795	-92.99142	Southbound
786	Point	118N05442	USA	Minnesota	Washington	3.34084	MN-36		45.03548	-92.9502	Westbound
787	Point	118N05490	USA	Minnesota	Hennepin	0.17958	CR-19	Oak St	44.898	-93.5678	Southbound

1 (0 out of 4781 Selected)

FHWA_Monthly_Static_File_MN_Q22013

Figure 4-4 Snapshot of TMC Monthly Static File

The TMC static point along the NHS network in Minnesota is displayed in Figure 4-5. Figure 4-6 illustrated the TMC static data in the Twin Cities 8-County metro area.

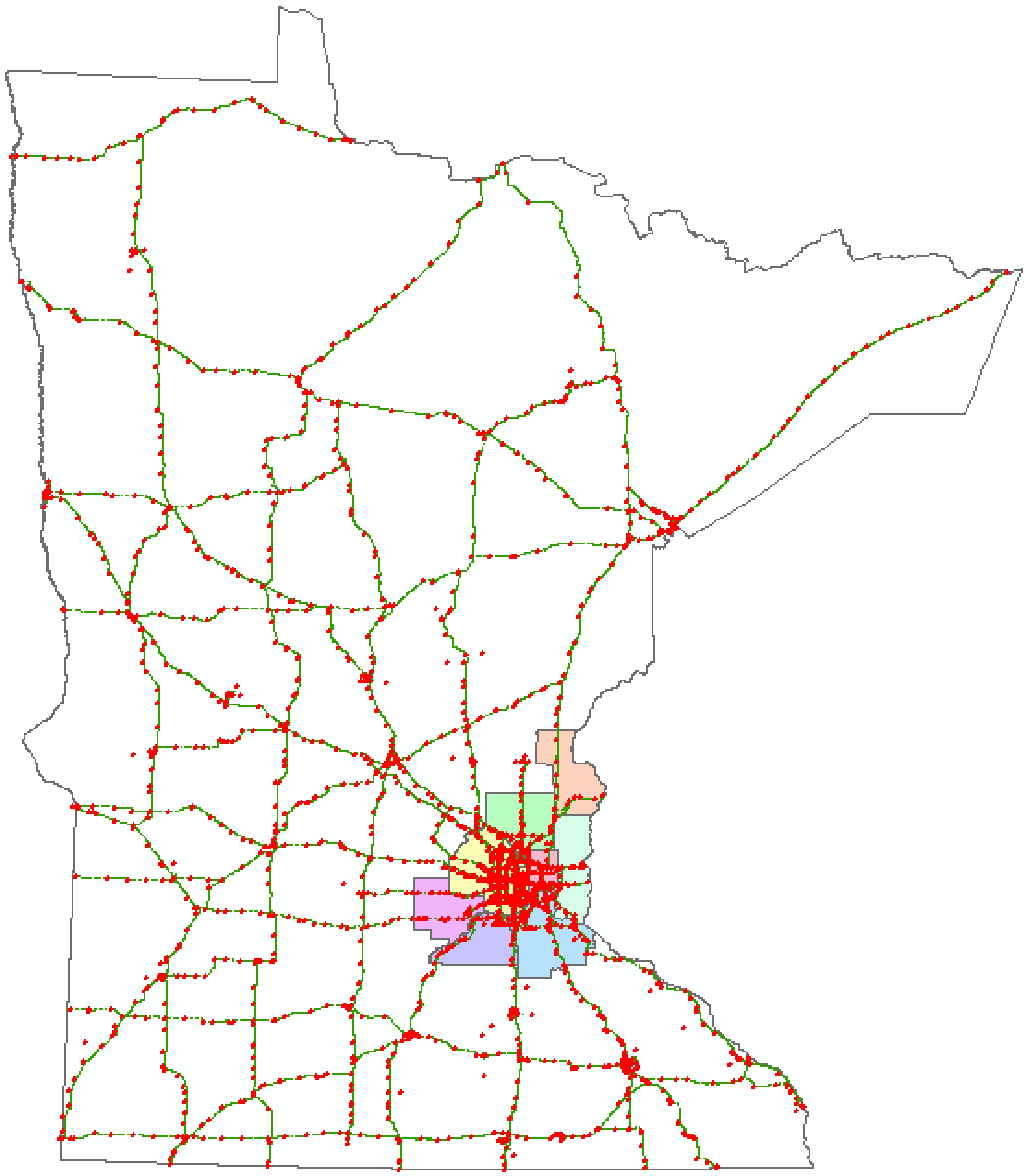


Figure 4-5 TMC Segment Static Data in MN

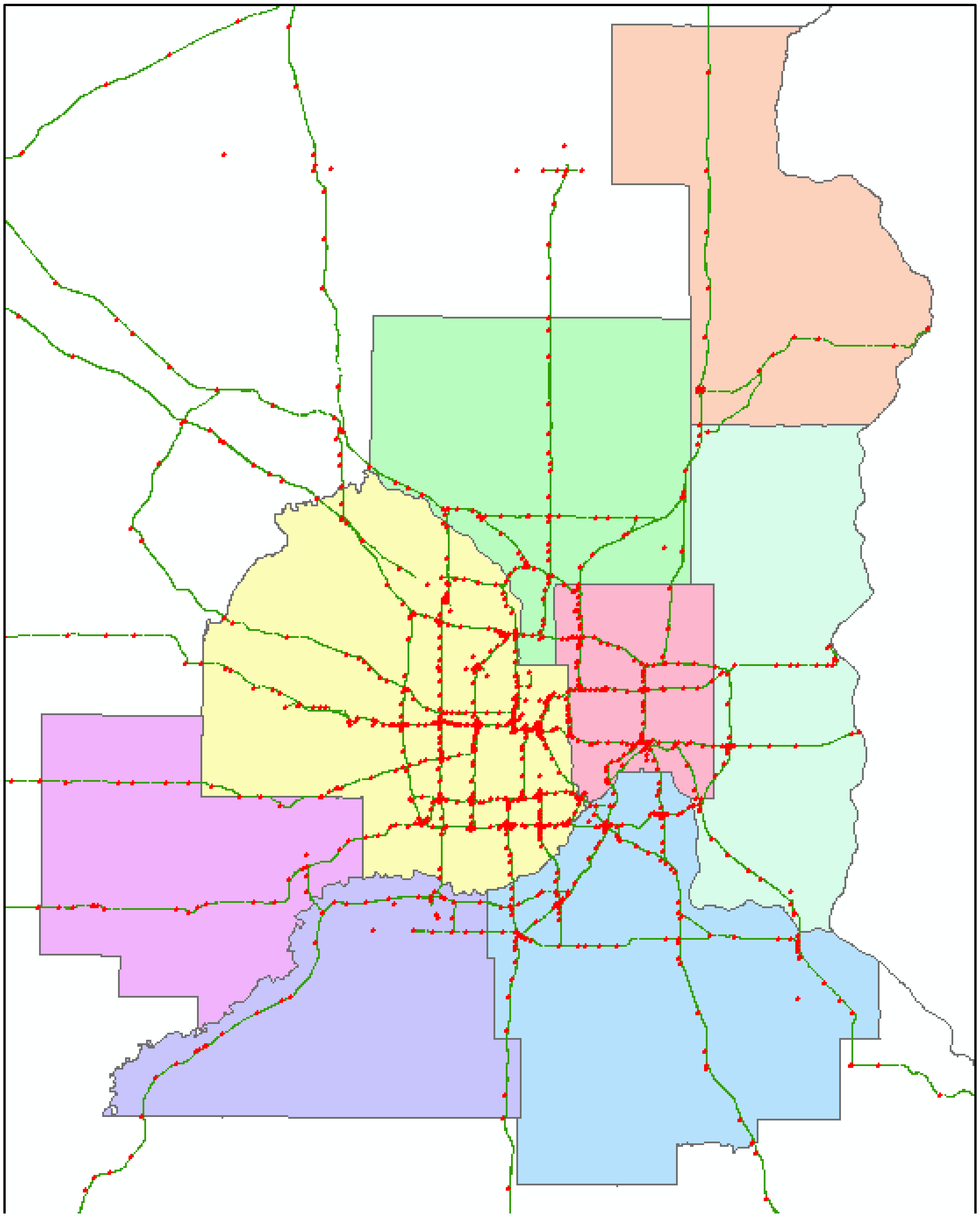


Figure 4-6 TMC Segment Static Data in Twin Cities 8-County Metro Area

4.3 Speed Analysis Example Using NPMRDS Data

Average travel times of passenger vehicles, trucks, and all vehicles during AM (6-9AM) and PM peak (3-6PM) periods in Nov. 2013 were processed by querying the NPMRDS database. The resulting average travel time of each TMC segment is joined to the corresponding TMC segment in the NHS shapefile as described in section 4.2. Average speeds of passenger vehicles, trucks, and all vehicles at each TMC segment were computed by dividing the segment distance by the corresponding average travel time. Figure 4-7 displays the average truck speed during AM Peak Period in Nov. 2013 using NPMRDS data. Figure 4-8 displays the average truck speed in Twin Cities 8-county area during AM Peak Period in Nov. 2013 using NPMRDS data. The average truck speed derived from NPMRDS during PM Peak Period in Nov. 2013 is displayed in Figure 4-9. The average truck speed derived from NPMRDS in the Twin Cities 8-county area during PM Peak Period in Nov. 2013 is displayed in Figure 4-10.

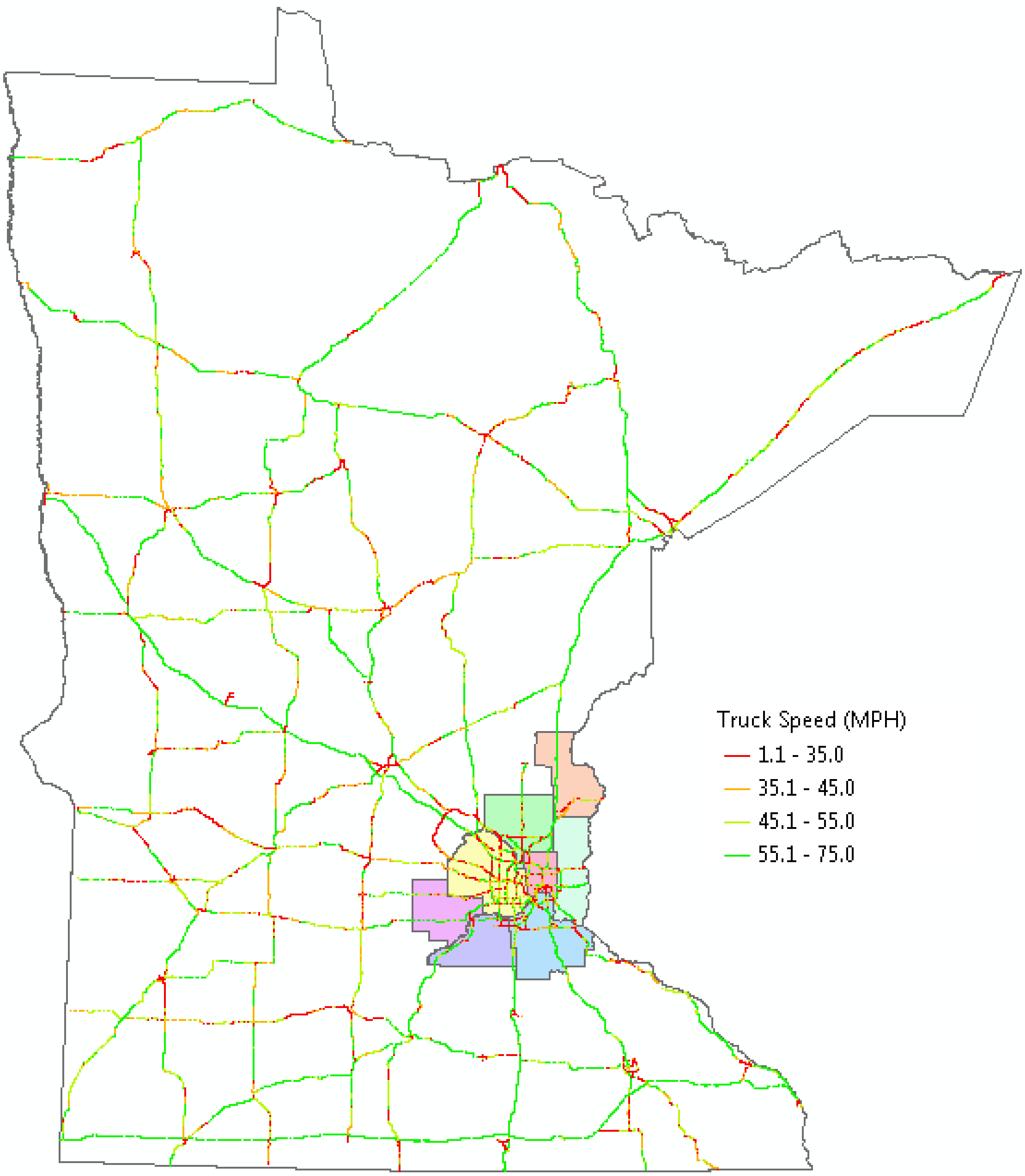


Figure 4-7 Average Truck Speed during AM Peak Period in Nov. 2013

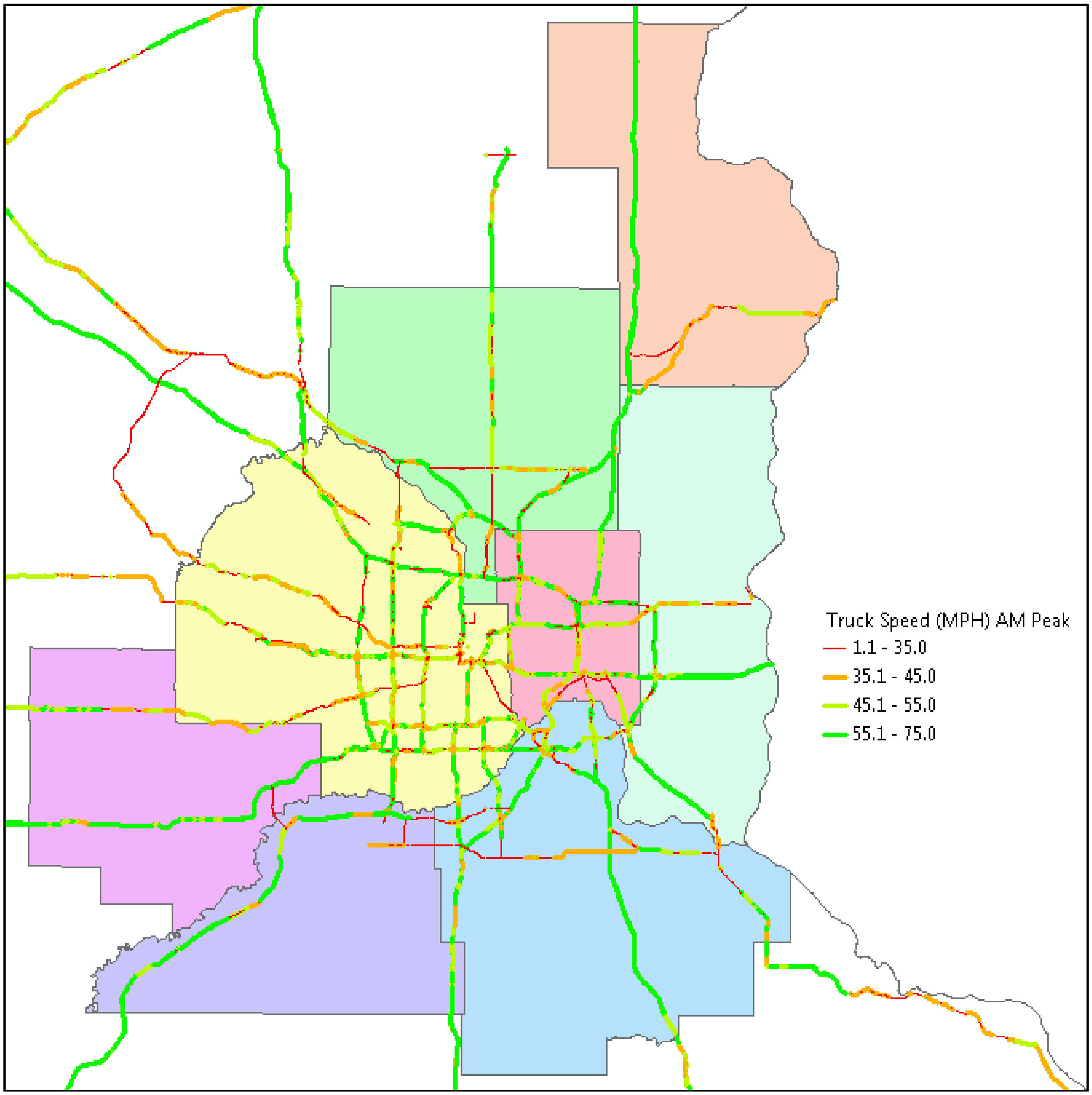


Figure 4-8 Average Truck Speed in TCMA during AM Peak Period in Nov. 2013

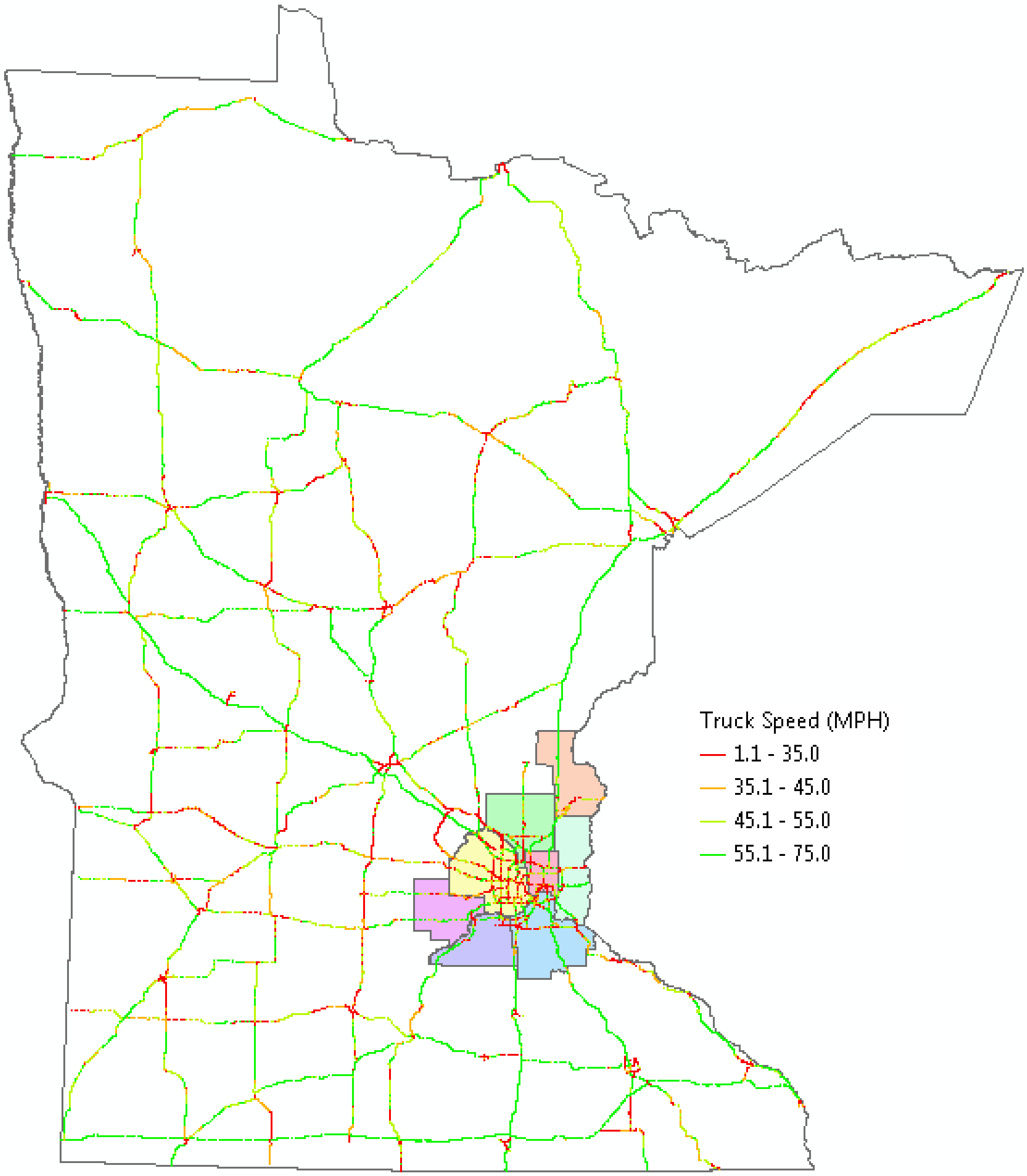


Figure 4-9 Average Truck Speed during PM Peak Period in Nov. 2013

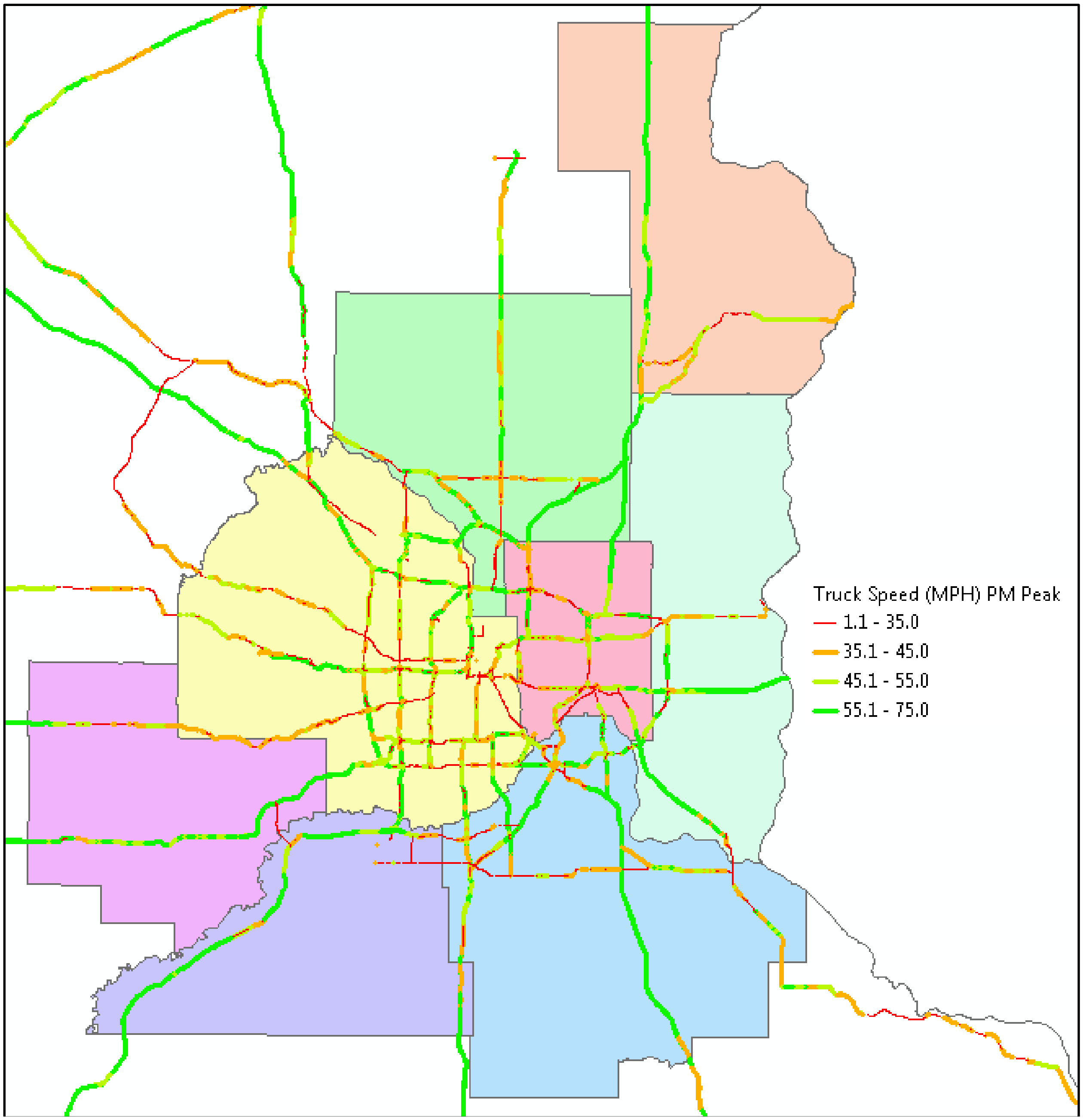


Figure 4-10 Average Truck Speed in TCMA during PM Peak Period in Nov. 2013

5. SUMMARY AND CONCLUSIONS

Accurate and reliable data on freight activity is vital for freight planning, forecasting, and decision making on infrastructure investment. Integrating freight flow, demand, and truck travel time information provides essential parameters to support a comprehensive freight or truck model. In addition to the data currently collected by public agencies, various types of truck data are regularly collected by private companies for logistic planning and operations. Private data is generally more difficult to obtain and requires substantial effort to coordinate and to fuse different data type from various sources. The partnership between the ATRI and the data providers presents opportunities for developing relevant measures for truck performance on highways. For example, the truck mobility measure could be used to identify surface freight congestions and capacity bottlenecks.

Building on our previous efforts to analyze freight mobility and reliability, a data processing and analysis methodology was developed to study the freight performance of trucks along 38 freight corridors in the Twin Cities metro area (TCMA). To ensure the accuracy of the computed truck traveling speed and traffic flow data, it is necessary to compare and validate the derived performance measures with general traffic data collected by the state DOTs. Particularly in urban area, satellite receptions may be limited and traffic congestions are more common. Truck speed and hourly volume percentage computed from GPS data were compared with data from weigh-in-motion (WIM) stations and automatic traffic recorder (ATR) devices for quality and reliability verification.

Several performance measures, such as truck mobility and delay and the reliability index, were computed and statistically analyzed by route, roadway segment (1-mile), and time of day. In addition, the research team identified key freight corridors by comparing percentage of miles with HCAADT greater than 7,500 and HCAADT per lane greater than 1,500 in the TCMA. Truck bottlenecks were also identified and ranked based on delay hours and number of hours with speed less than the target speed during the AM and PM peak periods.

After generating truck performance measures, the research team also identified truck bottlenecks by comparing the average truck delay per mile in the TCMA. In addition to the delay based approach, the research team evaluated truck bottlenecks based on number of hours in peak periods with speed less than target speeds.

Regarding freight corridors, the interstate highway I-94, I-694, I-494, and I-35W in the TCMA carry the highest freight movement and activities. Two mobility measures, (1) average speed, and (2) number of hours in peak periods with average speed below threshold speed, were used to analyze the freight mobility in the TCMA. The second measure helps identify the intensity of truck congestion in AM and PM peak periods.

To measure network reliability, an 80^{th} percentile travel time reliability index (RI) was used to measure the reliability of the 38 freight corridors. The reliability measure was further divided into three categories: reliable (RI < 1.5), moderate reliable ($1.5 \leq RI < 2.0$) and unreliable ($RI \geq 2.0$) to visualize the system performance. I-94 eastbound into downtown Minneapolis, TH-36 westbound after I-35E, and I-35E between I-494 & I-94 in AM have some of the least reliable congestion in TCMA. In PM peak hours, I-94 westbound before Lowry tunnel, I-94 eastbound into downtown St. Paul, I-494 eastbound before I-35W, TH62 between I-35W and TH-100, and TH-36 eastbound at TH-280 have some of the least reliable congestion in TCMA

The top 5 locations in TCMA with significant truck delays during the combined AM and PM peak periods were identified. Most of the bottleneck locations are nearby an interchange. I-494 EB at between TH-169 and I-35W has the highest combined truck delay of 55.9 hours on a weekday. I-394 EB to downtown Minneapolis has the second highest truck delay of 26.2 hours in combined AM & PM peaks. The third highest truck delay (25.2 hours) occurs at I-494 SB south of I-94 in Maple Grove.

In addition to performance measures, the cost of traffic mobility deficiencies as a means of expressing the financial impact of congestion can be estimated. These congestion cost measures can have utility to both transportation decision-makers and system users if they accurately reflect the tangible costs of transportation use on congested facilities.

The annual Urban Mobility Report (UMR) produced by Texas Transportation Institute (TTI) measures the costs of congestion at both the national and the local levels. The 2012 report estimated that the overall cost of congestion in the United States was $121 billion in 2011 based on wasted fuel and lost productivity. In Minneapolis-St. Paul, MN area, annual truck congestion cost was $232 million and the total congestion cost was $1.26 billion in 2011. Cost of truck congestion used in the 2012 UMR was $88 per hour. The American Transportation Research Institute (ATRI) has conducted an analysis to assess the operational costs of truck delays since 2008. The recent update of the ATRI study in 2013 reported that the total marginal costs for the industry across all sectors, fleet sizes and regions were $1.63 per mile and $65.29 per hour in 2012.

Of the 38 corridors studied in this project, several of them are county roads or state highways with traffic signals. Total truck congestion cost in the TCMA was about 0.8 million per weekday using the ATRI's operation cost per hour. The corresponding annual congestion cost was $212 million (assuming no delays on weekends). When using the TTI's congestion cost rate, the total truck congestion cost in the TCMA was about 1.1 million per weekday with corresponding annual congestion cost around $286 million (assuming no delays on weekends). Using the simple cost calculation methodology, daily or annual truck congestion cost measures can be derived by applying industry operating cost rate to truck delays derived from empirical truck speed/time data at a corridor level or in a region.

The FHWA recently announced National Performance Management Research Data Set (NPMRDS), which includes probe vehicle based travel time data (for both passenger and freight vehicles) for all National Highway System (NHS) facilities. The NPMRDS will provide useful data resources for transportation agencies to systematically monitor roadway performance using a comprehensive and reliable set of measures developed by the agencies. This report also explored the feasibility of using one month (November 2013) of NPMRDS data in Minnesota to compute freight mobility and speed variations along Minnesota's NHS during the AM and PM peak periods.

Freight performance analysis using GPS data from heavy commercial vehicles presents opportunities to support surface freight planners in identifying freight bottleneck, infrastructure improvement needs, and operational strategy that promotes efficient freight movement. The resulting performance measures, including truck mobility and delay and the reliability index, indicated that the measures derived using truck GPS data are useful to support the USDOT performance measure initiative. They can also be used to support regional freight planning and decision making on future infrastructure investment.

6. FUTURE RESEARCH OPPORTUNITIES

The truck GPS data from ATRI is limited to data collected from onboard communications equipment installed on commercial trucks (e.g. vehicle class 9 through 13 with tractor-trailer combinations). There is an opportunity to conduct data collection and analysis for smaller trucks, including single-unit trucks which handle a large portion of local freight deliveries throughout the metro area.

MnDOT recently set up a Wavetronix test unit in the TCMA (I-94 in St. Paul) to evaluate the performance of solar panels and battery life. Wavetronix collects traffic by bins. They are able to collect 8 bins. It is possible to collect individual vehicle speed and class, but the units do not have enough storage to retain the per vehicle data. The Wavetronix unit has to either be connected directly to an IP address or a computer to store individual vehicle data.

Currently, most of the automatic traffic recorders and WIM sensors that collect vehicle speed and classification counts are located on the metropolitan freeway system outside the I-494/694 ring in the TCMA. However, truck movements on these highways could be very different than those on the freeway system.

It is likely that movements of trucks within the I-494/694 ring are more complex, more local, serve more origins and destinations directly, and involve a greater share of truck trips made by independent truckers or smaller trucks (for which data are not necessary captured by current GPS data set), and are impacted by more frequent and more severe congestion than trucks travelling outside the I-494/694 ring.

Due to these differences, there is a need for more comprehensive truck classification count data on the metropolitan highway system (i.e., freeways) within the I-494/I-694 ring during the most congested periods of the day. More comprehensive truck classification and speed data on the congested freeway segments within the ring would create a better data set from which to verify GPS speed and freight activities in the core areas of the metro.

Another opportunity is to leverage the coverage and availability of the national performance measure research data set (NPMRDS) on the national highway system (NHS). Additional GPS data can be collected to cover the local highways and key freight corridors for performance monitoring and planning.

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APPENDIX A: FREIGHT PERFORMANCE MEASURES

Suggested Freight Performance Measures for an Emerging User (Schofield & Harrison, 2007)

Table A-1 Suggested Freight Performance Measures

Category	Potential Indicators
Mobility	Intercity Travel Times
	Average Speed on Freeways, by Route and Time of Day
	Major City Congestion Levels Compared to Other Metro Areas
	Volume/Capacity of All Vehicles on Freeway Segments
Reliability	Deviation of Travel Times or Speeds from the Average
	Density of Nonrecurring Delays
	Portion of On-Time Motor Carrier Arrivals
Economic	State Transportation Investment vs. Gross State Product
Public Impact	Emissions
	Freight Related Accident Rates
Infrastructure	Pavement and Bridge Quality
	Delay at Border Crossings

APPENDIX B: RELIABILITY MEASURES

List of Reliability Measures (Lomax et al., 2003; Pu, 2011)

Here is a list of reliability measures found in the literature.

- Percentile, For example, $P(80\%)$ for 80th percentile.
- Standard Deviation (σ), Median and Mean (μ)
- Coefficient of Deviation (C_σ)

$$C_\sigma = \frac{\sigma}{\mu}$$

- Percent Deviation (C_p)

$$C_p = C_\sigma \times 100\%$$

- Skew Statistics (S_k)

$$S_k = \frac{P(90\%) - \text{median}}{\text{median} - P(10\%)}$$

- Mean Based Buffer Index (BI_μ)

$$BI_\mu = \frac{P(95\%) - \text{mean}}{\text{mean}}$$

- Median Based Buffer Index (BI_m)

$$BI_m = \frac{P(95\%) - \text{median}}{\text{median}}$$

- Planning Time Index (PTI)

$$\text{PTI} = \frac{P(95\%)\ \text{TT}}{\text{free\_flow TT}}$$

- Travel Time Index (TTI)

$$\text{TTI} = \frac{actual\ \text{TT}}{\text{free\_flow TT}}$$

- Frequency of Congestion (F_c)

F_c: Probability that TT ≥ 2× free_flow TT

- Failure Rate (or Percent On-Time Rate):
100% - % of on-time arrival

Note[1]: The Urban Congestion Report suggests,

- Using 15 percentile travel time as free-flow travel time
- Using 95 percentile travel time for calculating planning time index
- Using 45 mph as the threshold for computing congestion delay

[1] The Urban Congestion Report (UCR): Documentation and Definitions, http://www.ops.fhwa.dot.gov/perf_measurement/ucr/documentation.htm

APPENDIX C: WEIGH-IN-MOTION (WIM) DATA

A listing ASCII vehicle data records as collected and stored by the system, including diagnostic and calibration records. A file in this format may be used as input to other data processing programs. Each record ends with a carriage return (ASCII code 013); fields are delimited by commas. Each record will contain between 47 and 67 fields. Fields without data are filled with zeroes, with the exception of the external data tag and external information fields, which have a null entry if there is no data (the field delimiting commas will still be present). The external data tag and external information fields are optional; if present they always appear as a pair. There may be between 0 and 10 pairs of external data/information fields; the number of pairs used will be determined by the requirements of the data collection site, but will be a fixed number for that site.

The data fields include:

- year,
- month,
- day,
- hour,
- minute,
- second,
- error number,
- status code
- record type,
- lane,
- speed,
- class,
- length,
- GVW,
- ESAL,
- weight axle 1,
- axle spacing 1-2,
- weight axle 2,
- axle spacing 2-3,
- weight axle 3,
- axle spacing 3-4,

…

- weight axle 13,
- axle spacing 13-14,
- weight 14,
- External data tag 1 (optional), External information 1 (optional),

…

- External data tag n (optional), External information n (optional),
- temperature

The sample below is a report listing raw ASCII records of vehicle data for a 3 minute period starting at 12:00 PM on May 15, 2012 at WIM station #39:

```
12,5,15,12, 0, 8,0,00000000,12,1,54,9,61,74.4,1.7040,12.0,14.5,16.8,4.4,15.7,29.8,14.2,4.7,15.8,0.0,. . . ,,,91
12,5,15,12, 0,13,0,00000000,12,1,50,2,15,3.0,0.0004,1.6,8.7,1.4,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 0,21,0,00000000,12,1,48,3,18,5.5,0.0013,3.2,11.6,2.4,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 0,58,0,00000000,12,1,47,2,15,4.2,0.0013,3.0,9.0,1.2,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
```

```
12,5,15,12, 1, 9,0,00000000,12,1,17,2,12,4.2,0.0004,2.1,8.9,2.1,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 1,22,0,00000000,12,2,45,9,57,71.9,1.6885,10.5,12.8,14.1,4.2,14.7,28.2,16.6,4.2,15.9,0.0,. . . ,,,91
12,5,15,12, 1,25,0,00000000,12,2,43,2,14,3.5,0.0004,2.0,8.6,1.5,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 1,27,0,00000000,12,2,45,2,18,3.2,0.0004,2.1,9.6,1.2,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 1,31,0,00000000,12,2,48,3,27,5.3,0.0013,3.0,12.0,2.3,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 1,33,0,00000000,12,2,47,2,16,3.0,0.0004,1.9,8.7,1.1,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 1,35,0,00000000,12,2,46,3,17,5.3,0.0013,3.3,9.9,2.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 1,39,0,00000000,12,2,48,5,15,7.4,0.0062,5.3,8.9,2.1,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 1,39,0,00000000,12,1,46,9,72,49.1,0.3365,10.8,16.4,9.3,4.3,9.0,36.4,9.9,4.2,10.0,0.0,. . . ,,,91
12,5,15,12, 1,41,0,00000010,12,1,44,5,15,10.0,0.0612,8.5,9.6,1.5,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 1,48,0,00000000,12,1,51,2,15,3.5,0.0004,2.0,8.6,1.5,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 1,54,0,00000000,12,2,47,2,20,2.8,0.0004,1.9,8.7,0.9,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 1,57,0,00000000,12,1,52,2,16,3.9,0.0004,2.3,9.3,1.5,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 2,19,0,00000000,12,2,51,5,21,11.2,0.0160,5.4,13.0,5.9,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 2,23,0,00000000,12,1,60,3,17,3.5,0.0004,2.3,10.7,1.2,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 2,26,0,00000000,12,2,57,3,18,3.8,0.0004,2.3,10.0,1.5,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 2,27,0,00000000,12,2,58,3,13,3.8,0.0004,2.2,9.9,1.6,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 2,35,0,00000000,12,1,53,9,63,25.7,0.0992,10.0,18.5,5.8,4.3,5.1,29.9,2.1,4.1,2.6,0.0,. . . ,,,91
12,5,15,12, 2,38,0,00000000,12,1,52,5,24,11.0,0.0240,3.6,14.7,7.4,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 2,48,0,00000000,12,1,59,3,17,4.5,0.0013,2.6,10.0,1.9,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 2,58,0,00000000,12,1,52,2,5,2.0,0.0004,0.8,5.3,1.2,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 3,19,0,00000000,12,1,48,2,16,3.3,0.0004,2.0,9.2,1.3,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 3,20,0,00000000,12,1,50,3,18,4.7,0.0013,2.8,11.3,1.8,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 3,21,0,00000000,12,2,48,2,14,3.6,0.0004,2.1,8.8,1.5,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 3,23,0,00000000,12,2,48,2,17,3.7,0.0004,2.4,9.3,1.3,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 3,25,0,00000000,12,2,45,3,20,4.8,0.0013,2.2,11.2,2.6,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 3,28,0,00000000,12,2,48,3,18,4.0,0.0004,2.4,9.9,1.7,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 3,30,0,00000000,12,2,46,2,15,3.8,0.0004,2.2,8.6,1.5,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 3,31,0,00000000,12,2,46,3,19,5.6,0.0013,3.3,12.5,2.3,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 3,39,0,00000000,12,2,47,2,11,3.2,0.0004,1.7,6.7,1.5,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 3,43,0,00000000,12,1,58,2,17,3.6,0.0004,2.2,9.0,1.4,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 3,52,0,00000000,12,2,55,2,16,4.0,0.0004,2.0,8.7,2.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 4,14,0,00000000,12,2,46,6,38,24.2,0.0810,8.5,18.2,7.8,4.2,7.9,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 4,15,0,00000000,12,1,41,2,16,3.3,0.0004,2.1,9.3,1.2,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 4,17,0,00000000,12,2,44,2,15,2.7,0.0004,1.7,8.8,1.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 4,18,0,00000000,12,2,43,2,13,2.1,0.0004,1.4,8.7,0.8,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
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12,5,15,12, 4,19,0,00000000,12,1,48,5,23,15.5,0.0710,6.3,14.3,9.2,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 4,22,0,00000000,12,1,50,3,18,4.3,0.0004,2.5,11.2,1.8,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 4,31,0,00000000,12,1,47,9,50,26.0,0.0700,9.3,15.2,4.3,4.2,5.4,21.3,3.8,4.2,3.2,0.0,. . . ,,,91
12,5,15,12, 4,49,0,00001000,12,1,48,9,61,73.0,1.9270,7.7,18.0,17.5,4.3,17.6,28.9,14.2,4.1,16.1,0.0,. . . ,,,91
12,5,15,12, 4,52,0,00000000,12,1,45,2,17,3.8,0.0004,2.3,9.7,1.4,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 4,54,0,00000000,12,1,44,3,18,5.0,0.0013,3.3,10.5,1.7,0.0,0.0,0.0,0.0,0.0,0.0,0.0,. . . ,,,91
12,5,15,12, 4,58,0,00000000,12,1,45,9,56,27.9,0.0745,9.4,13.7,6.0,4.7,4.8,27.9,2.5,4.0,5.3,0.0,. . . ,,,91
```

APPENDIX D: DATA ANALYSIS AND COMPARISONS

D.1 ATRI Data Distribution

The pie graph displayed in Figure D-1 illustrates the percentage of ATRI GPS data distribution by vehicle configuration. The ATRI data consists of 5-axle dry van 35%, 5-axle refrigerated 19%, 5-axle flatbed 10%, axle-tanker 21%, straight truck 6%, and other trucks 9%.

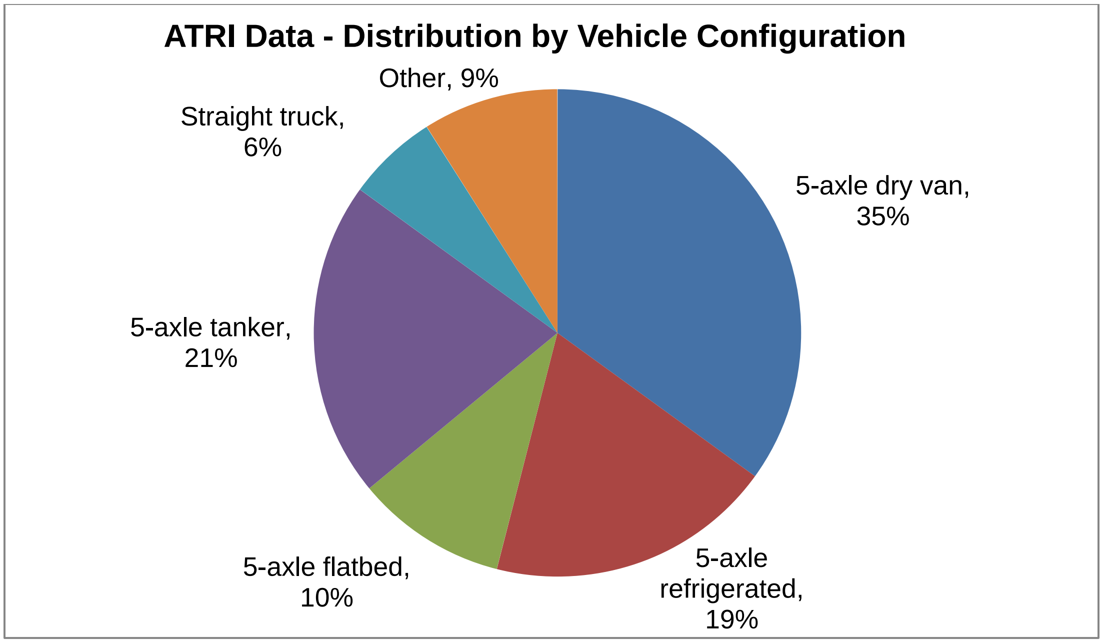

Figure D-1 ATRI Data Distribution by Vehicle Configuration

The pie graph displayed in Figure D-2 illustrates the percentage of ATRI data distribution by fleet size. The ATRI data consists of very large fleet 46%, large fleet 26%, medium fleet 18%, and small fleet 10%.

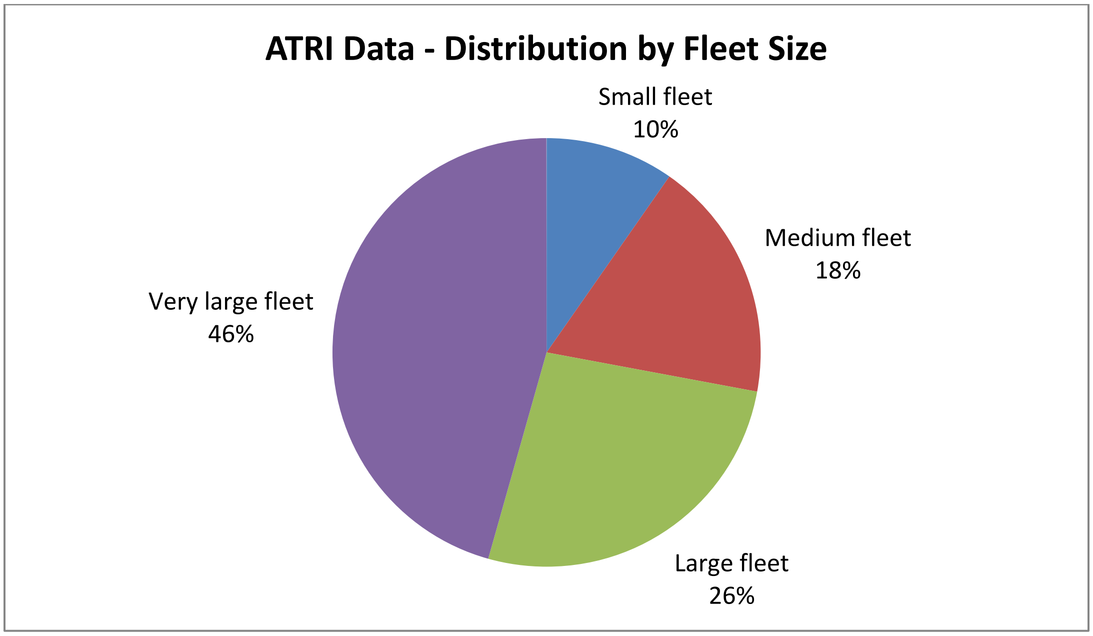

Figure D-2 ATRI Data Distribution by Fleet Size

D.2 Truck GPS Data Distribution by Route

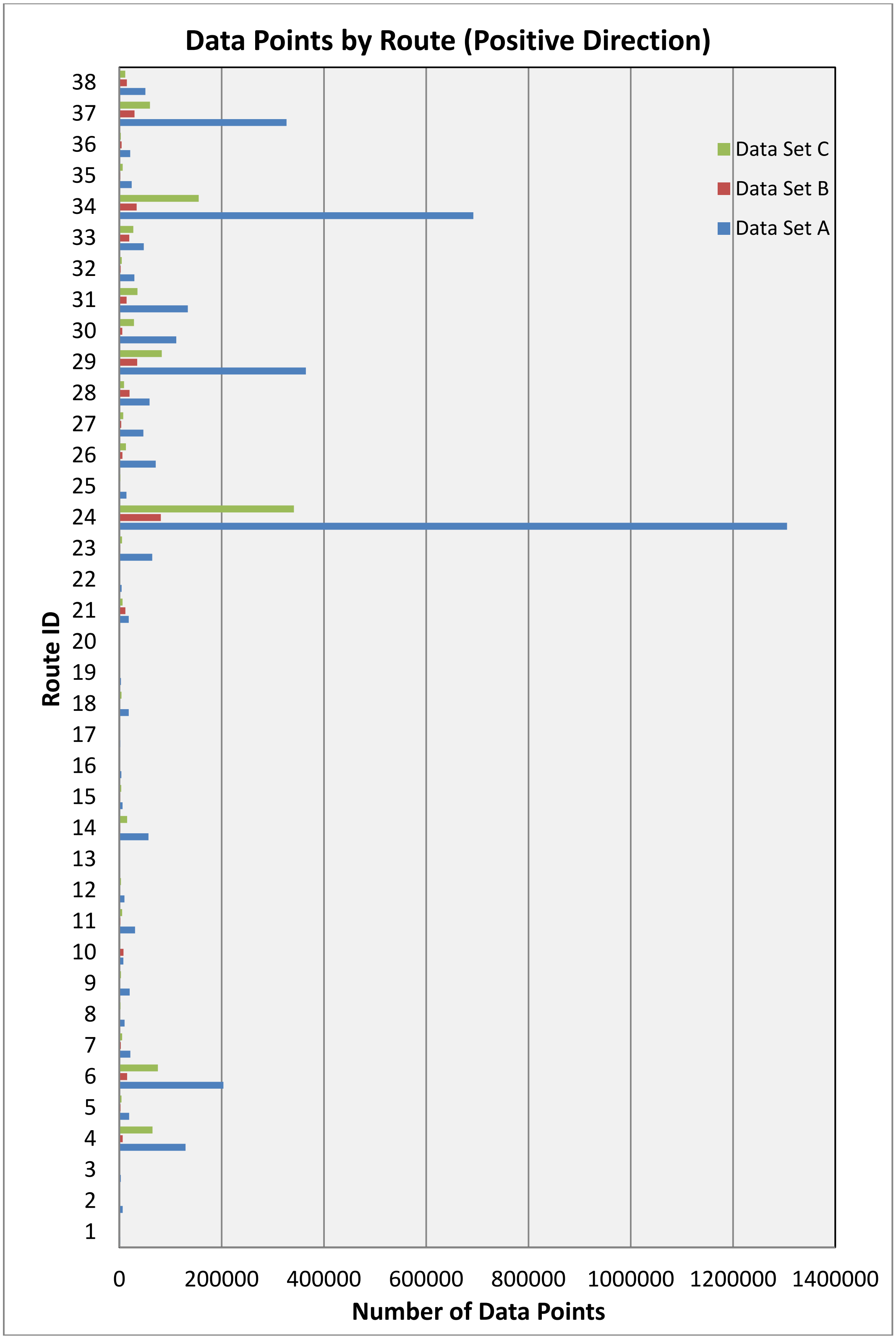

Figure D-3 GPS Point Distribution by Route (Positive Direction)

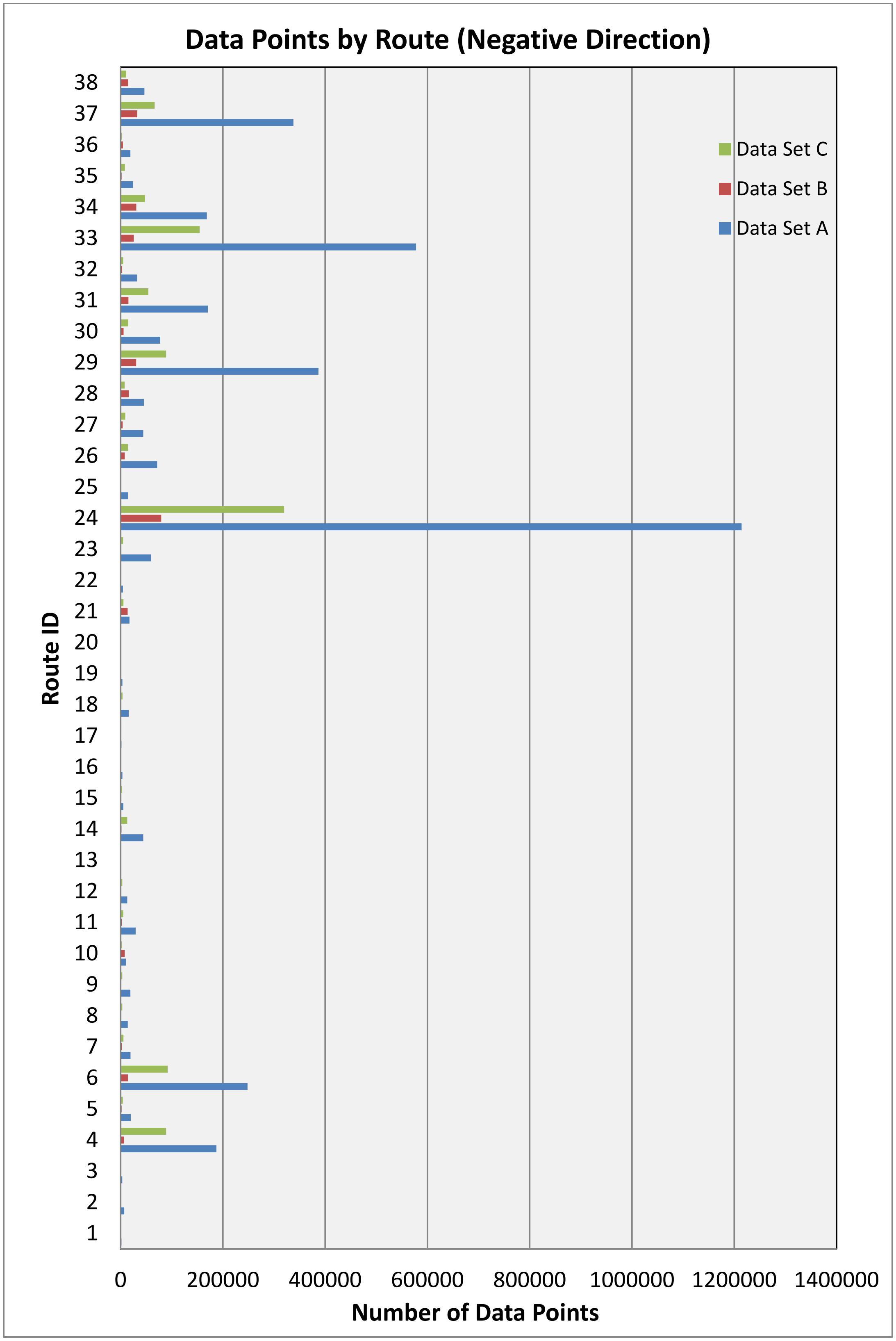

Figure D-4 GPS Point Distribution by Route (Negative Direction)

D.3 Data Proximity by Route

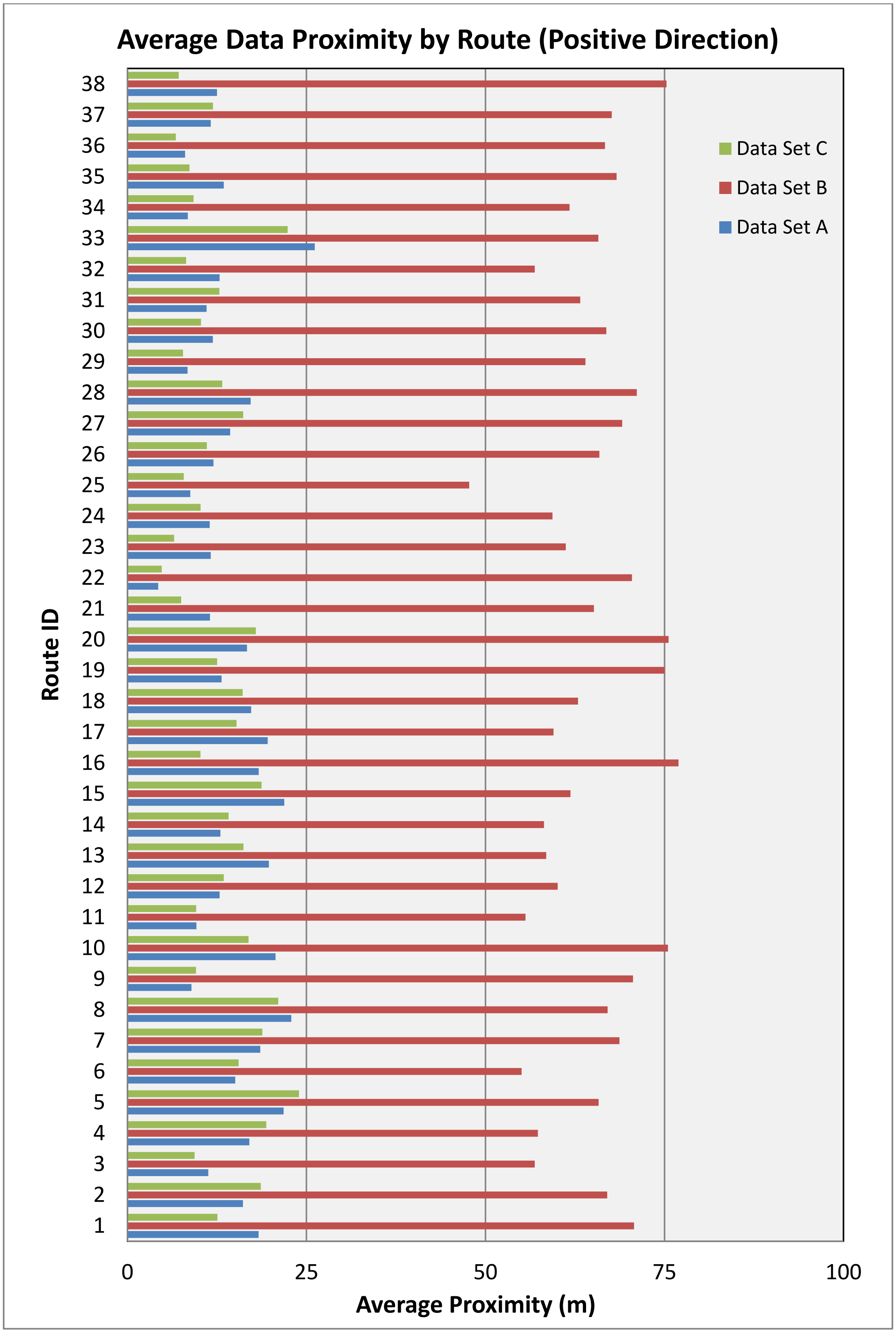

Figure D-5 Data Proximity by Route (Increasing Mile Marker Direction)

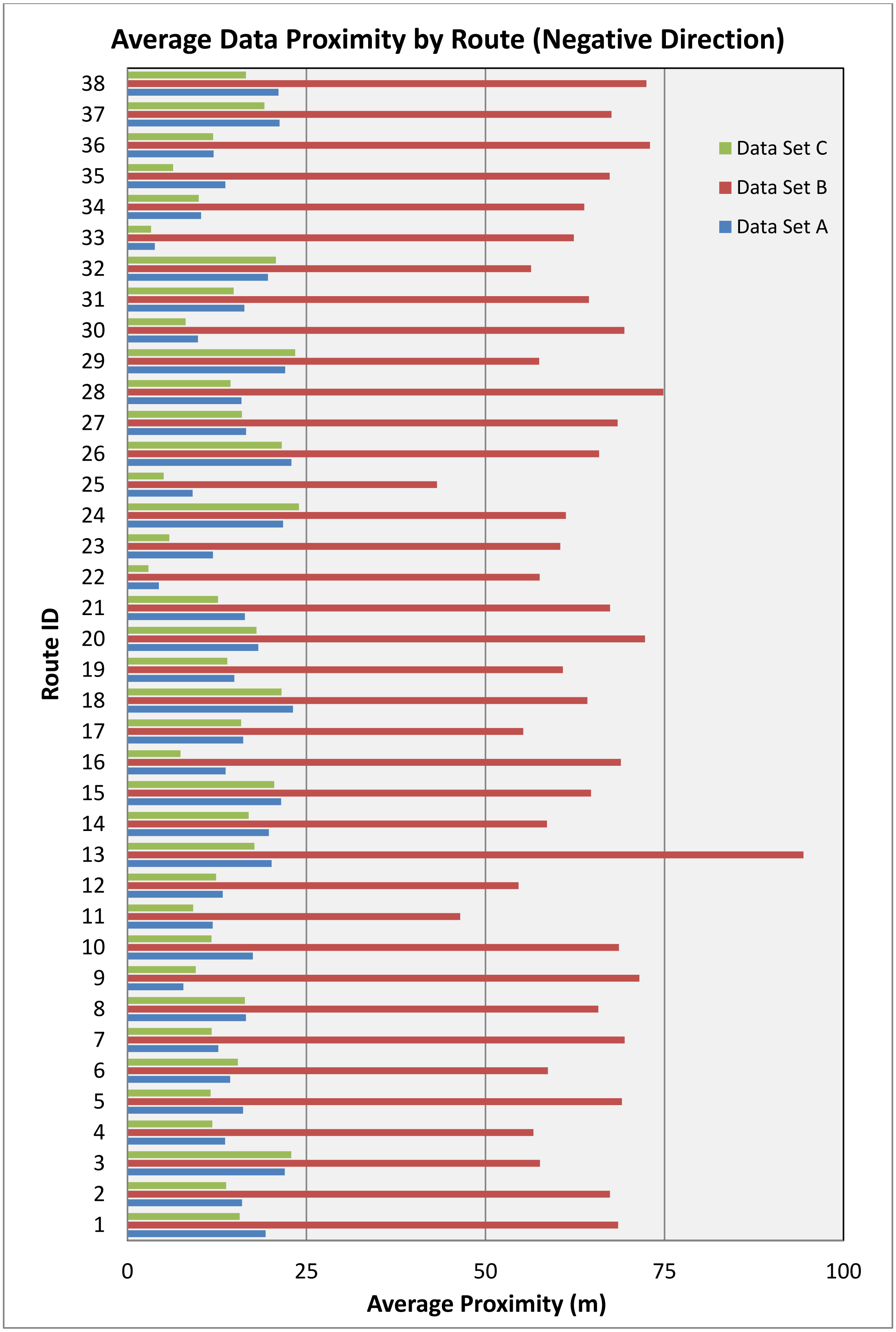

Figure D-6 Data Proximity by Route (Decreasing Mile Marker Direction)

D.4 Point vs. Space Mean Speed Comparisons

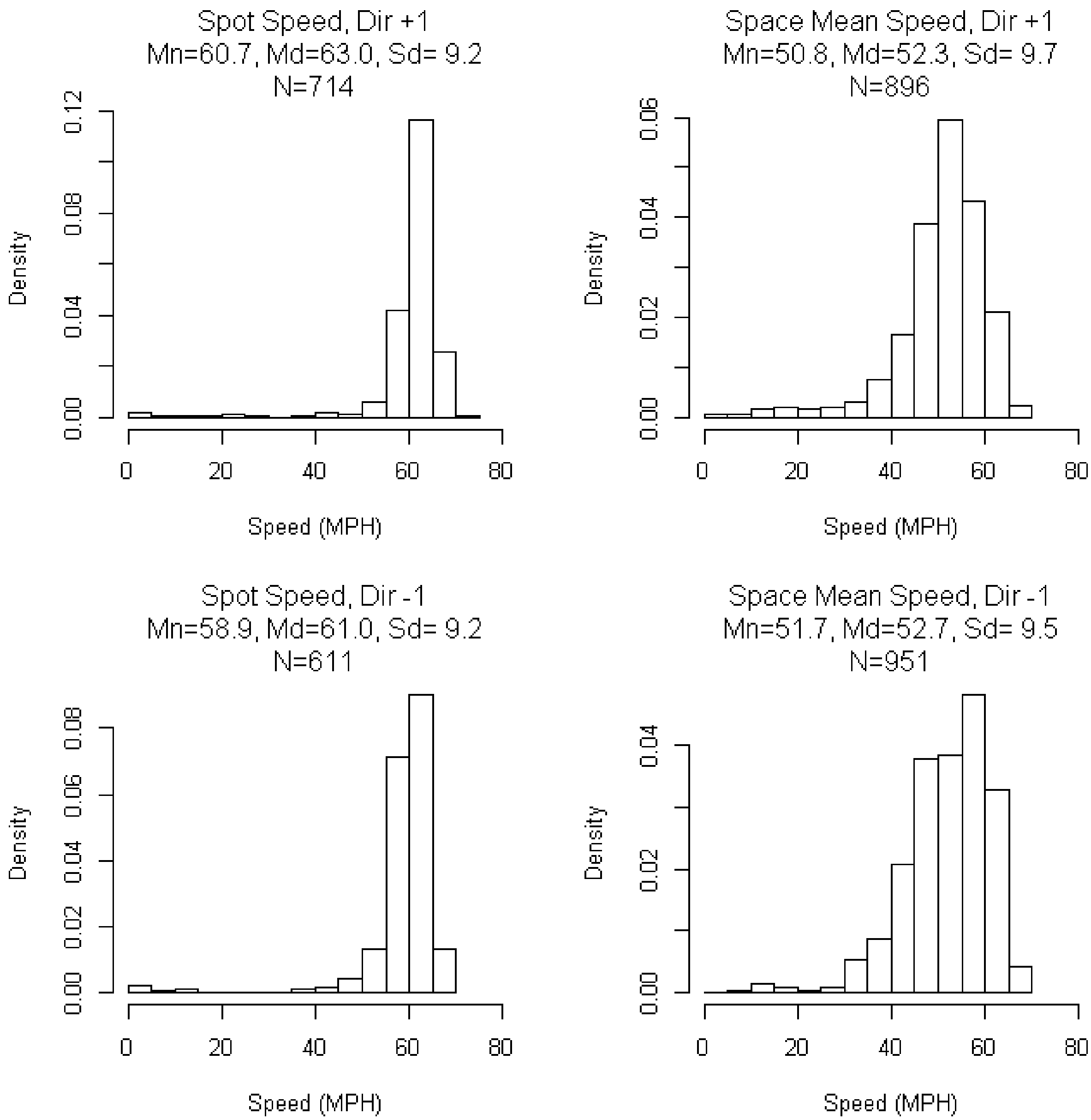

Figure D-7 Spot Speed vs. Space Mean Speed on Route State Highway 36 at Mile Post 15

(Nearby Lake Elmo, WIM#36)

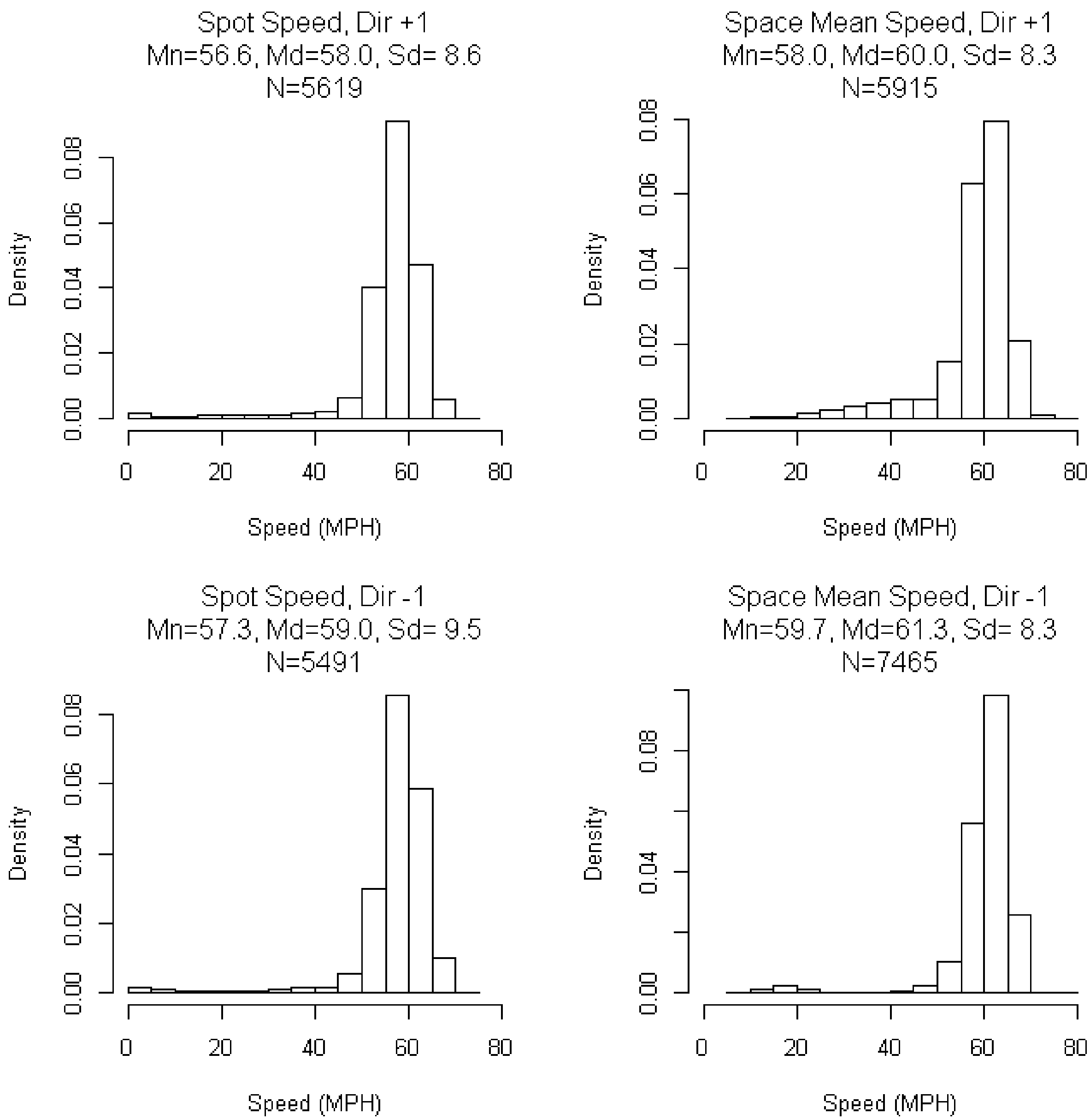

Figure D-8 Spot Speed vs. Space Mean Speed on Route U.S. Highway 52 at Mile Post 81

(Nearby CSAH14 in West St. Paul, WIM#40)

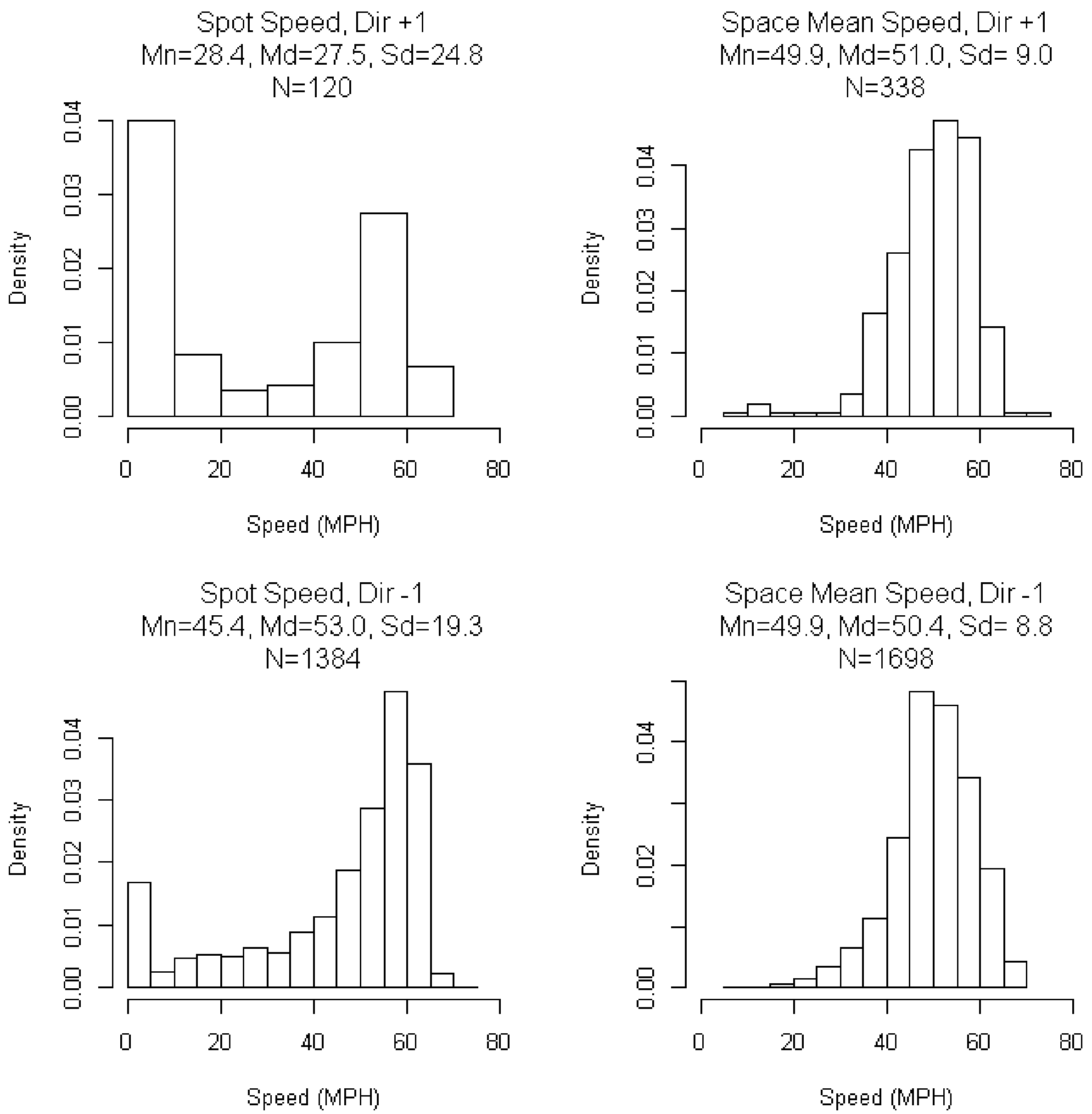

Figure D-9 Spot Speed vs. Space Mean Speed on Route U.S. Highway 61 at Mile Post 16

(South of TH95 in Cottage Grove, WIM#42)

D.5 Probe Vehicle vs. WIM Speed Comparisons

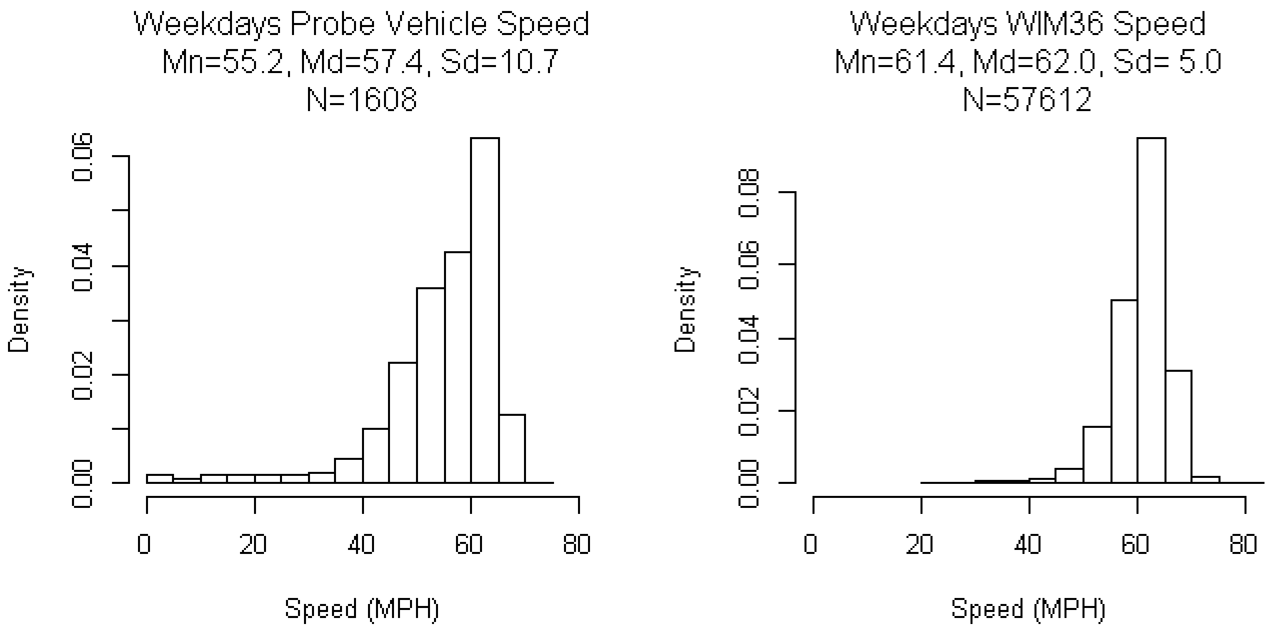

Figure D-10 Probe Vehicle Speed vs. WIM Speed at WIM#36

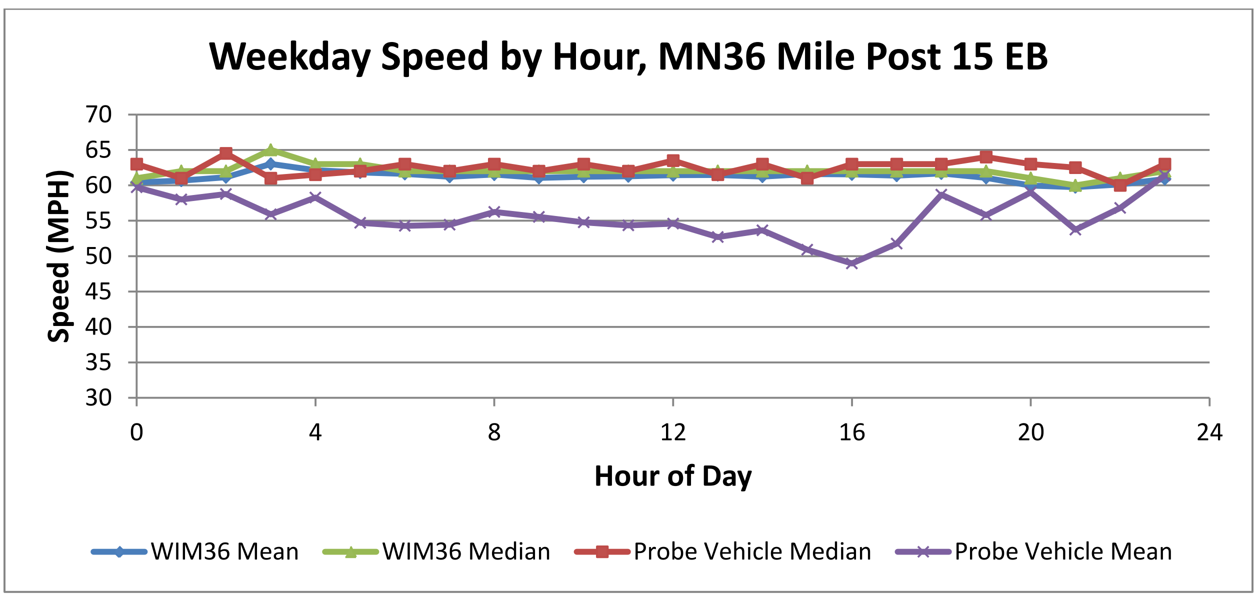

Figure D-11 Probe Vehicle Median Speed vs. WIM Speed by Hour at WIM#36

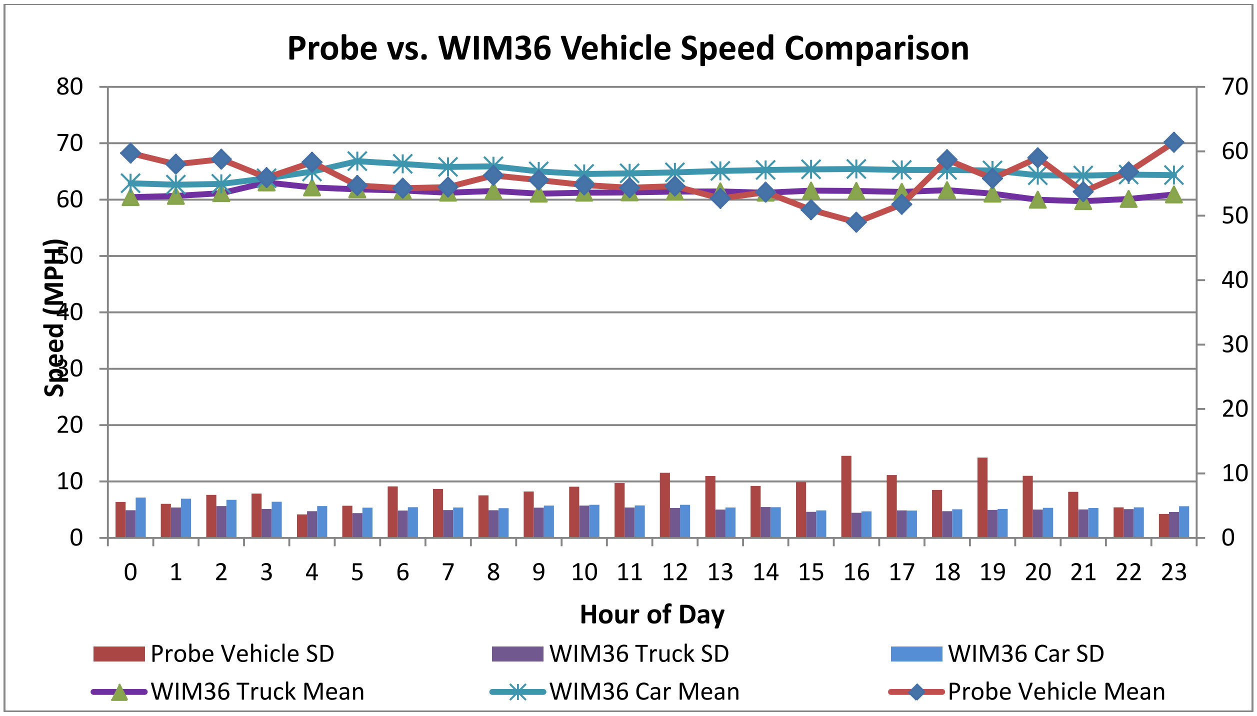

Figure D-12 Probe Vehicle Speed vs. WIM Speed by Hour at WIM#36

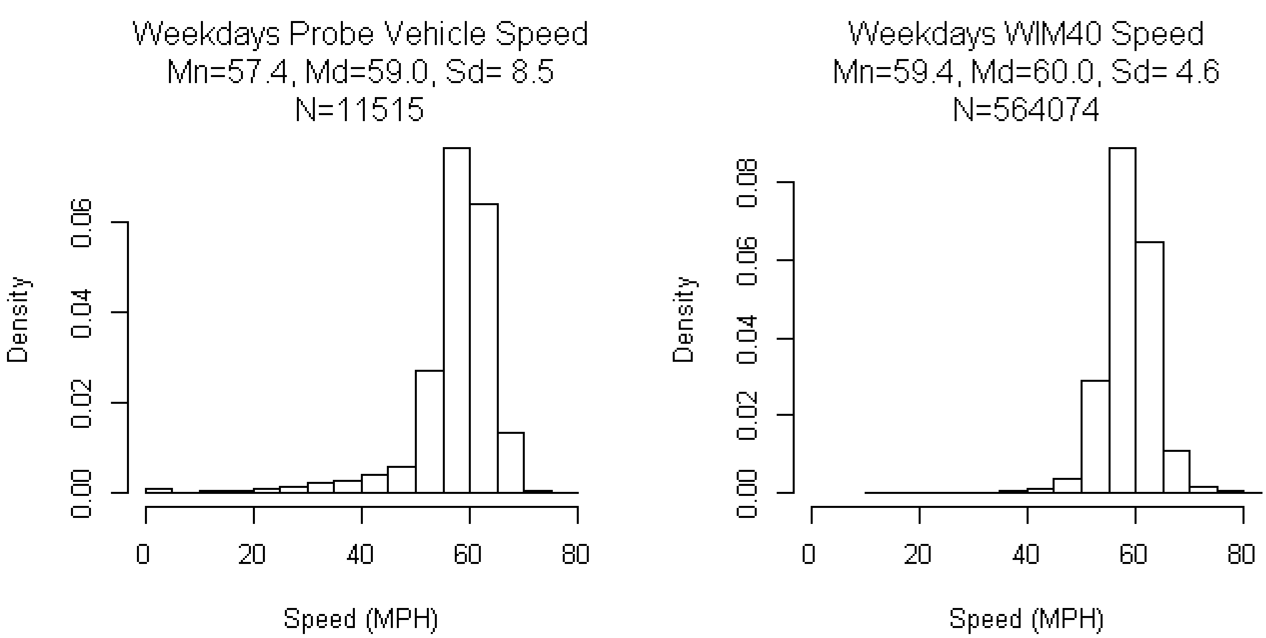

Figure D-13 Probe Vehicle Speed vs. WIM Speed at WIM#40

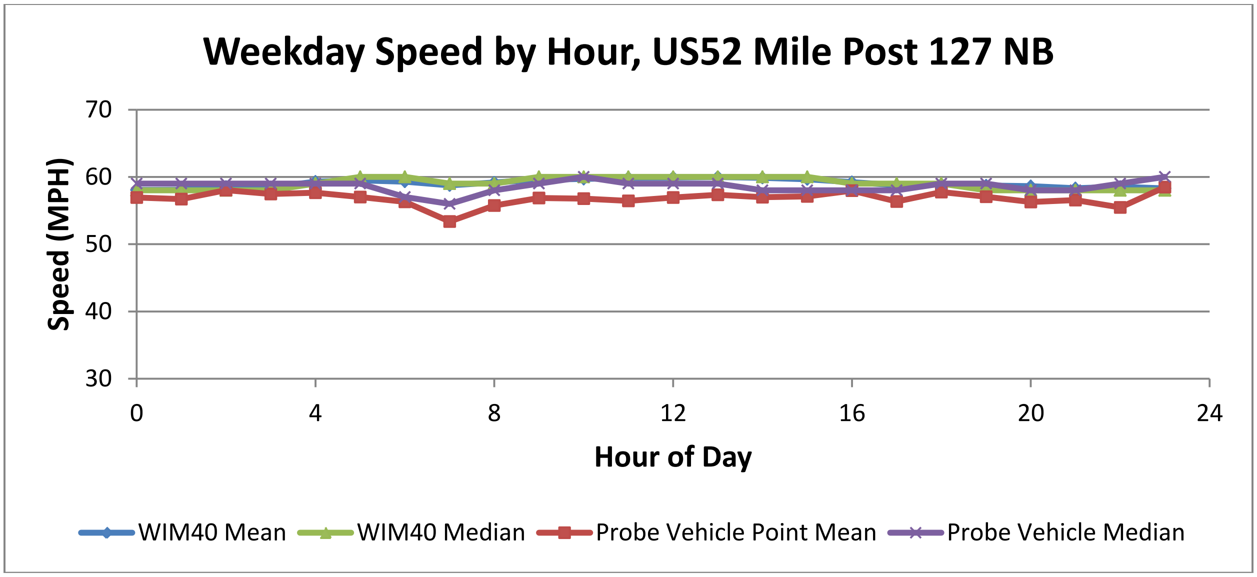

Figure D-14 Probe Vehicle Median Speed vs. WIM Speed by Hour at WIM#40

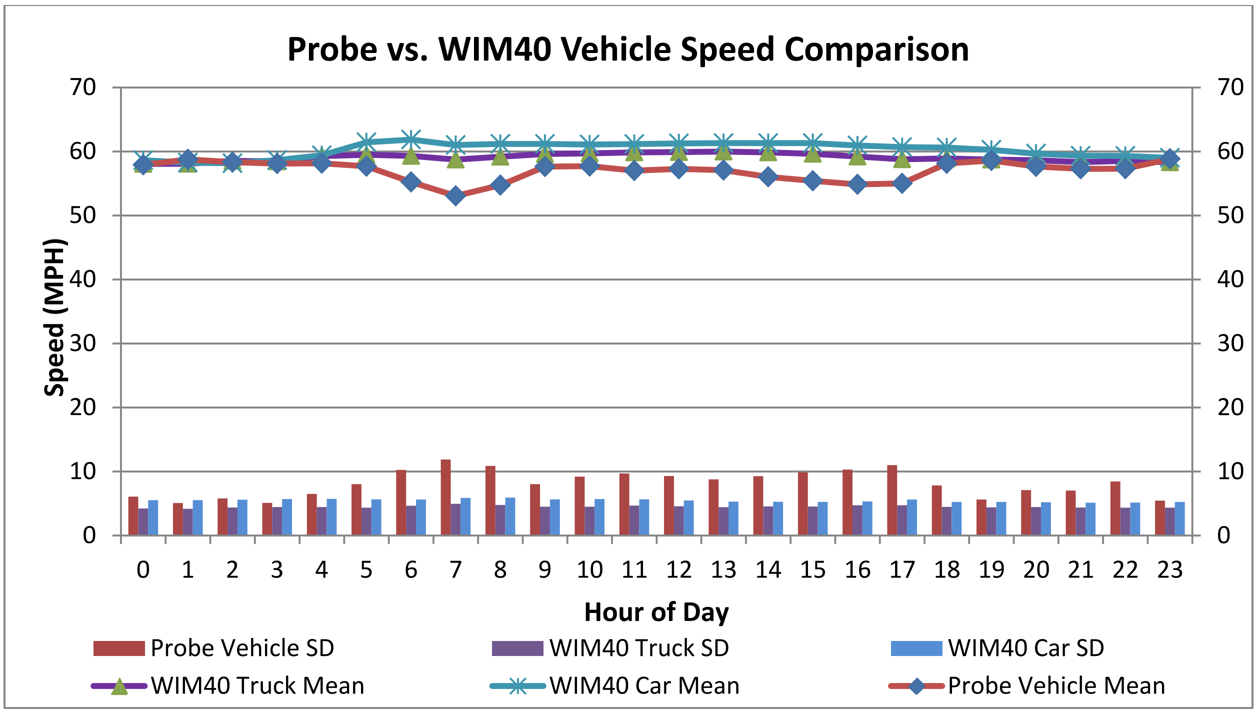

Figure D-15 Probe Vehicle Speed vs. WIM Speed by Hour at WIM#40

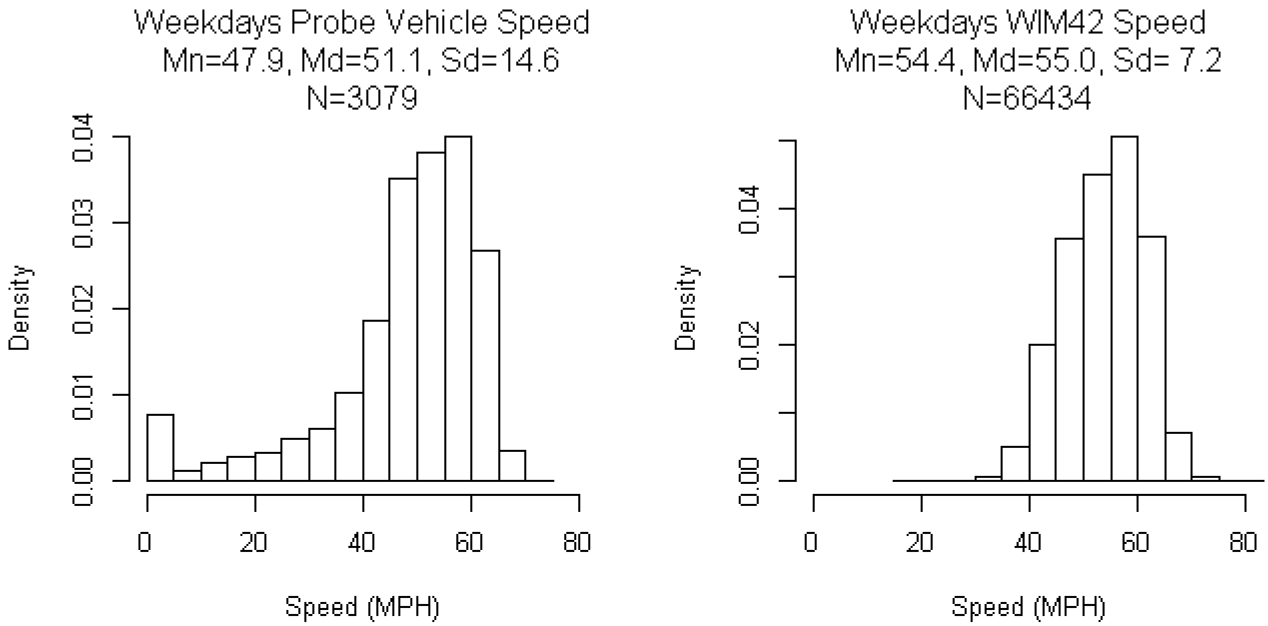

Figure D-16 Probe Vehicle Speed vs. WIM Speed at WIM#42

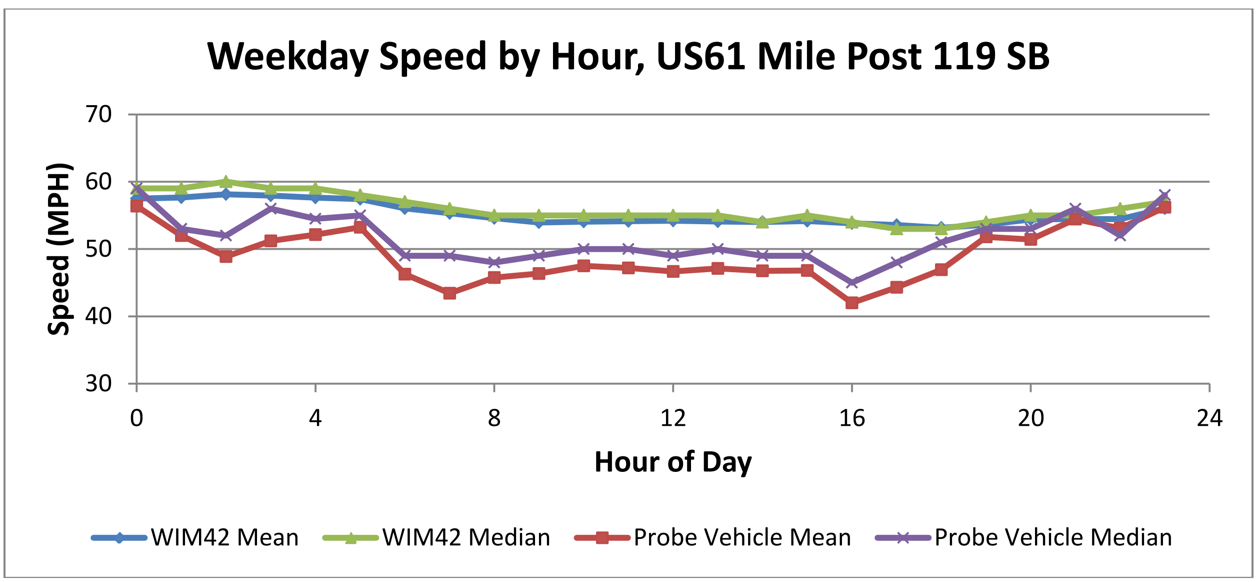

Figure D-17 Probe Vehicle Median Speed vs. WIM Speed by Hour at WIM#42

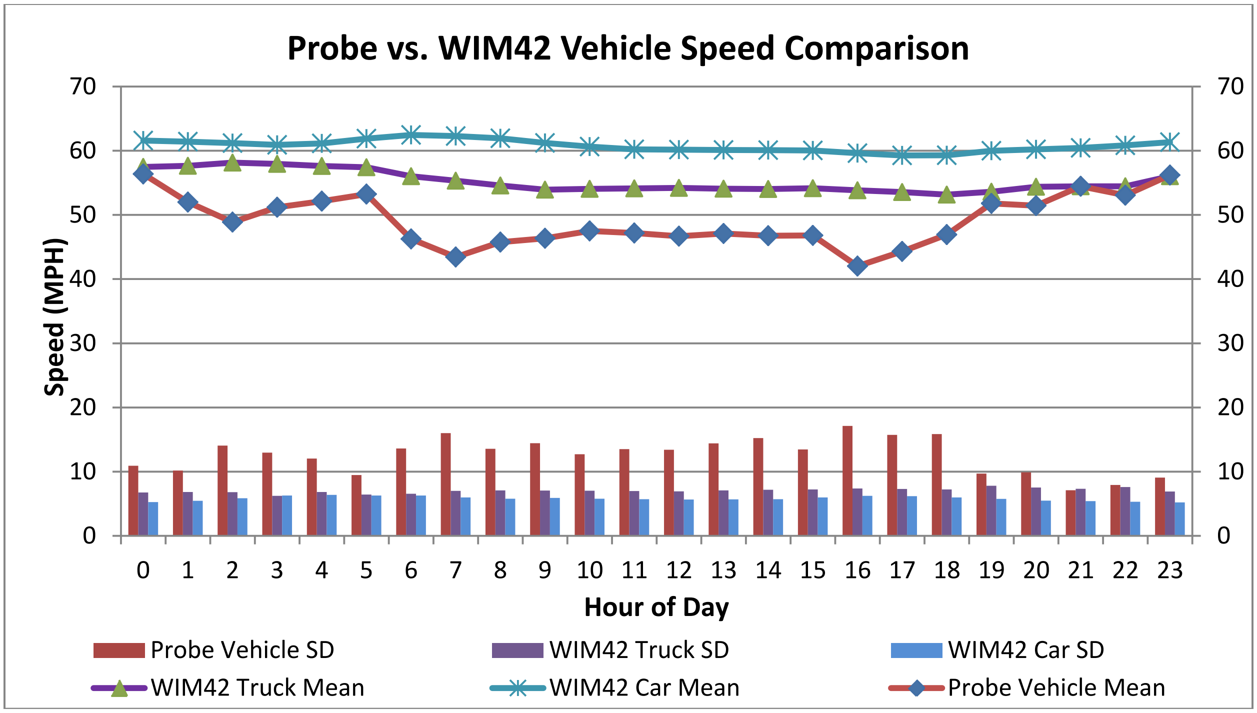

Figure D-18 Probe Vehicle Speed vs. WIM Speed by Hour at WIM#42

D.6 Probe Vehicle vs. WIM Heavy Vehicle Speed by Month and Hour

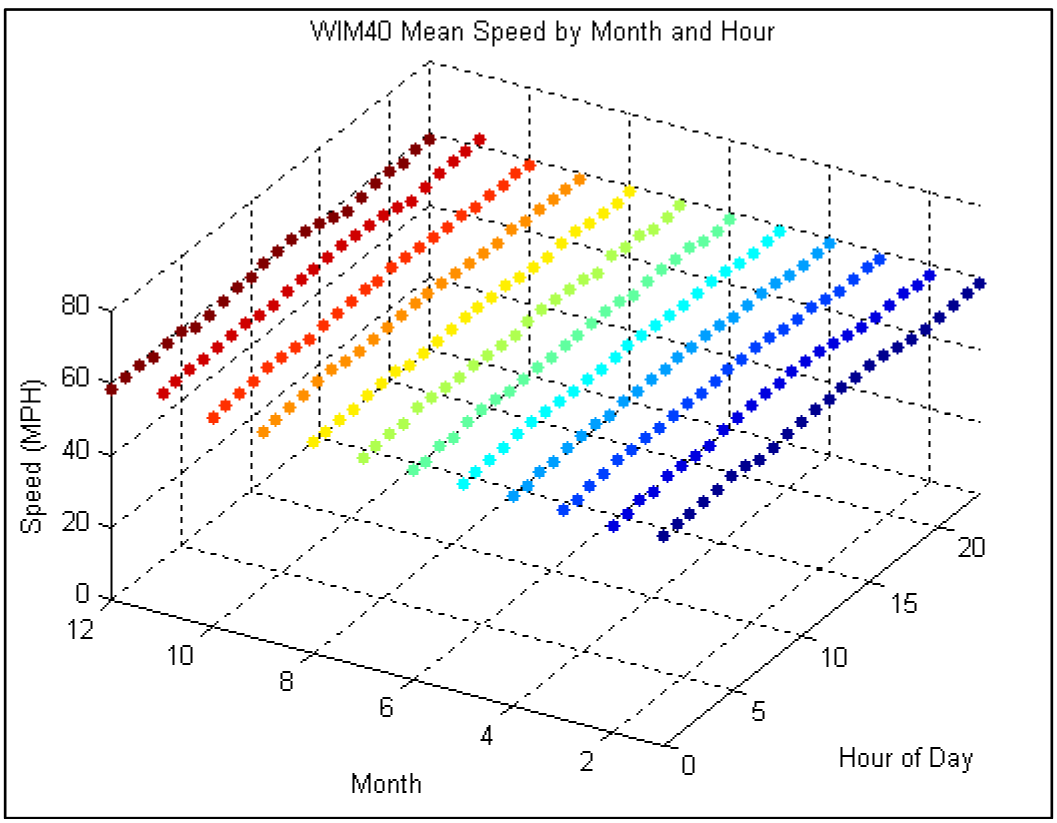

Figure D-19 WIM40 Heavy Vehicle Mean Speed by Month and Hour

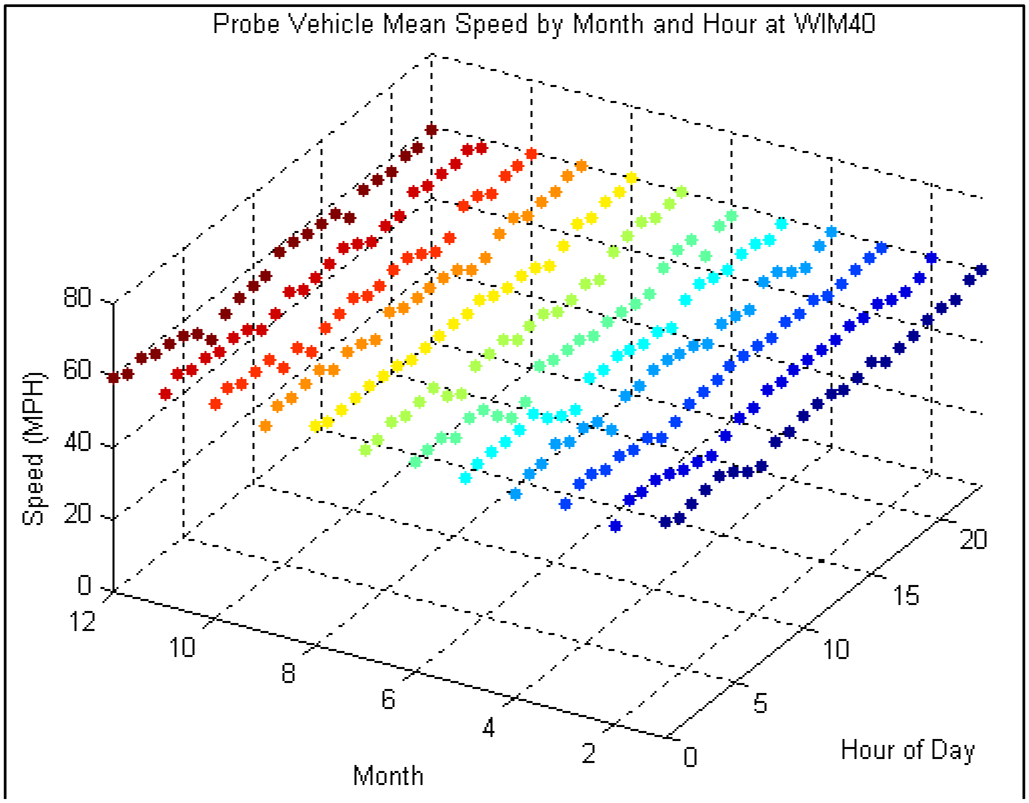

Figure D-20 Probe Vehicle Mean Speed by Month and Hour at WIM40

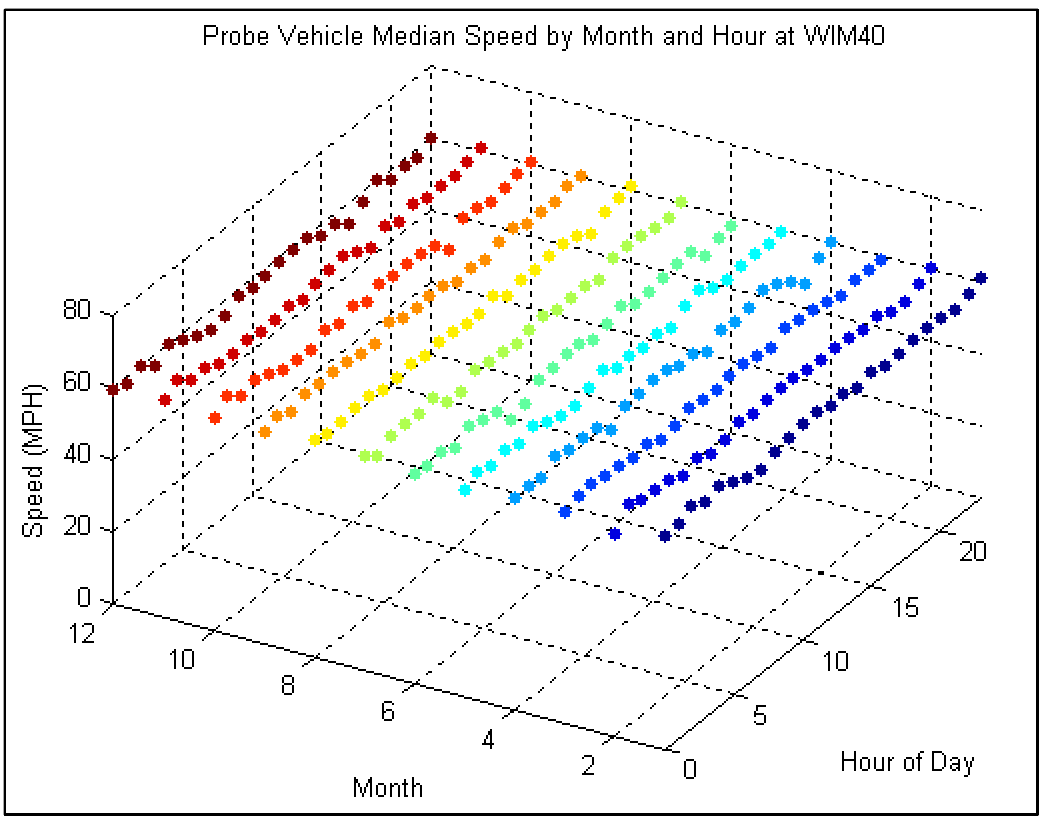

Figure D-21 Probe Vehicle Median Speed by Month and Hour at WIM40

D.7 Probe Vehicle vs. WIM Volume Percentage Comparisons

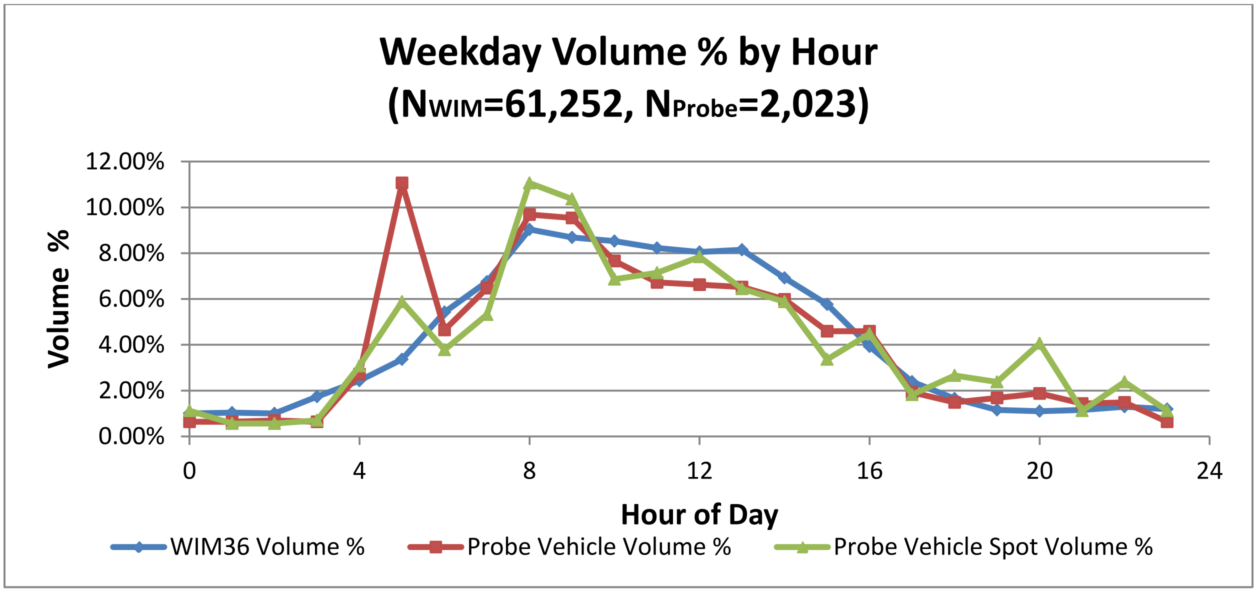

Figure D-22 Probe Vehicle vs. WIM Volume % by Hour at WIM#36

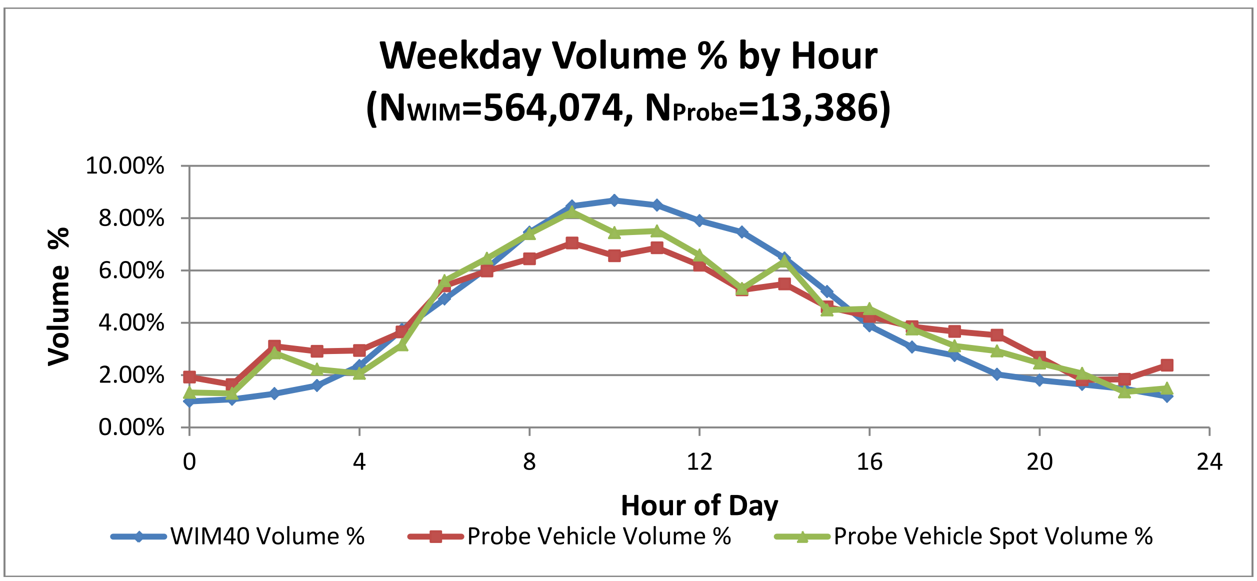

Figure D-23 Probe Vehicle vs. WIM Volume % by Hour at WIM#40

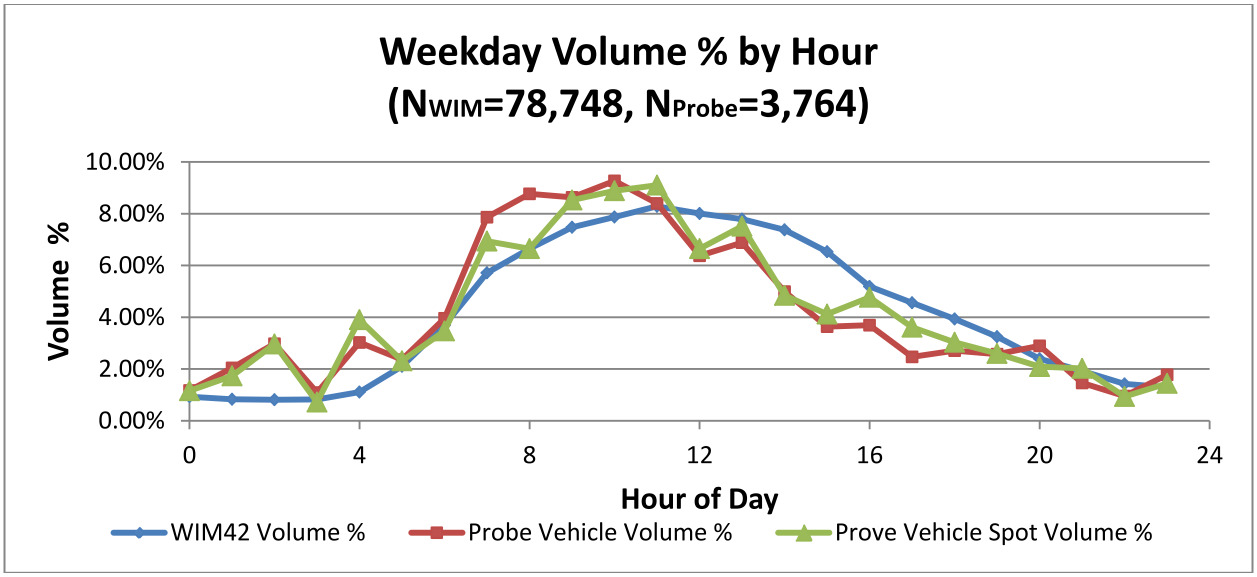

Figure D-24 Probe Vehicle vs. WIM Volume % by Hour at WIM#42

APPENDIX E: DATA COMPARISON OF AUTOMATIC TRAFFIC RECORDER (ATR)

E.1 ATR Truck Volume Comparison by Hour

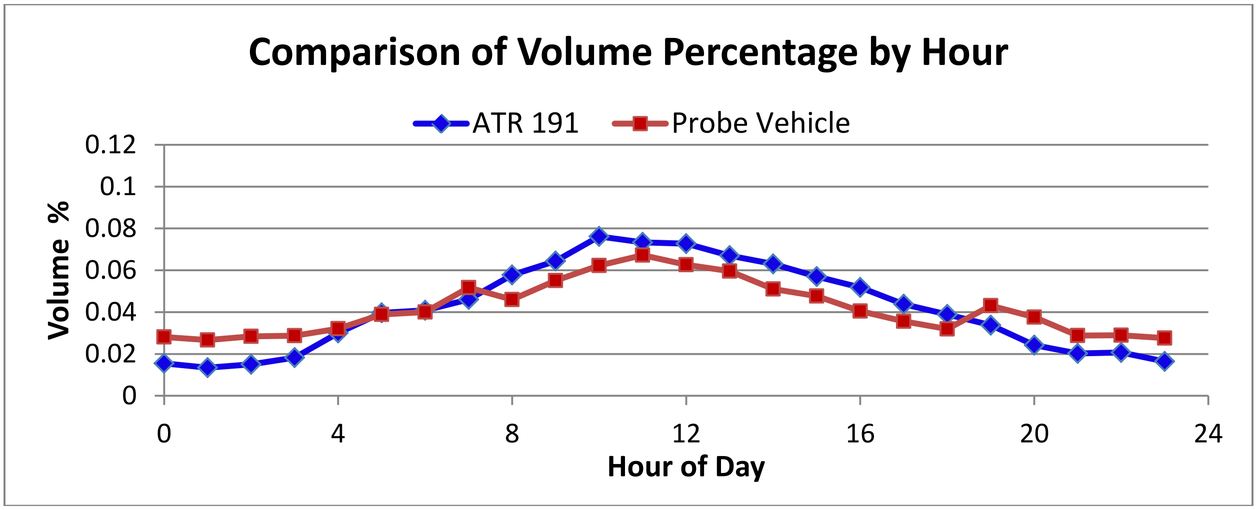

Figure E-1 Comparison of Truck Volume Percentage by Hour (ATR Station #191)

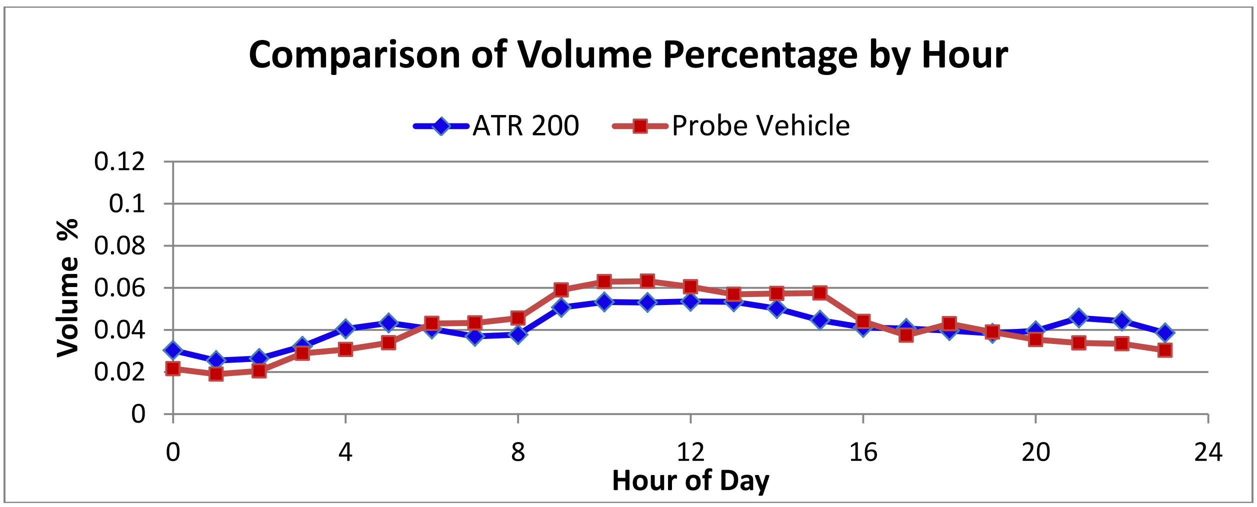

Figure E-2 Comparison of Truck Volume Percentage by Hour (ATR Station #200)

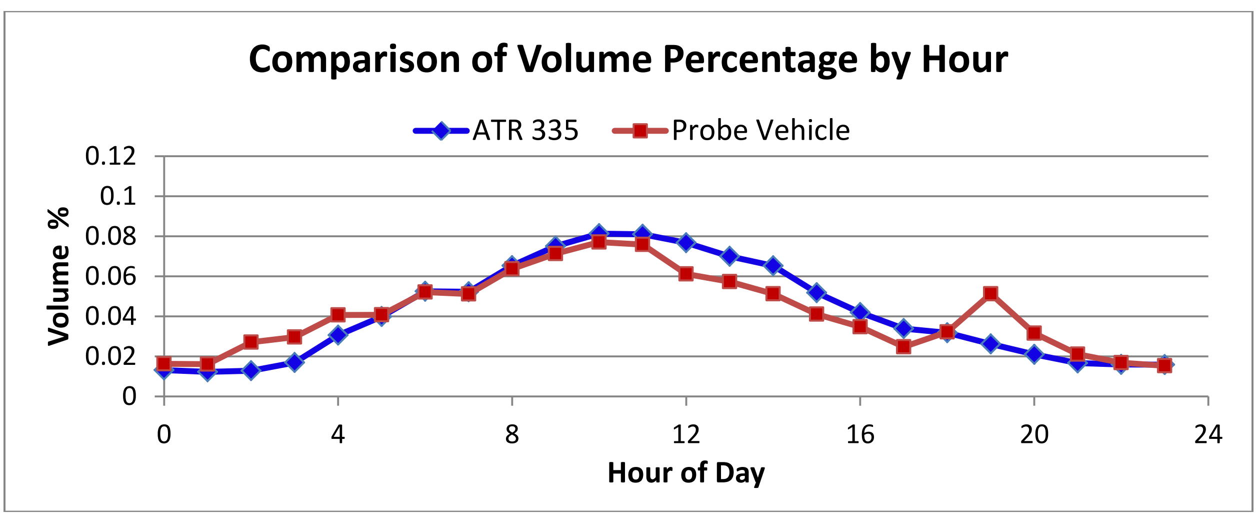

Figure E-3 Comparison of Truck Volume Percentage by Hour (ATR Station #335)

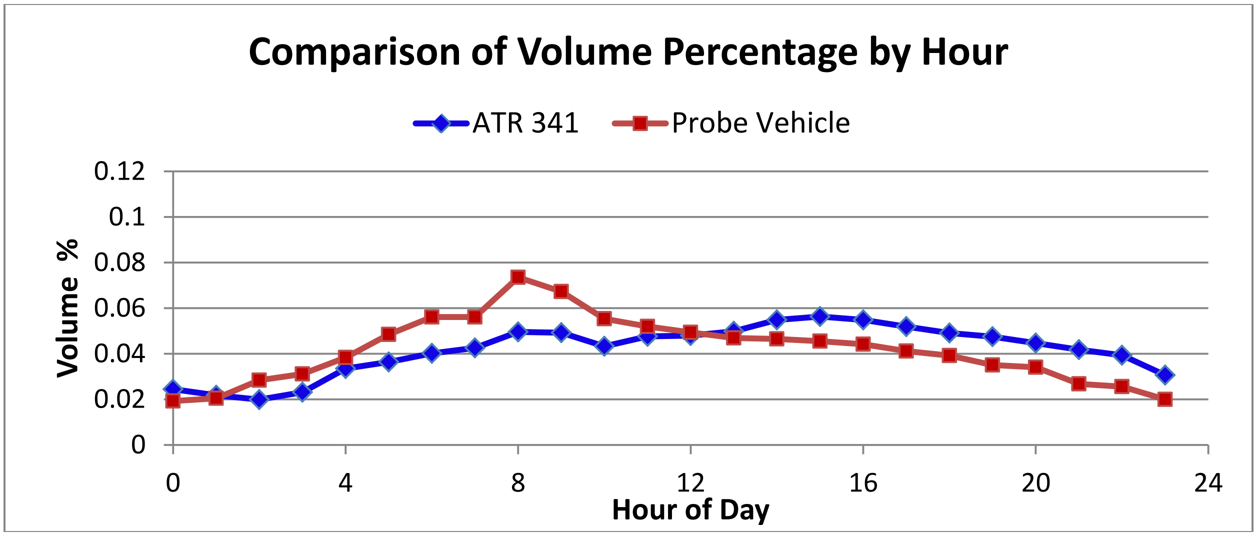

Figure E-4 Comparison of Truck Volume Percentage by Hour (ATR Station #341)

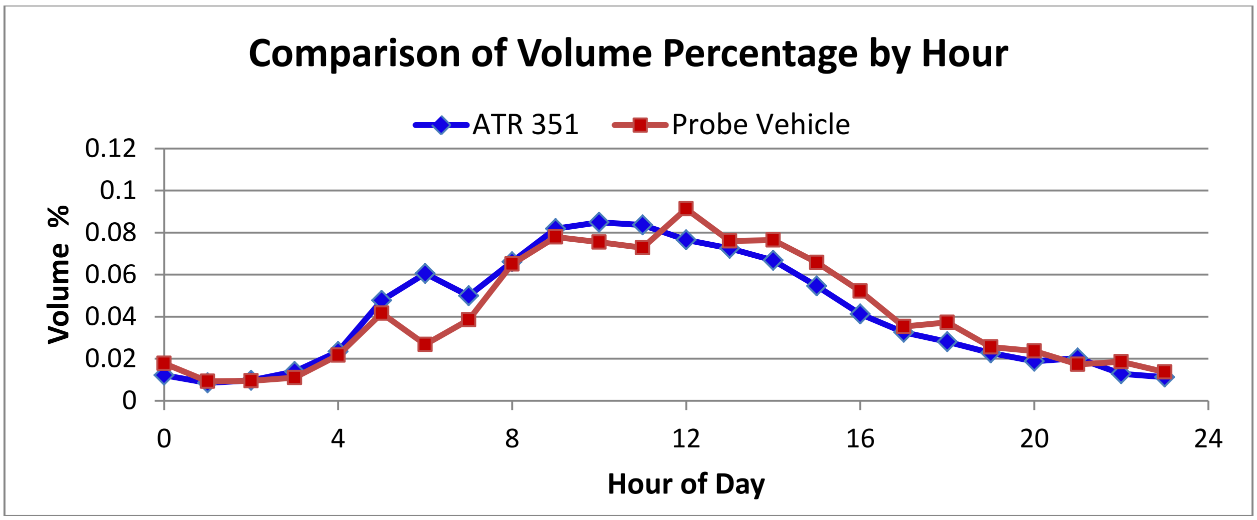

Figure E-5 Comparison of Truck Volume Percentage by Hour (ATR Station #351)

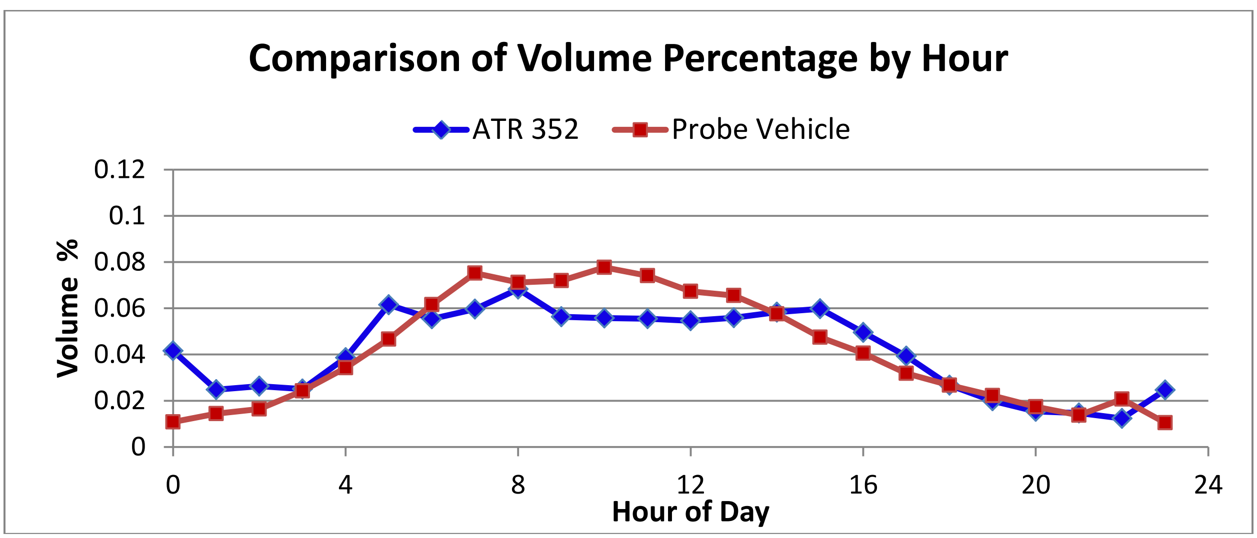

Figure E-6 Comparison of Truck Volume Percentage by Hour (ATR Station #352)

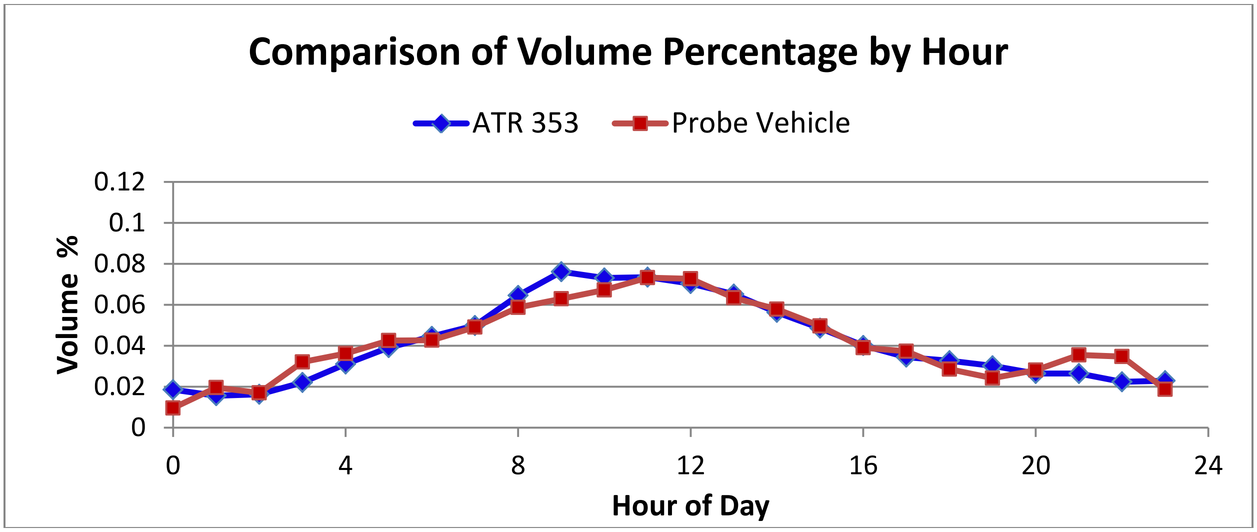

Figure E-7 Comparison of Truck Volume Percentage by Hour (ATR Station #353)

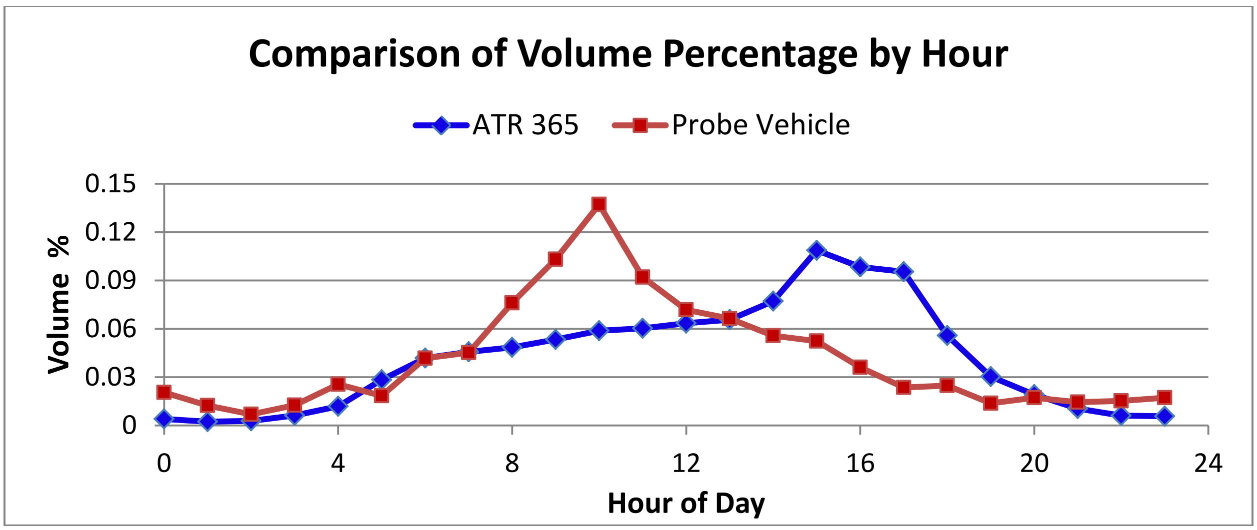

Figure E-8 Comparison of Truck Volume Percentage by Hour (ATR Station #365)

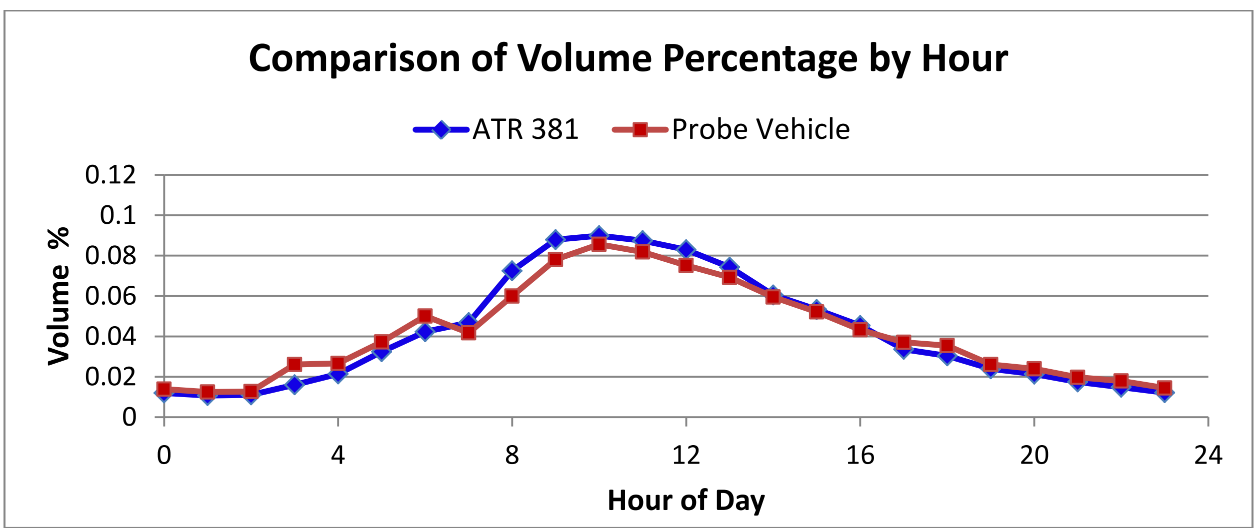

Figure E-9 Comparison of Truck Volume Percentage by Hour (ATR Station #381)

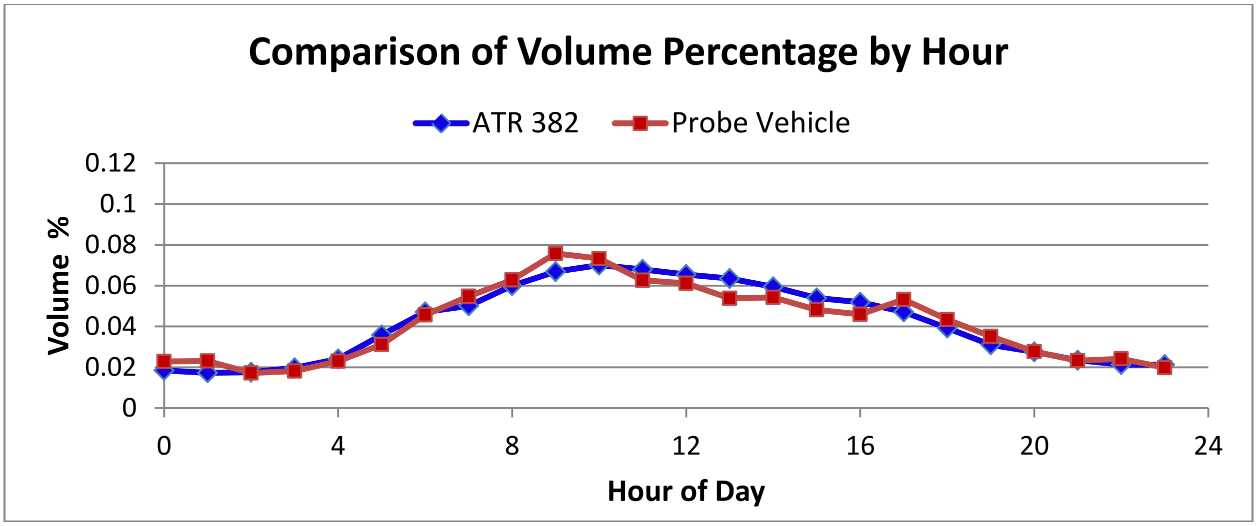

Figure E-10 Comparison of Truck Volume Percentage by Hour (ATR Station #382)

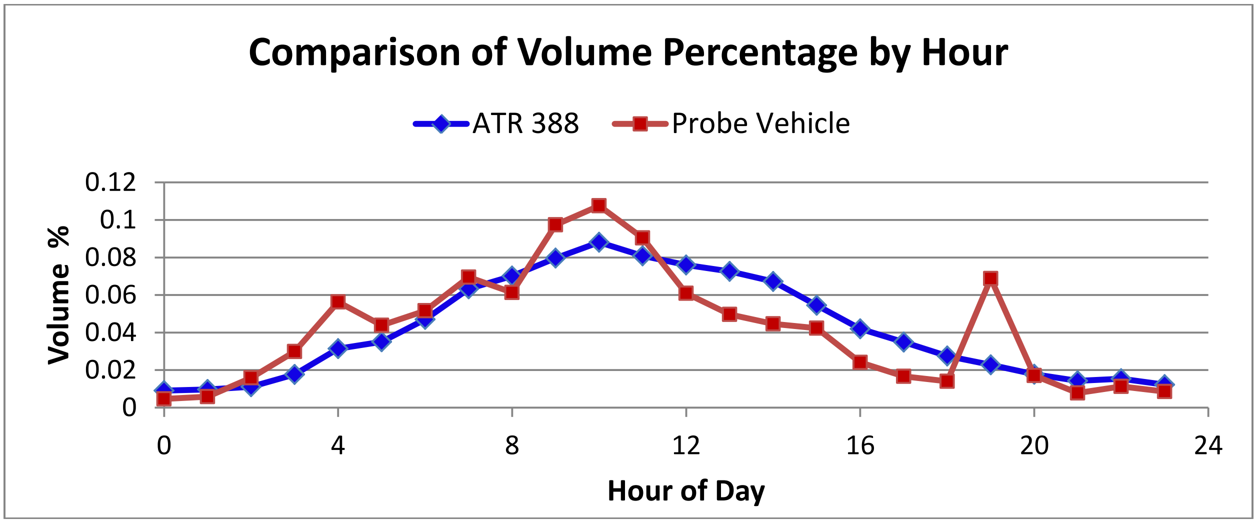

Figure E-11 Comparison of Truck Volume Percentage by Hour (ATR Station #388)

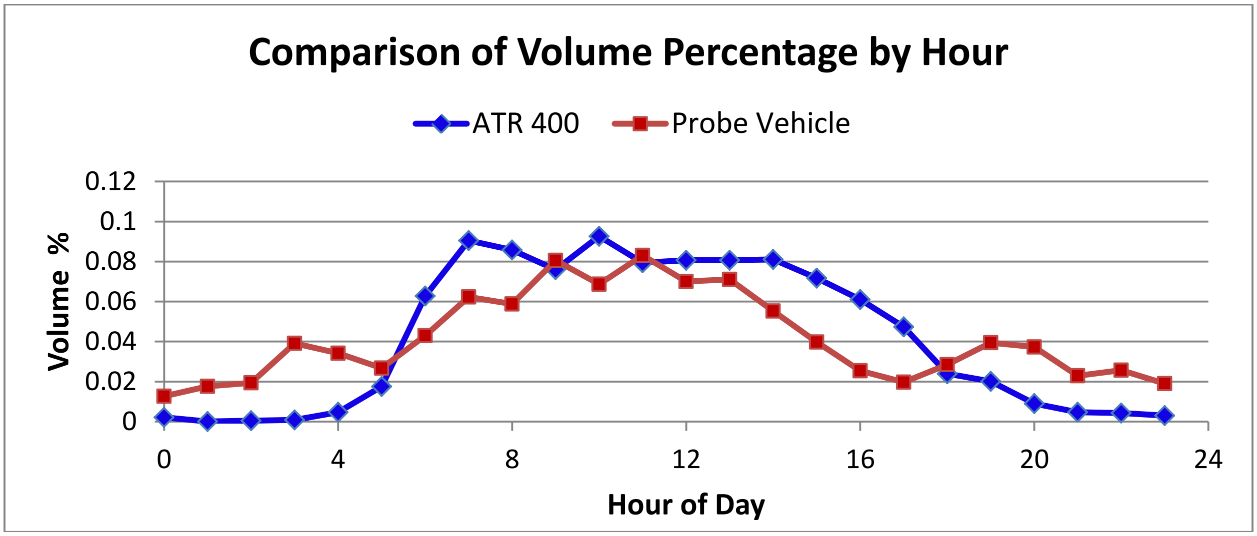

Figure E-12 Comparison of Truck Volume Percentage by Hour (ATR Station #400)

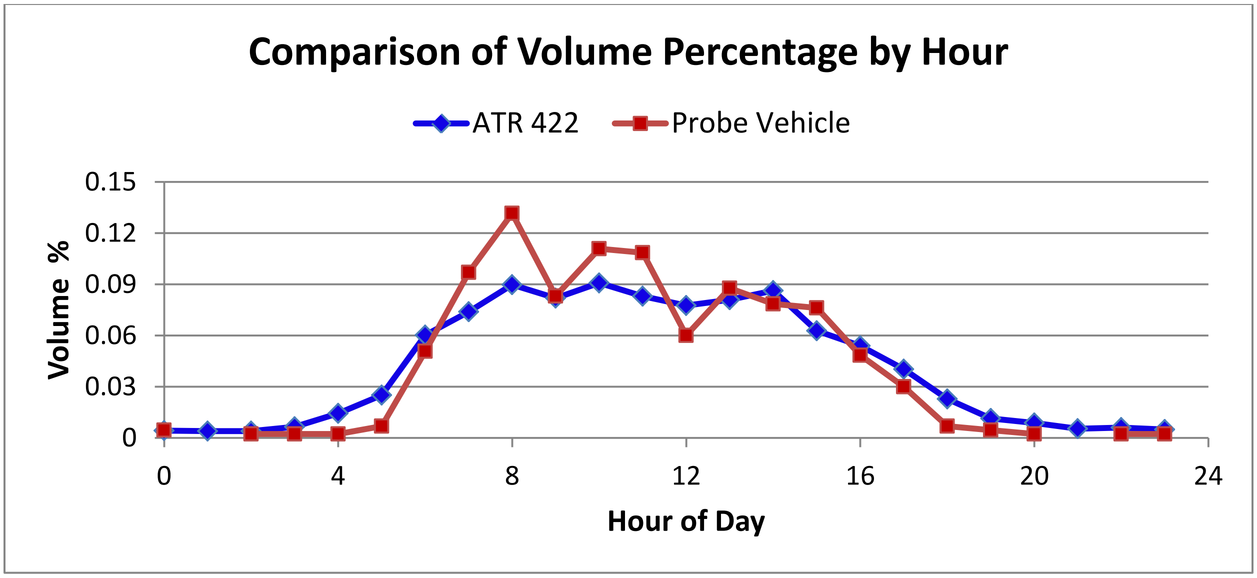

Figure E-13 Comparison of Truck Volume Percentage by Hour (ATR Station #422)

E.2 ATR Truck Speed Comparison by Hour

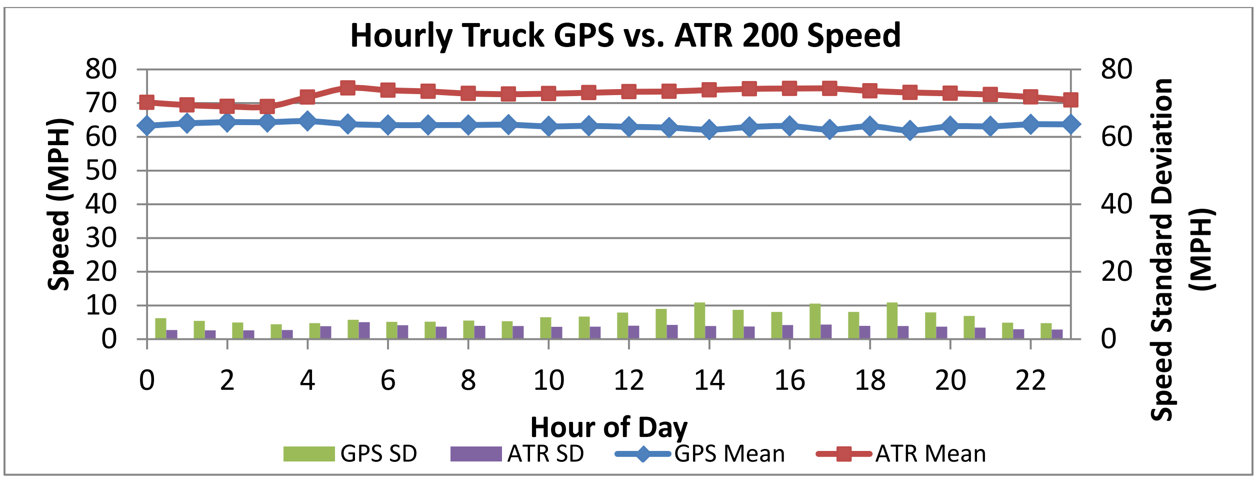

Figure E-14Weekday Hourly Truck GPS vs. ATR 200 Speed Comparisons

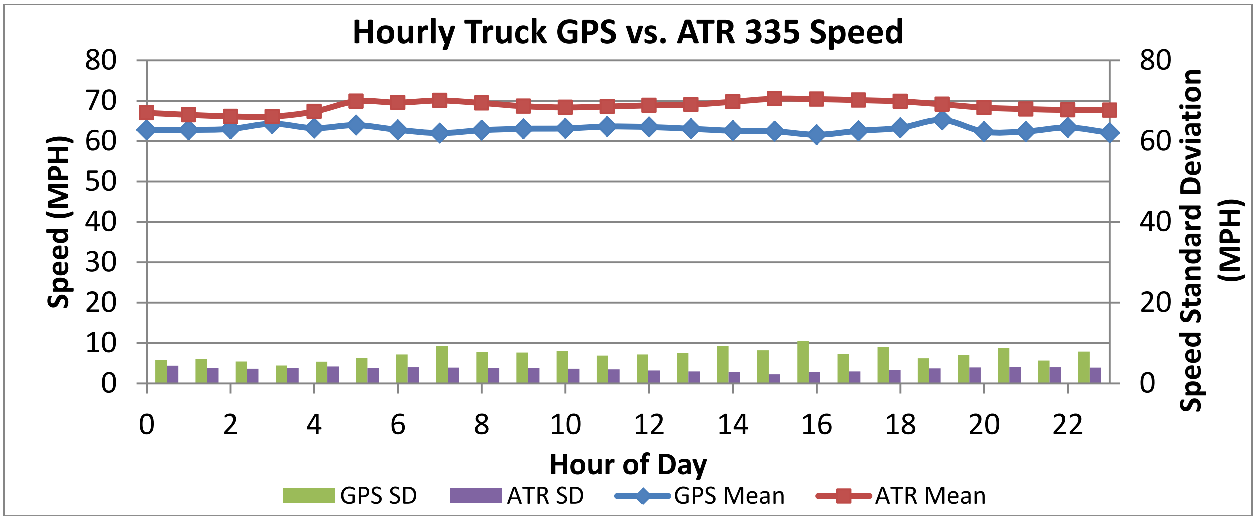

Figure E-15 Weekday Hourly Truck GPS vs. ATR 335 Speed Comparisons

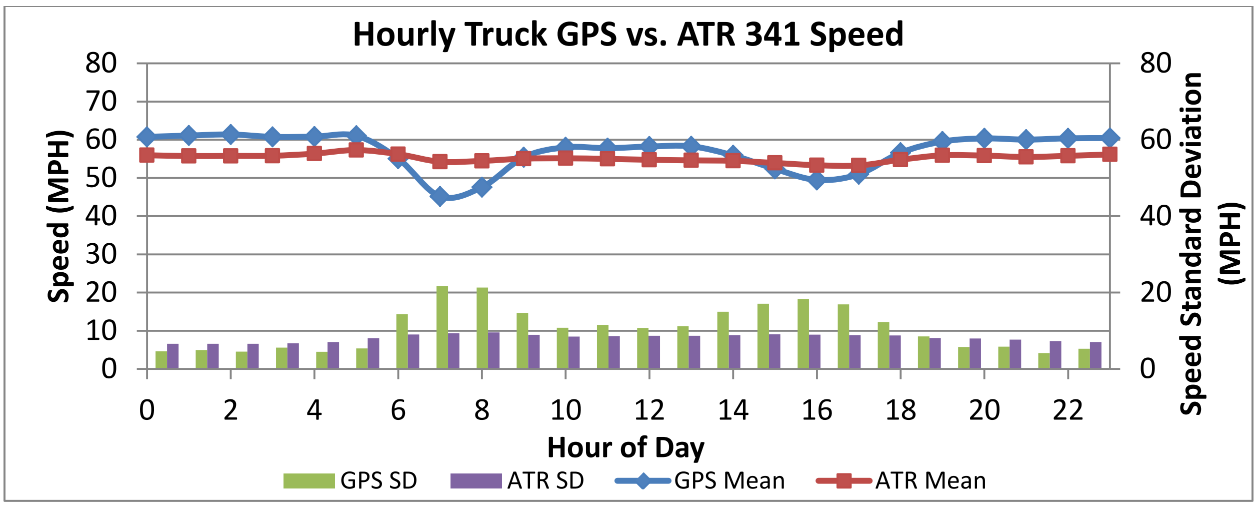

Figure E-16 Weekday Hourly Truck GPS vs. ATR 341 Speed Comparisons

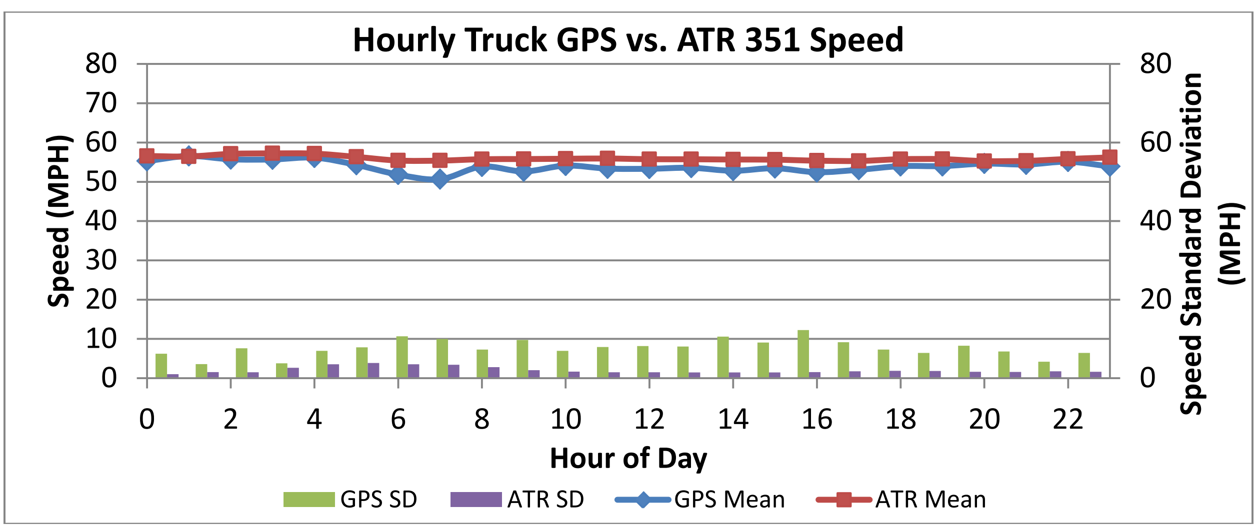

Figure E-17 Weekday Hourly Truck GPS vs. ATR 351 Speed Comparisons

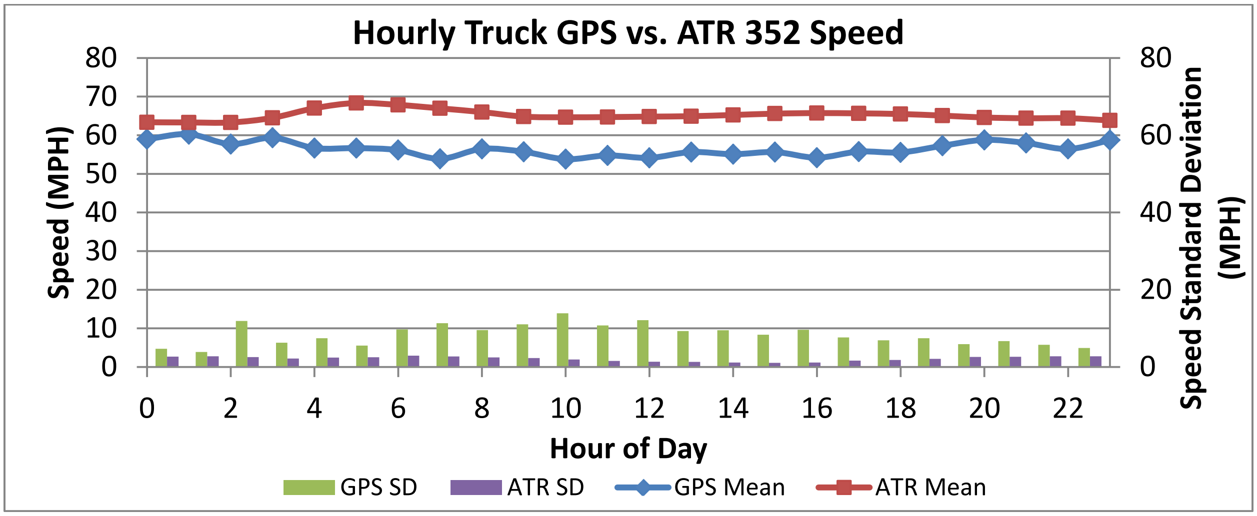

Figure E-18 Weekday Hourly Truck GPS vs. ATR 352 Speed Comparisons

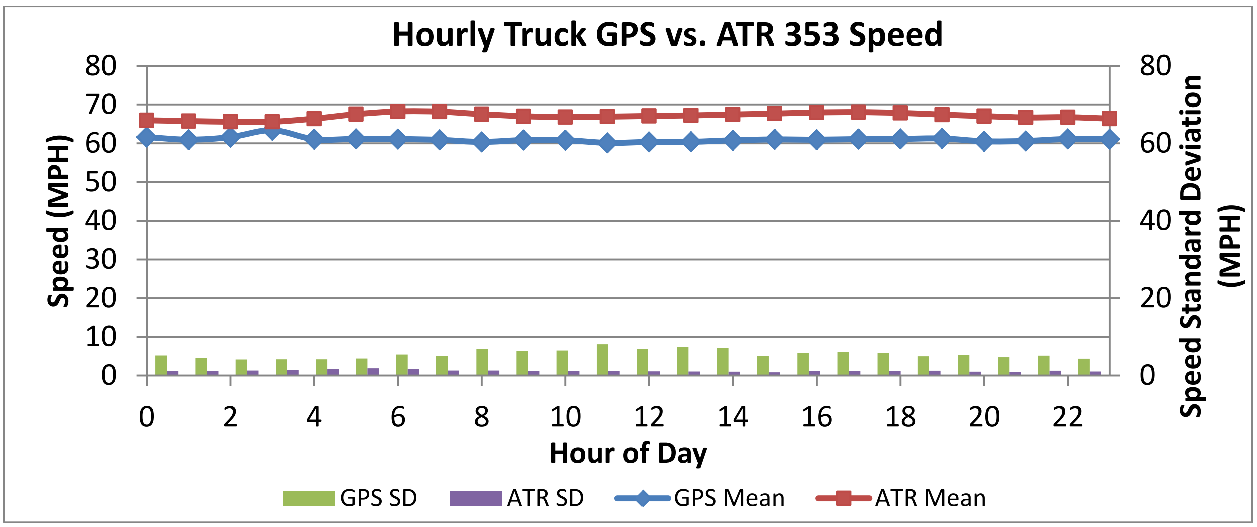

Figure E-19 Weekday Hourly Truck GPS vs. ATR 353 Speed Comparisons

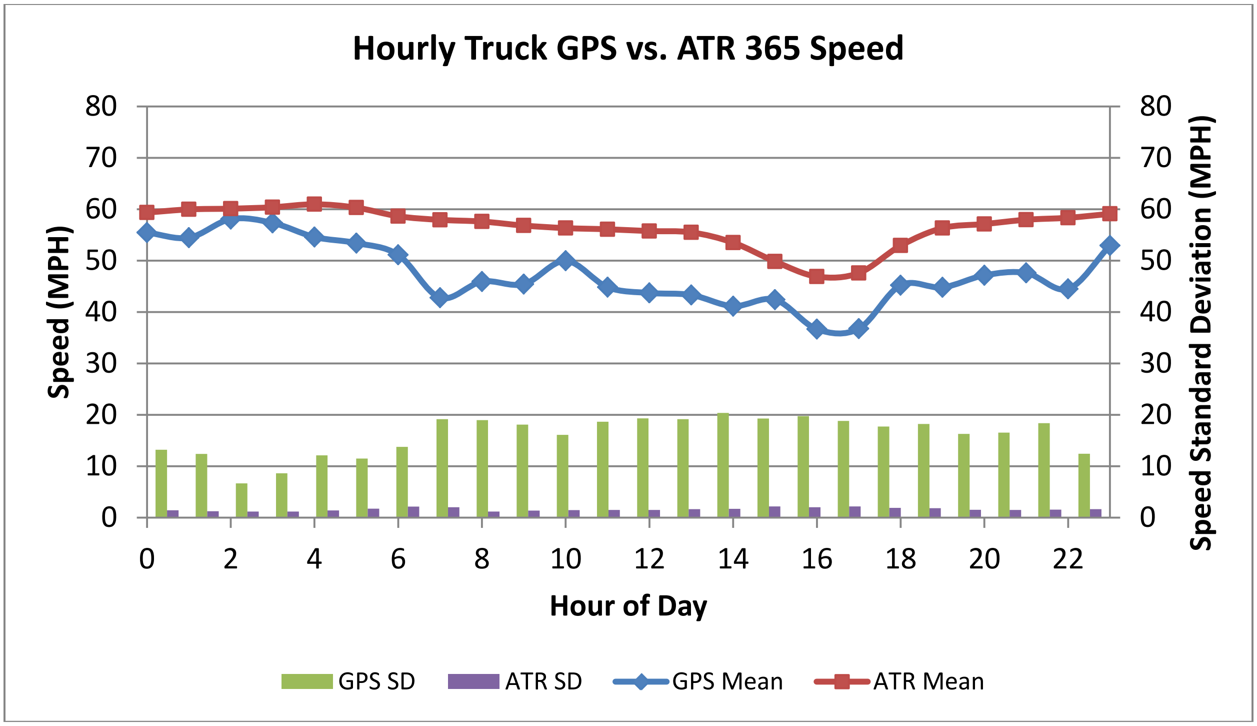

Figure E-20 Weekday Hourly Truck GPS vs. ATR 365 Speed Comparisons

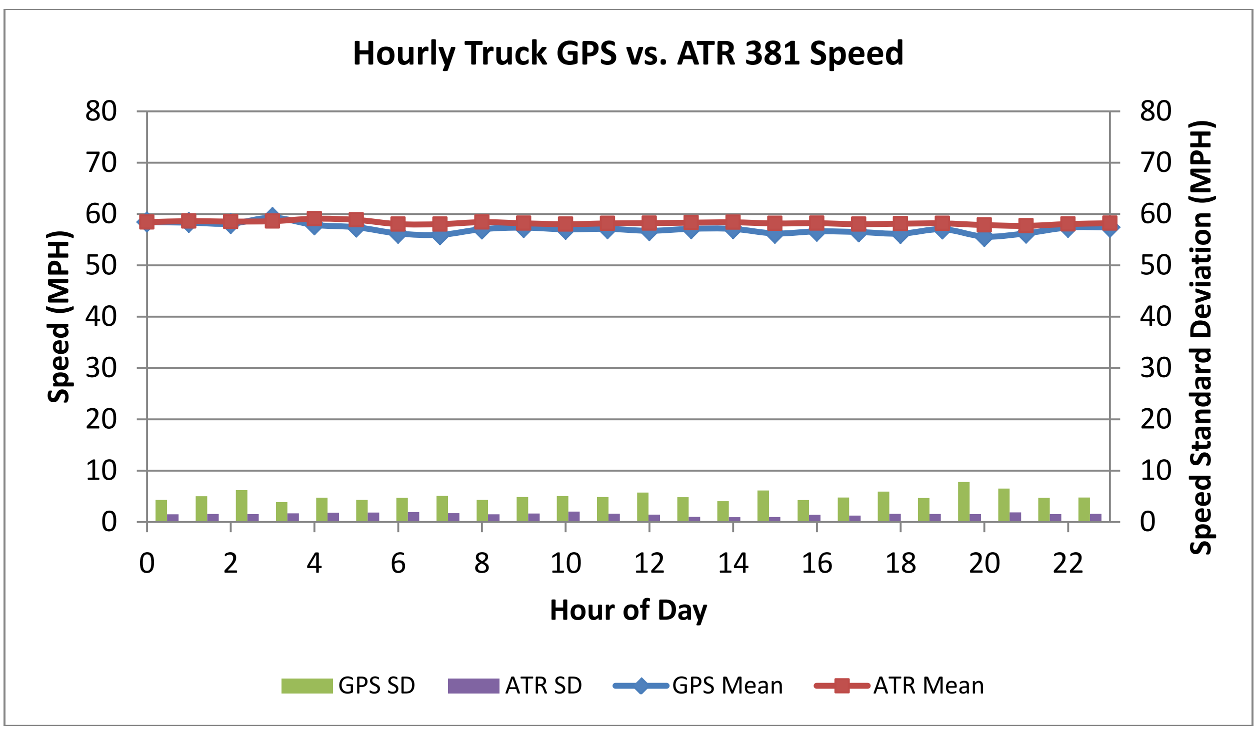

Figure E-21 Weekday Hourly Truck GPS vs. ATR 381 Speed Comparisons

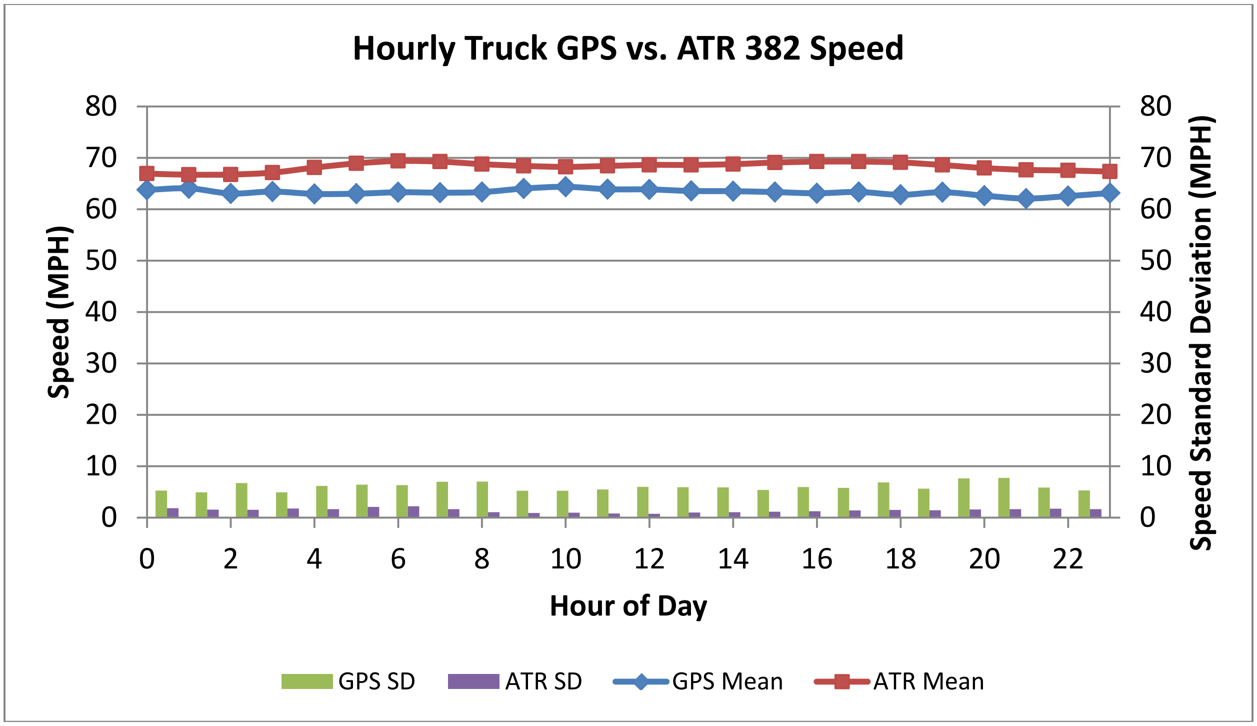

Figure E-22 Weekday Hourly Truck GPS vs. ATR 382 Speed Comparisons

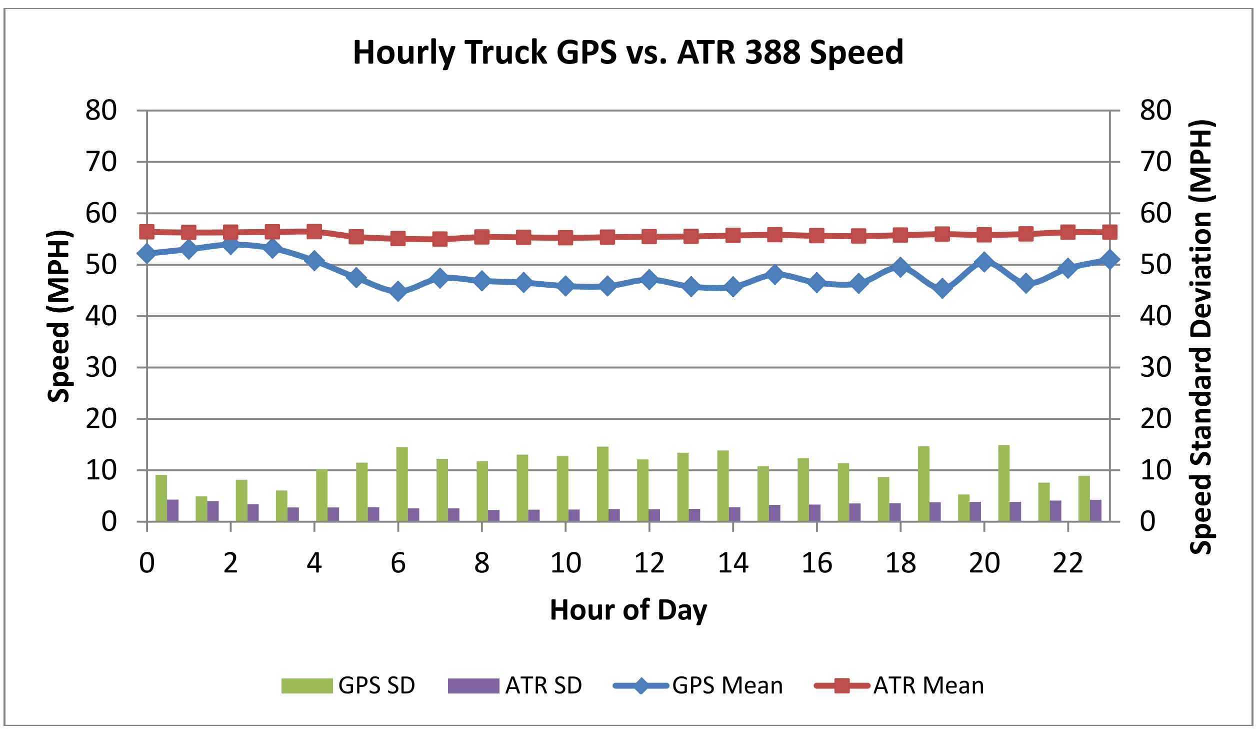

Figure E-23Weekday Hourly Truck GPS vs. ATR 388 Speed Comparisons

APPENDIX F: DATA COMPARISON OF LOOP DETECTOR DATA

F.1 MnDOT Data Plot Application

MnDOT data plot applet is available online (http://data.dot.state.mn.us/datatools/dataplot.html). Individual loop detector volume and speed can be queried and visualized (Figure F-1).

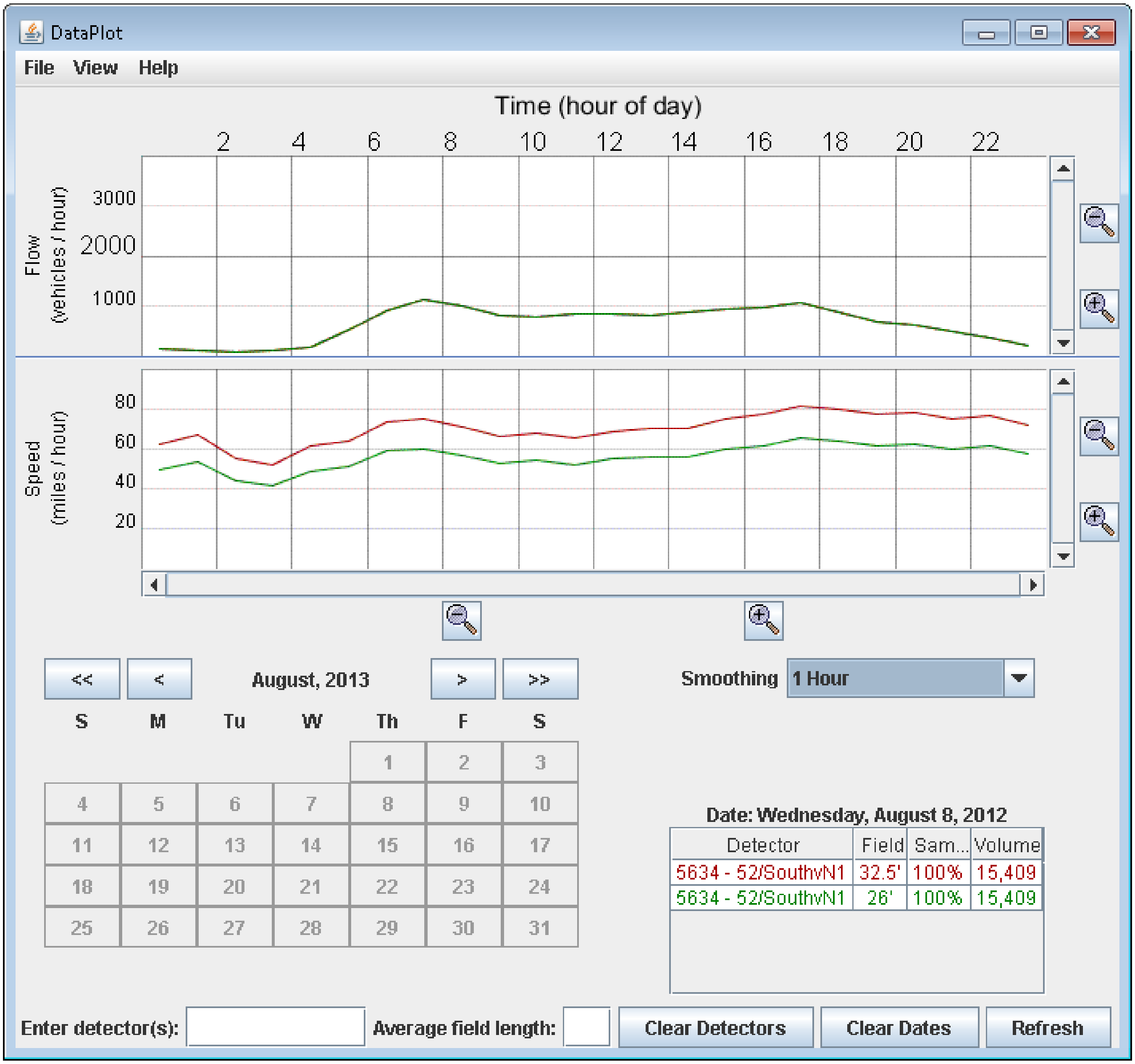

Figure F-1 Snapshot of MnDOT Data Plot Application

F.2 Loop Detector Volume Comparison with WIM Data

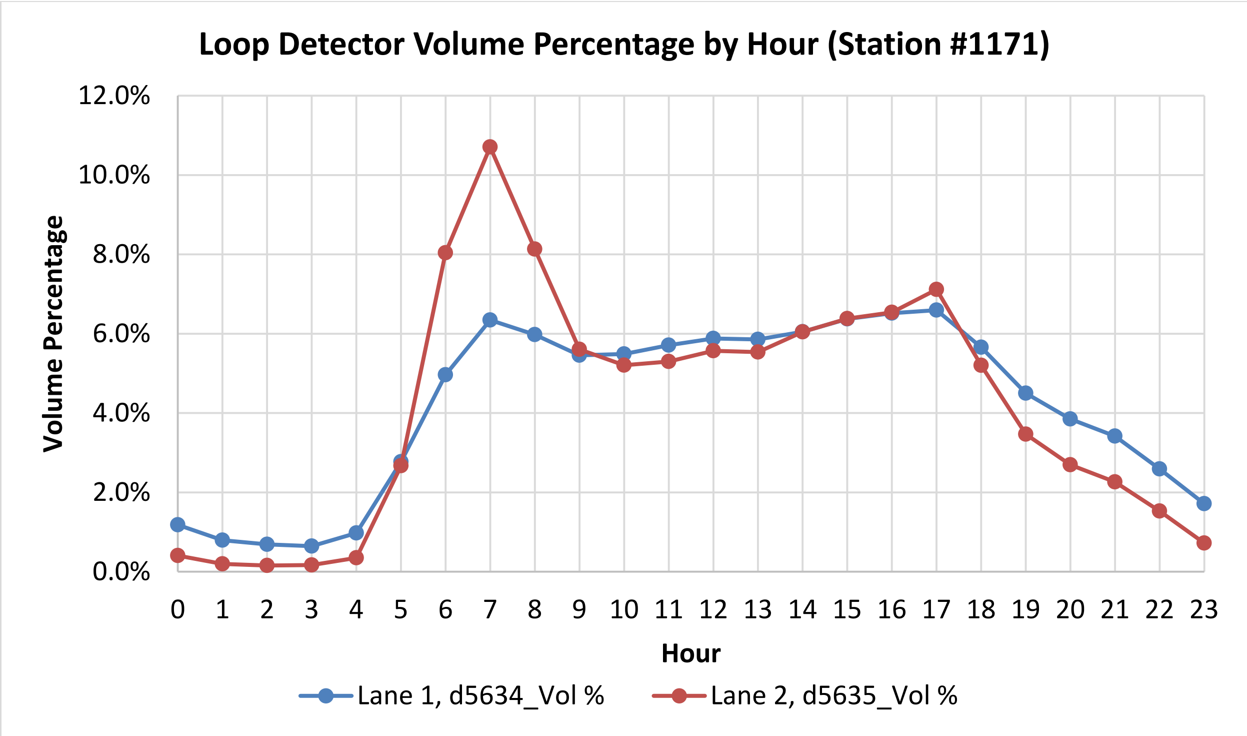

Figure F-2 Hourly Volume Percentages by Lane at Loop Detector Station #1171

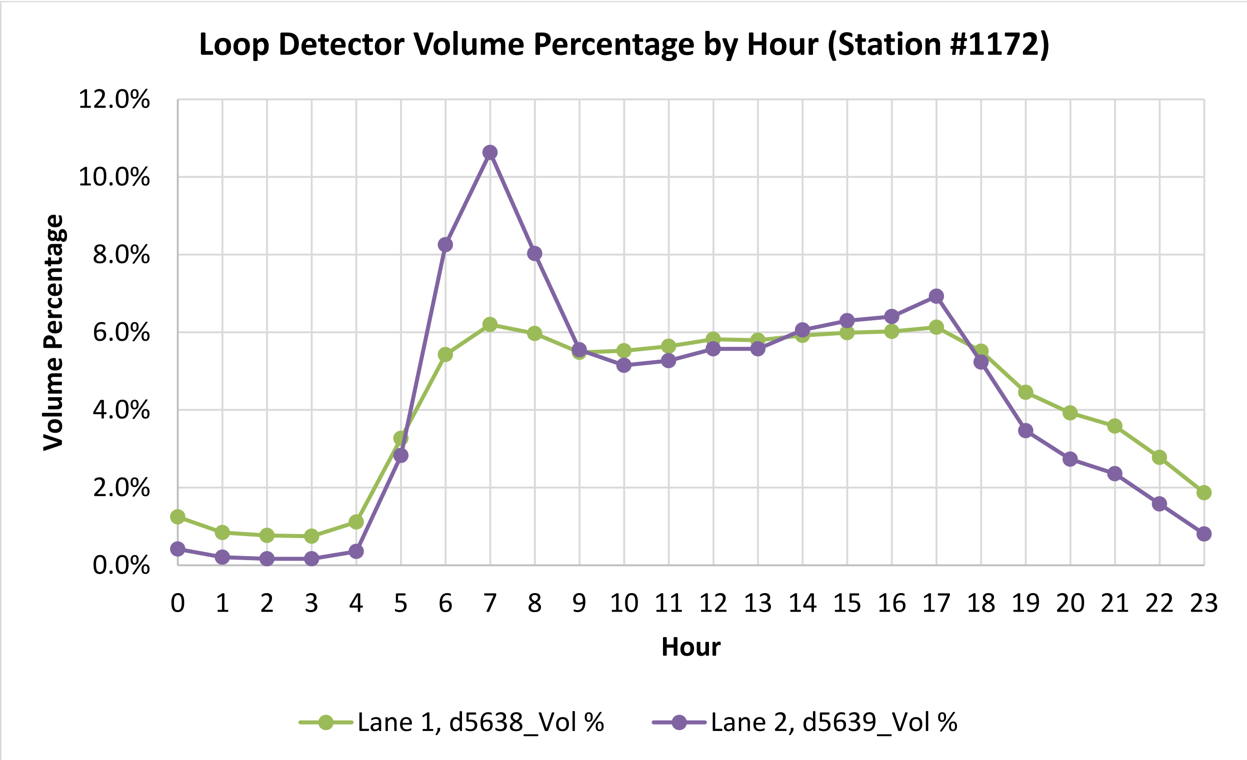

Figure F-3 Hourly Volume Percentages by Lane at Loop Detector Station #1172

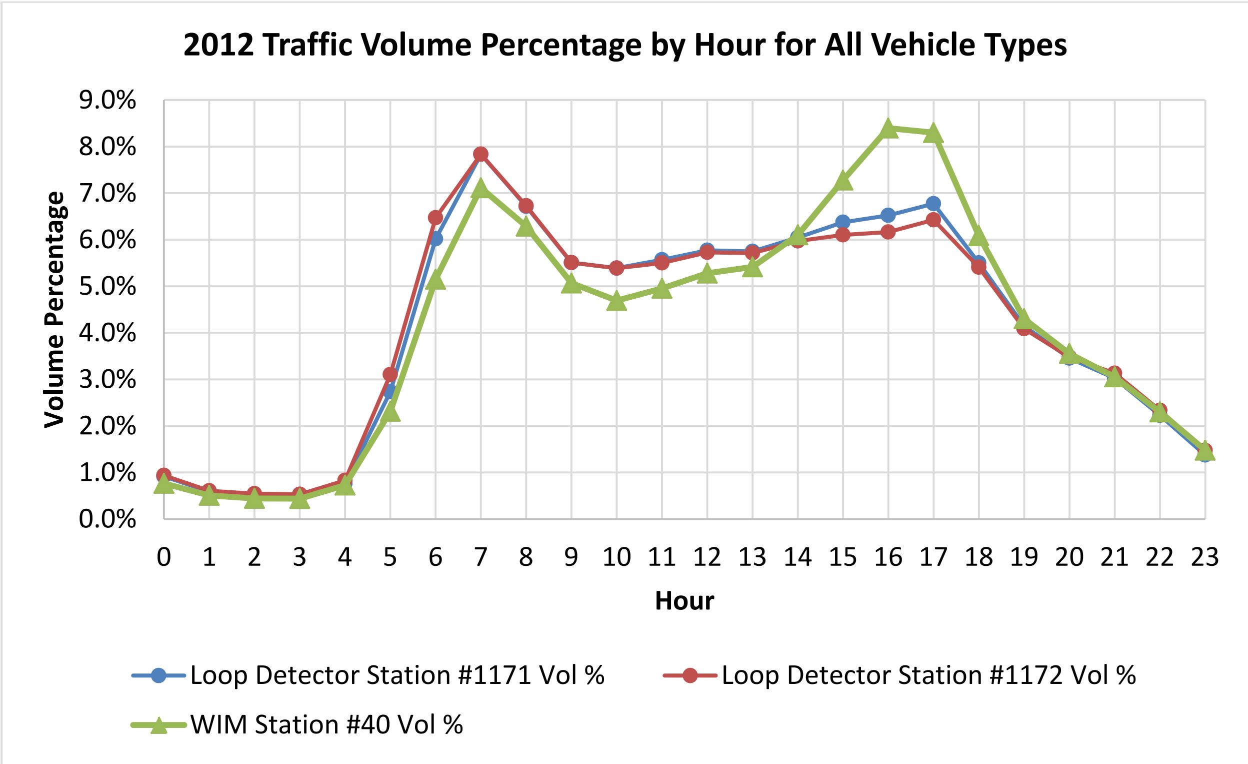

Figure F-4 Hourly Volume Percentage Comparisons (Loop Detector Station 1171 & 1172 vs. WIM 40)

F.3 Loop Detector Volume Comparison with ATR Data

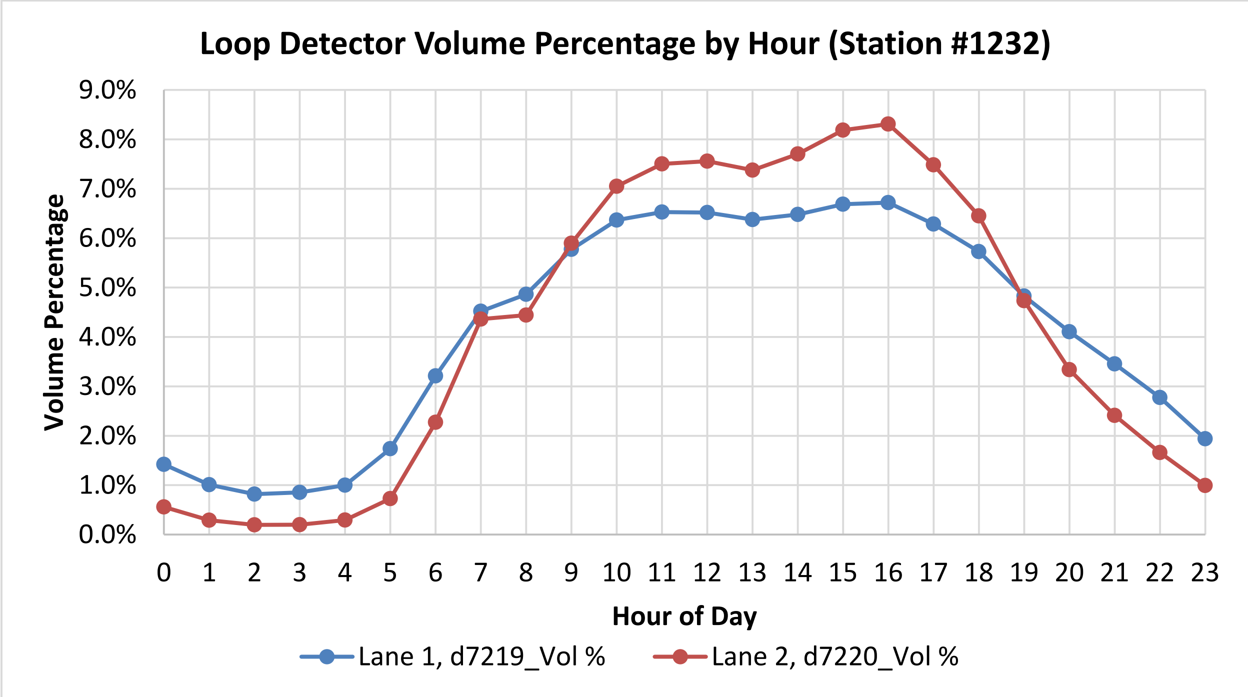

Figure F-5 Hourly Volume Percentages by Lane at Loop Detector Station #1232

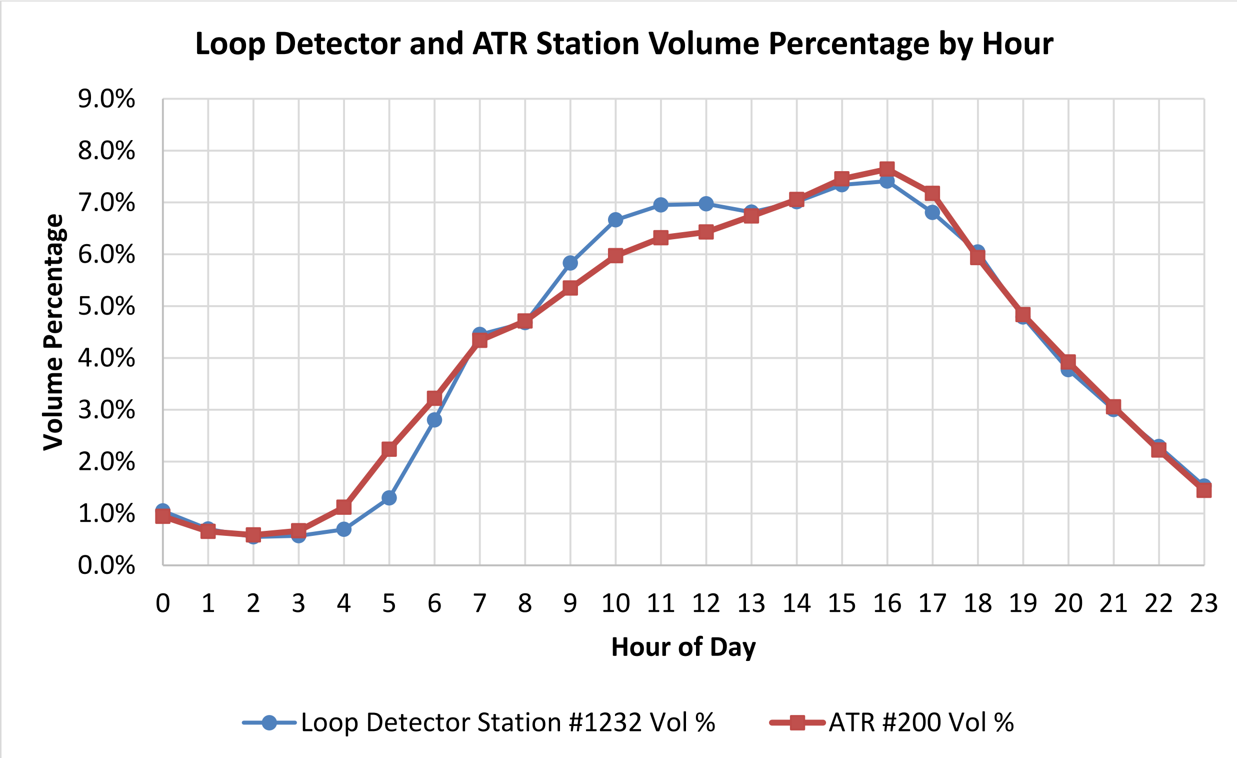

Figure F-6 Hourly Volume Percentage Comparisons (Loop Detector Station 1232 vs. ATR200)

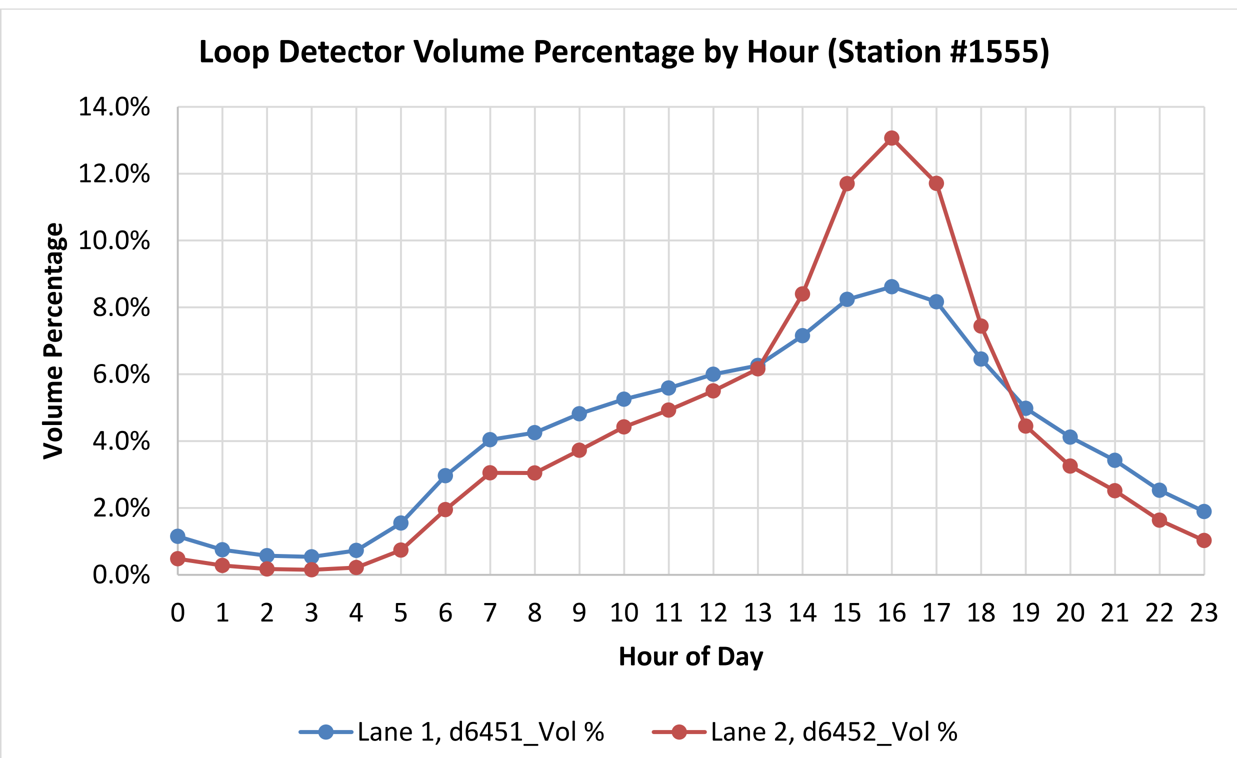

Figure F-7 Hourly Volume Percentages by Lane at Loop Detector Station #1555

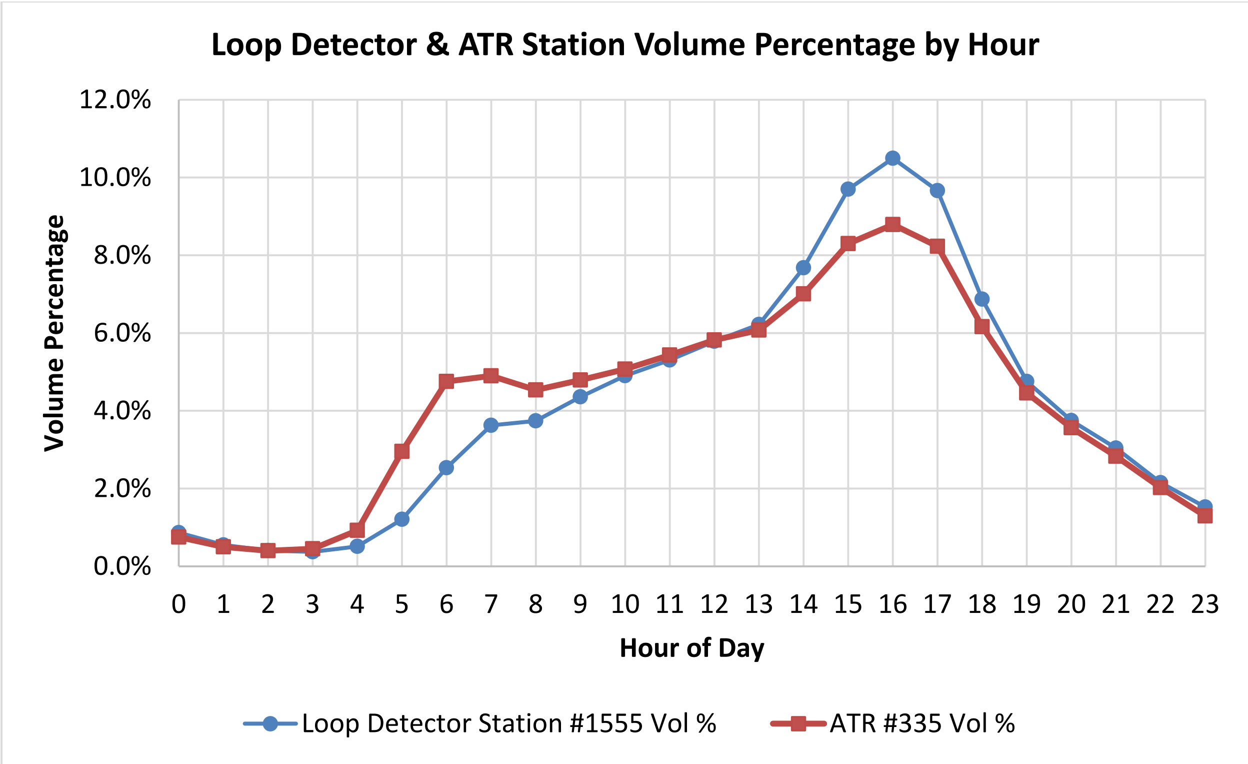

Figure F-8 Hourly Volume Percentage Comparisons (Loop Detector Station 1555 vs. ATR335)

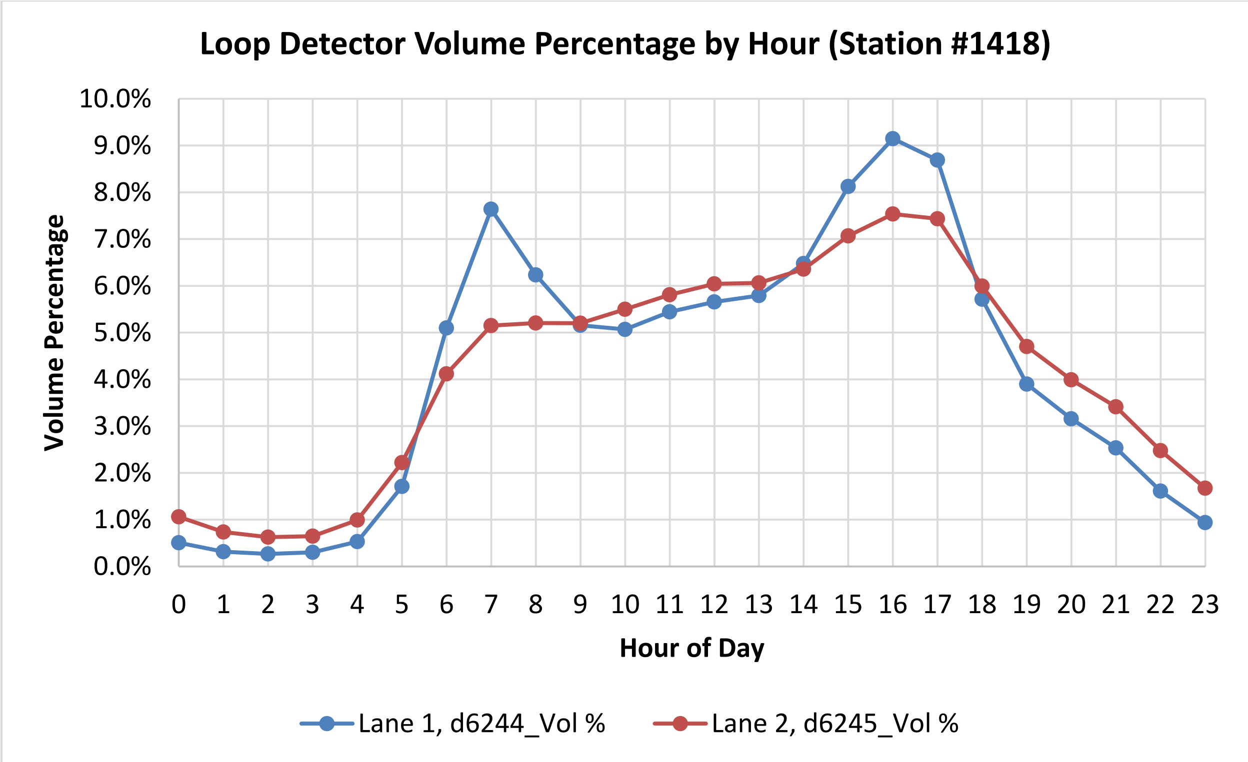

Figure F-9 Hourly Volume Percentages by Lane at Loop Detector Station #1418

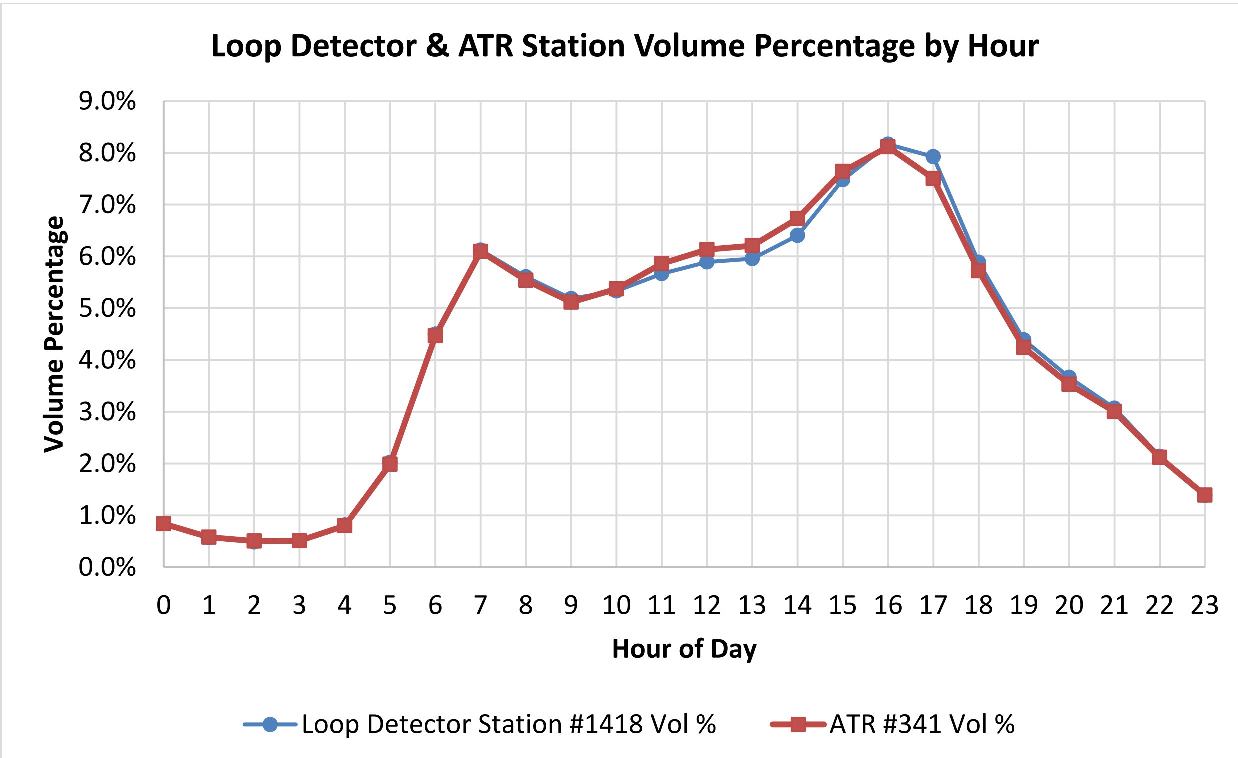

Figure F-10 Hourly Volume Percentage Comparisons (Loop Detector Station 1418 vs. ATR341)

F.4 Loop Detector Speed Comparison with ATR Data

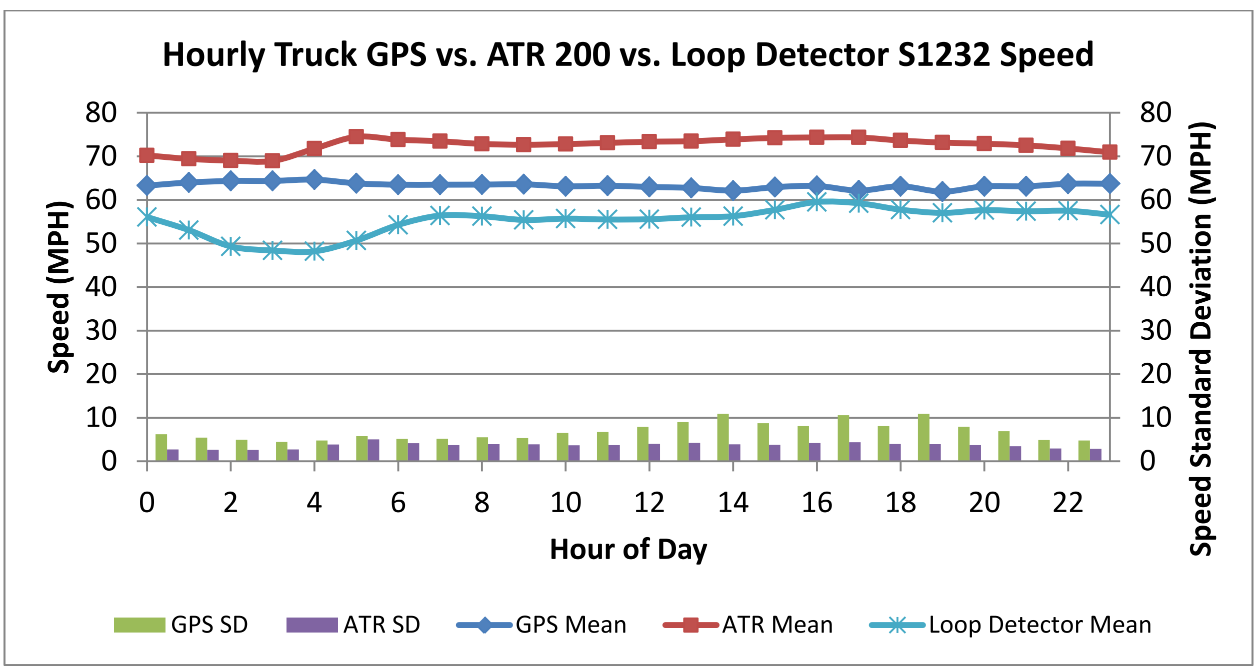

Figure F-11 Hourly Speed Comparisons (Loop Detector Station 1232 vs. ATR200)

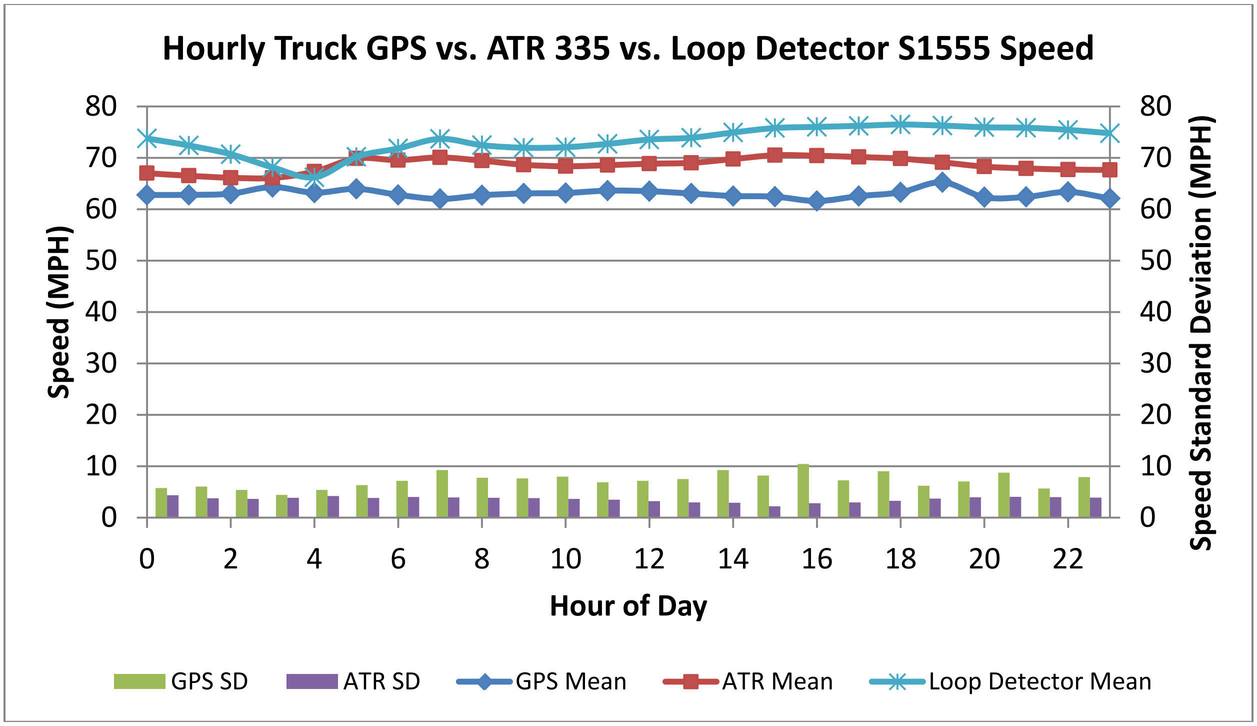

Figure F-12 Hourly Speed Comparisons (Loop Detector Station 1555 vs. ATR335)

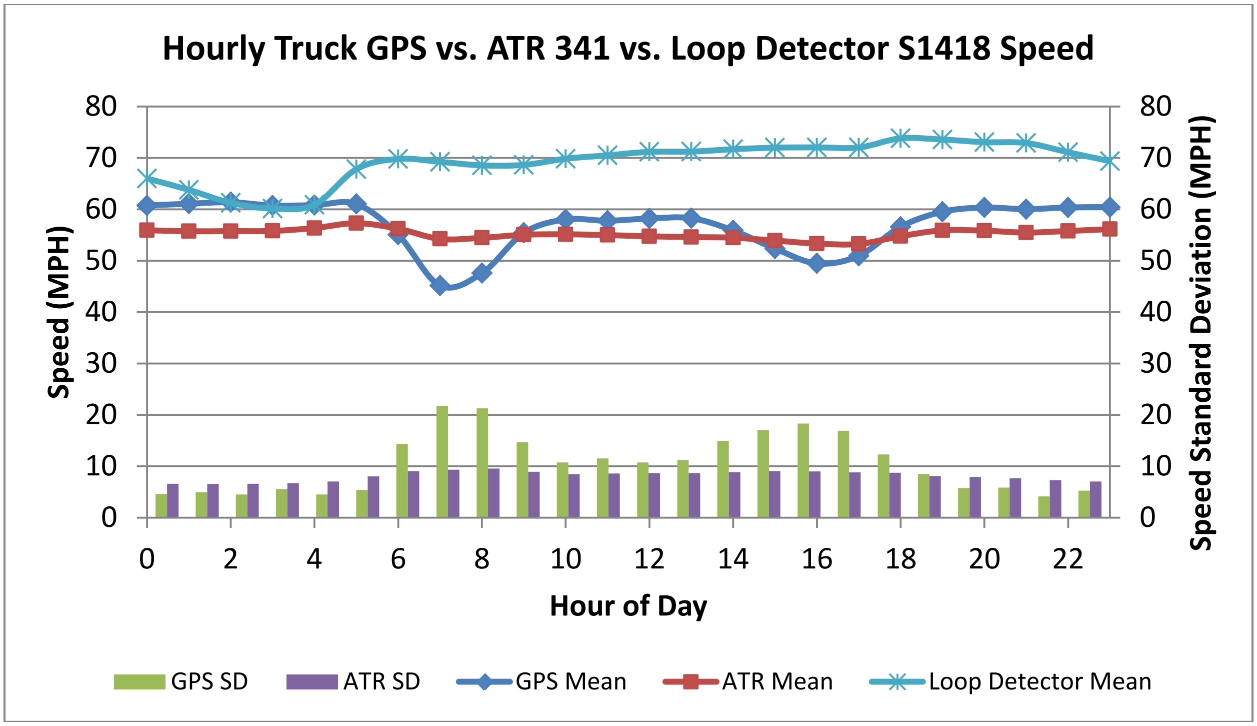

Figure F-13 Hourly Speed Comparisons (Loop Detector Station 1418 vs. ATR341)

F.5 Loop Detector Speed Comparison with Truck GPS Speed

One month of general traffic speed computed from loop detectors in the RTMC network was compared with GPS truck speed. It is assumed that the average vehicle length used for computing the general traffic speed was calibrated at each loop detector station. Figure F-14 displays the average general traffic speed computed from loop detectors at 7AM in October 2013. Figure F-15 illustrates the average truck GPS speed at 7AM in October 2013. The speed differences between the truck GPS speed and the general traffic speed derived from loop detectors are illustrated in Figure F-16. The red color in Figure 16 represents that average truck speed is 15 to 30 MPH lower than the general traffic. The yellow color represents that the average truck speed is 15 MPH less than the general traffic speed.

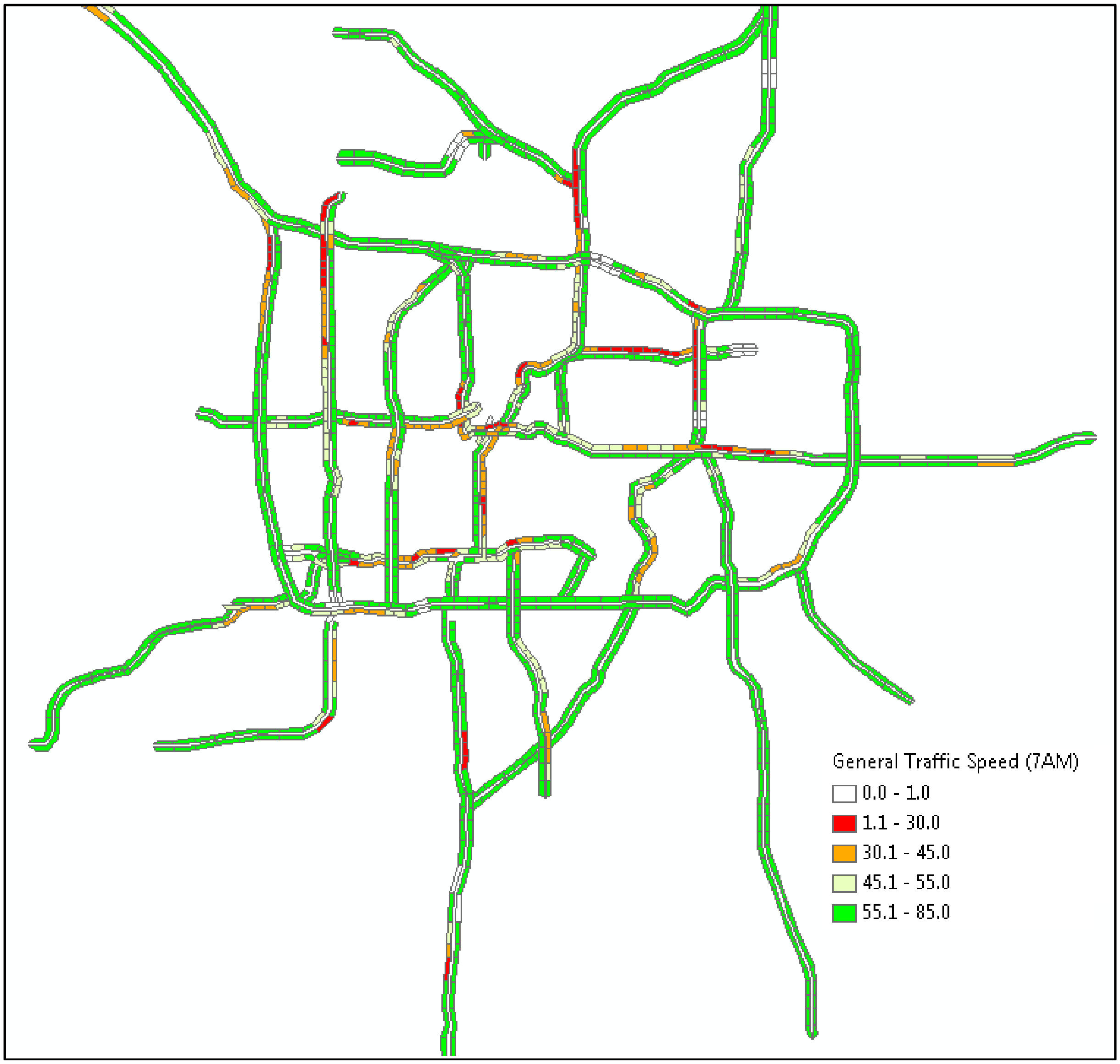

Figure F-14 General Traffic Speed from Loop Detectors (Oct. 2013 7AM)

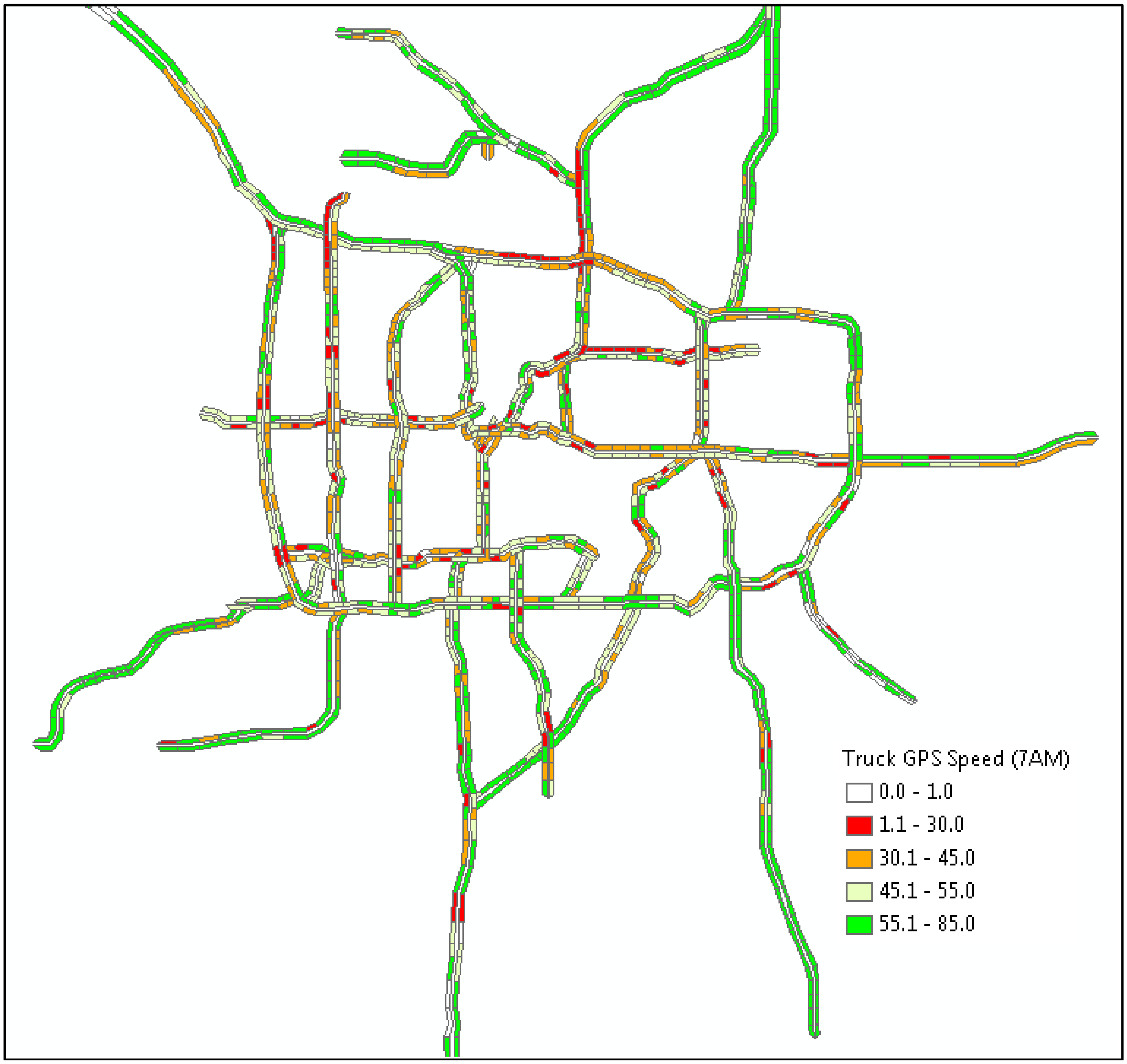

Figure F-15 Truck GPS Speed (Oct. 2013 7AM)

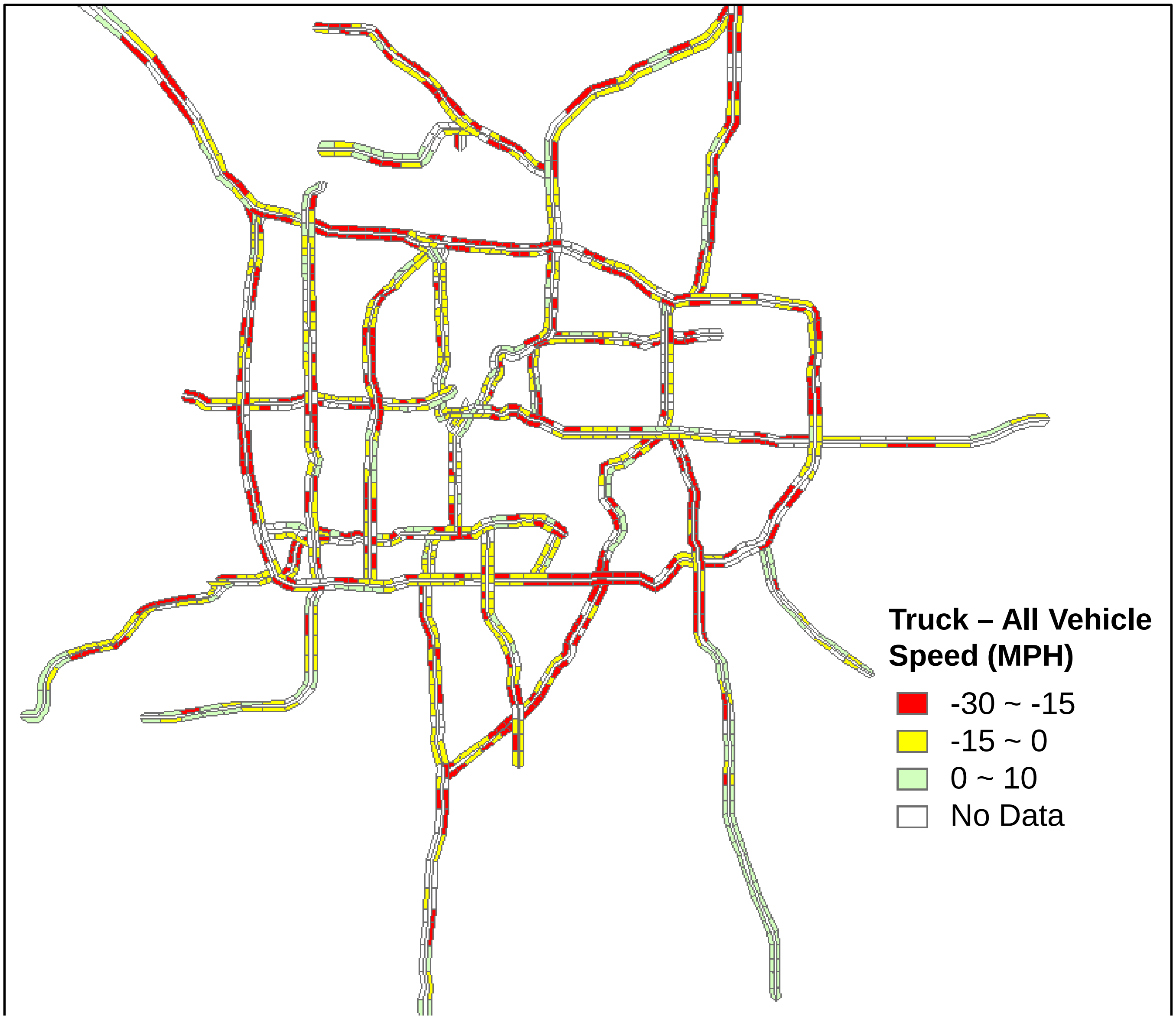

Figure F-16 Speed Difference: Truck GPS Speed – General Traffic Speed (Oct. 2013 7AM)

Figure F-17 displays the average general traffic speed computed from loop detectors at 4PM in October 2013. Figure F-18 illustrates the average truck GPS speed at 4PM in October 2013. The speed differences between the truck GPS speed and the general traffic speed derived from loop detectors are illustrated in Figure F-19. The red color in Figure 16 represents that average truck speed is 15 to 30 MPH lower than the general traffic. The yellow color represents that the average truck speed is 15 MPH less than the general traffic speed.

Table F-1 summarizes the average differences of speed derived from truck GPS and loop detector data. Based on the processed results from Oct. 2013, the average truck GPS speed is about 11 MPH below the general traffic speed during 7AM. Average truck speed at 4PM is about 12 MPH slower than the general traffic. The median truck GPS speed in the RTMC network is about 12 MPH below general traffic speed for both 7AM and 4PM periods.

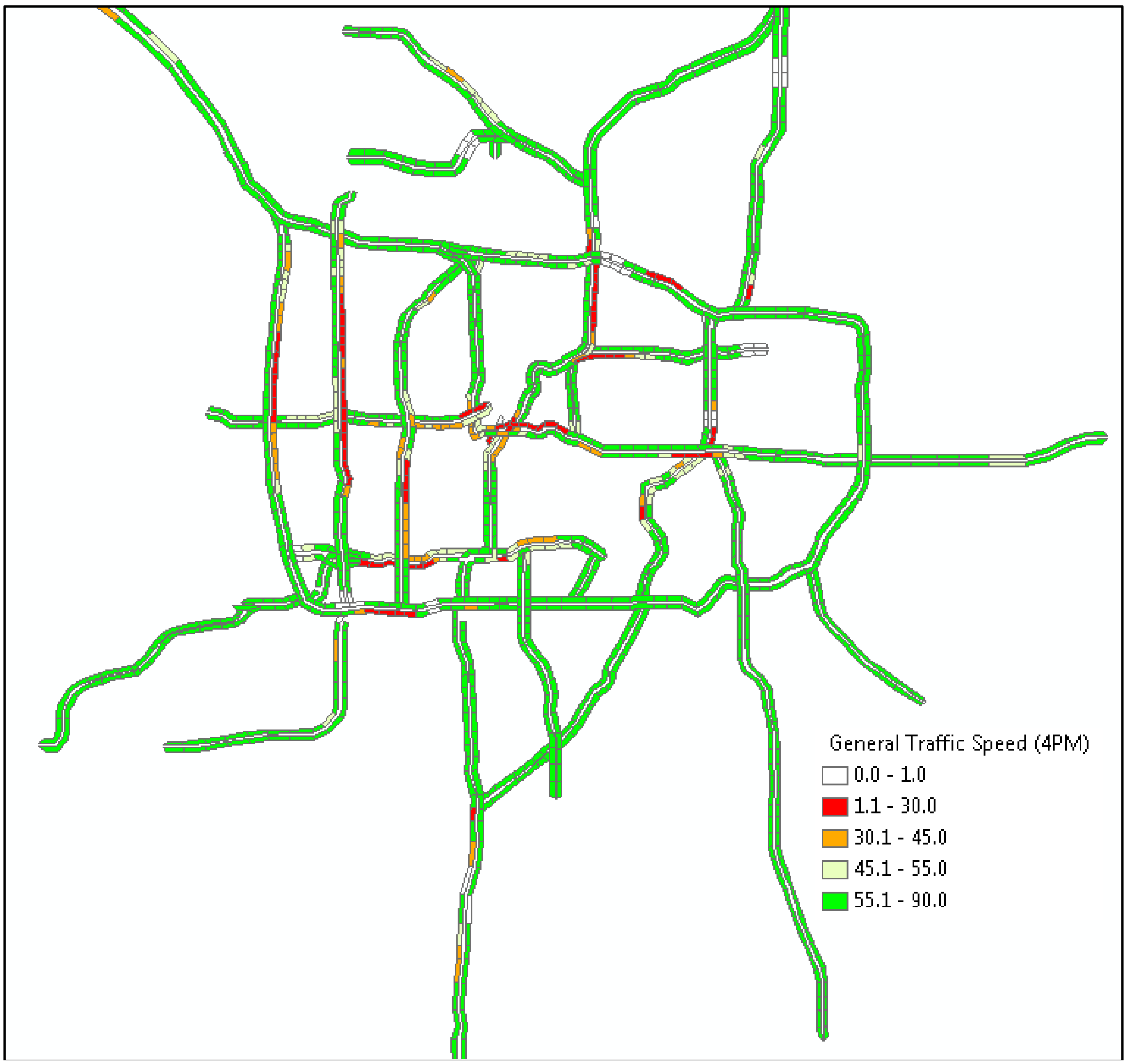

Figure F-17 General Traffic Speed from Loop Detectors (Oct. 2013 4PM)

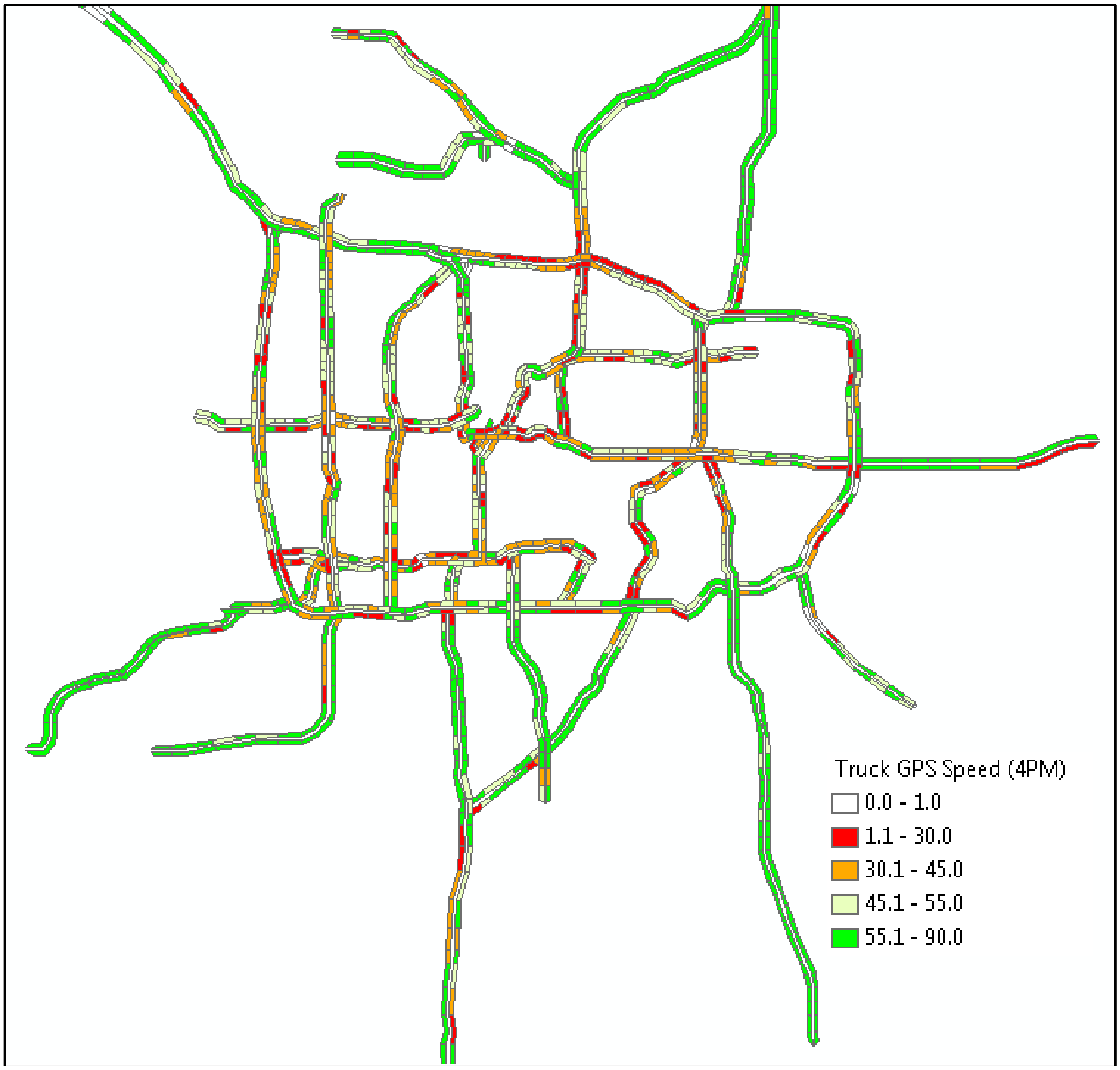

Figure F-18 Truck GPS Speed (Oct. 2013 4PM)

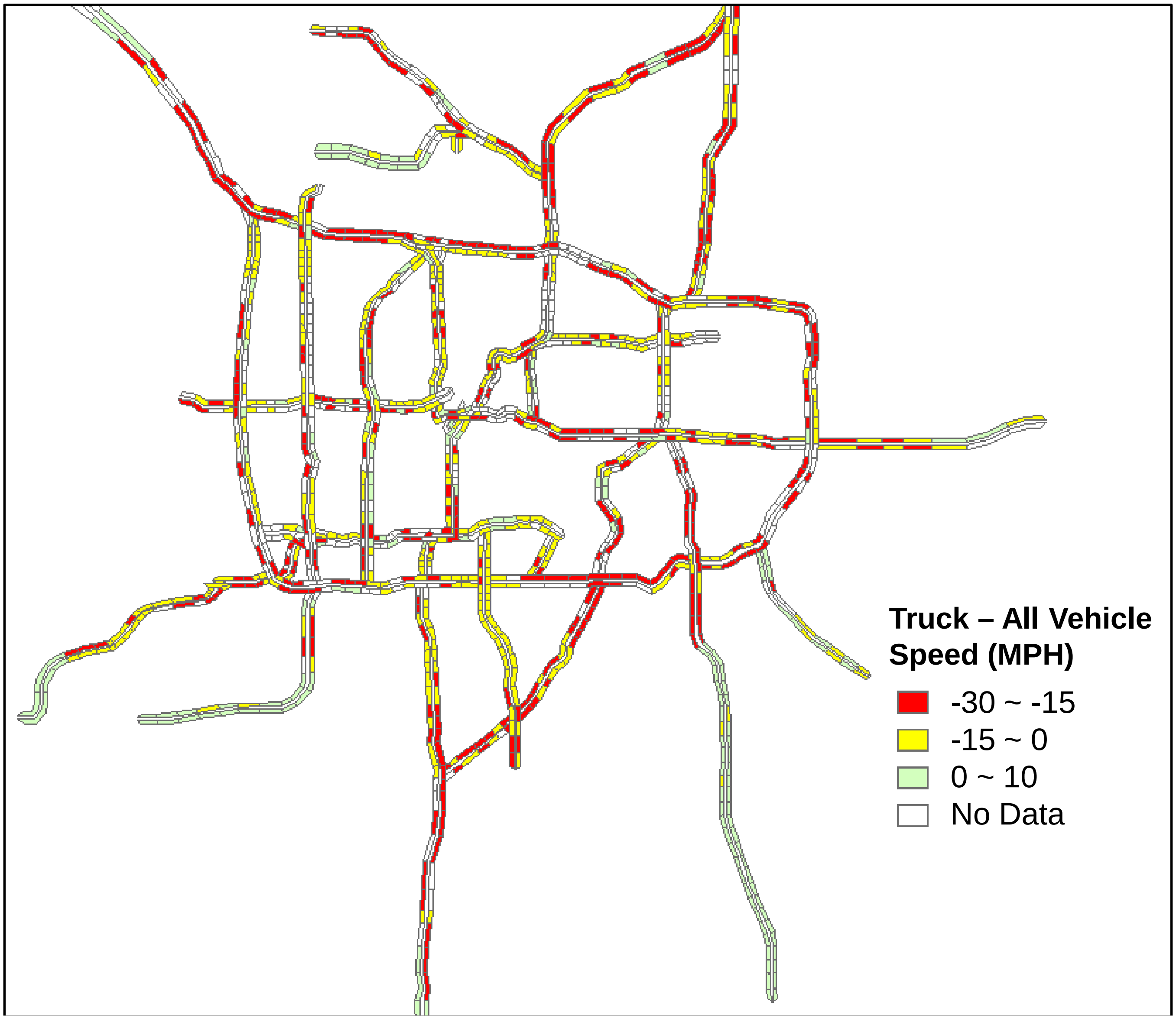

Figure F-19 Speed Difference: Truck GPS Speed – General Traffic Speed (Oct. 2013 4PM)

Table F-1 Summary of Speed Differences from Truck GPS and Loop Detectors

GPS Speed - Loop Detector Speed	Median (MPH)	Mean (MPH)	SD (MPH)	N
7 AM	-11.7	-10.7	14.9	1,337
4 PM	-12.2	-12.2	16.4	1,337

APPENDIX G. DATA PROCESSING SCRIPTS AND CODE SAMPLES

G.1 Sample SQL Scripts for GPS Data Processing

```
drop table if exists gps_snapped_ds_a2 ;
create table gps_snapped_ds_a2 (truckID varchar, gps_timestamp timestamp with time zone,
speed int, heading char(4),
pointID integer, routeID integer, segmentID integer, distance double precision, lref double precision);

create view tmp1 as
select pointid, min(distance) as distance from gps_snapped_ds_a
group by pointid;

insert into gps_snapped_ds_a2
select a.* from gps_snapped_ds_a a
inner join tmp1 b
on a.pointid=b.pointid
and abs(a.distance-b.distance)<1;
drop view tmp1 ;

-- Data Join to compute truck travel direction and space mean speed
-- sorted the table by trucked and gps_timestamp
drop table if exists gps_snapped_ds_a3 ;
create table gps_snapped_ds_a3 (ID SERIAL, truckID varchar, gps_timestamp timestamp with time zone,
speed int, heading char(4),
pointID integer, routeID integer, segmentID integer, distance double precision, lref double precision);

insert into gps_snapped_ds_a3 (truckID, gps_timestamp,
speed, heading, pointID, routeID, segmentID, distance, lref)
select truckID, gps_timestamp, speed, heading,
pointID, routeID, segmentID, distance, lref
from gps_snapped_ds_a2
order by truckid, gps_timestamp ;

-- join sorted table & compute speed
drop table if exists gps_snapped_ds_a4 ;
create table gps_snapped_ds_a4 (id1 integer, truckID varchar, gps_timestamp timestamp with time zone,
speed_mph1 int, heading char(4),
pointID integer, routeID integer, segmentID integer, distance double precision, lref double precision,
month int, day_of_week int, hour_of_day int,
id2 integer, gps_timestamp2 timestamp with time zone, speed_mph2 int,
mile_diff double precision, hour_diff double precision,
pointID2 integer, segmentID2 integer, distance2 double precision, lref2 double precision);

insert into gps_snapped_ds_a4
select a.*,
extract(month from a.gps_timestamp),
extract(dow from a.gps_timestamp),
extract(hour from a.gps_timestamp),
b.id, b.gps_timestamp, b.speed,
```

```
(b.segmentid-a.segmentid+b.lref-a.lref)* 0.621371,
(EXTRACT(EPOCH FROM b.gps_timestamp)-EXTRACT(EPOCH FROM a.gps_timestamp))/3600,
b.pointID, b.segmentID, b.distance, b.lref
from gps_snapped_ds_a3 a
left join gps_snapped_ds_a3 b
on a.truckid=b.truckid
and a.id+1=b.id
and a.routeid=b.routeid ;
```

G.2 Sample R Code for Statistical Analysis

```
par(mfrow=c(2,2))

# WEEKDAY ONLY
# DS-A
data<-read.csv(paste("E:/Chenfu/TCMA/Results/Exported CSV/Speed at intx/DS_A_weekday.csv",sep=""),
header=T)
p_spd = data$speed ;
p_spd_mean = mean(p_spd) ;
p_spd_mid = median(p_spd) ;
p_spd_sd = sd(p_spd) ;
hist(p_spd, main=sprintf("Space Mean Speed near Interchange, DS-A\nMn=%4.1f, Md=%4.1f,
Sd=%4.1f\nN=%d",p_spd_mean,p_spd_mid,p_spd_sd, length(p_spd)),
xlab="Speed (MPH)", xlim=c(0,100), freq=F, font.main=1)

# DS-B
data<-read.csv(paste("E:/Chenfu/TCMA/Results/Exported CSV/Speed at intx/DS_B_weekday.csv",sep=""),
header=T)
p_spd = data$speed ;
p_spd_mean = mean(p_spd) ;
p_spd_mid = median(p_spd) ;
p_spd_sd = sd(p_spd) ;
hist(p_spd, main=sprintf("Space Mean Speed near Interchange, DS-B\nMn=%4.1f, Md=%4.1f,
Sd=%4.1f\nN=%d",p_spd_mean,p_spd_mid,p_spd_sd, length(p_spd)),
xlab="Speed (MPH)", xlim=c(0,100), freq=F, font.main=1)

# DS-C
data<-read.csv(paste("E:/Chenfu/TCMA/Results/Exported CSV/Speed at intx/DS_C_weekday.csv",sep=""),
header=T)
p_spd = data$speed ;
p_spd_mean = mean(p_spd) ;
p_spd_mid = median(p_spd) ;
p_spd_sd = sd(p_spd) ;
hist(p_spd, main=sprintf("Space Mean Speed near Interchange, DS-C\nMn=%4.1f, Md=%4.1f,
Sd=%4.1f\nN=%d",p_spd_mean,p_spd_mid,p_spd_sd, length(p_spd)),
xlab="Speed (MPH)", xlim=c(0,100), freq=F, font.main=1)

# ALL DAYS ===================
```

```
par(mfrow=c(2,2))
# DS-A
data<-read.csv(paste("E:/Chenfu/TCMA/Results/Exported CSV/Speed at intx/DS_A.csv",sep=""), header=T)
p_spd = data$speed ;
p_spd_mean = mean(p_spd) ;
p_spd_mid = median(p_spd) ;
p_spd_sd = sd(p_spd) ;
hist(p_spd, main=sprintf("Space Mean Speed near Interchange, DS-A\nMn=%4.1f, Md=%4.1f,
Sd=%4.1f\nN=%d",p_spd_mean,p_spd_mid,p_spd_sd, length(p_spd)),
xlab="Speed (MPH)", xlim=c(0,100), freq=F, font.main=1)

# DS-B
data<-read.csv(paste("E:/Chenfu/TCMA/Results/Exported CSV/Speed at intx/DS_B.csv",sep=""), header=T)
p_spd = data$speed ;
p_spd_mean = mean(p_spd) ;
p_spd_mid = median(p_spd) ;
p_spd_sd = sd(p_spd) ;
hist(p_spd, main=sprintf("Space Mean Speed near Interchange, DS-B\nMn=%4.1f, Md=%4.1f,
Sd=%4.1f\nN=%d",p_spd_mean,p_spd_mid,p_spd_sd, length(p_spd)),
xlab="Speed (MPH)", xlim=c(0,100), freq=F, font.main=1)

# DS-C
data<-read.csv(paste("E:/Chenfu/TCMA/Results/Exported CSV/Speed at intx/DS_C.csv",sep=""), header=T)
p_spd = data$speed ;
p_spd_mean = mean(p_spd) ;
p_spd_mid = median(p_spd) ;
p_spd_sd = sd(p_spd) ;
hist(p_spd, main=sprintf("Space Mean Speed near Interchange, DS-C\nMn=%4.1f, Md=%4.1f,
Sd=%4.1f\nN=%d",p_spd_mean,p_spd_mid,p_spd_sd, length(p_spd)),
xlab="Speed (MPH)", xlim=c(0,100), freq=F, font.main=1)
```

G.3 Sample SQL Scripts for Delay Calculation

```
drop table if exists truck_delay_para;

create table truck_delay_para (
routeid int,
segmentid int,
hour_of_day int,
spd_avg double precision,
cnt int,
length double precision,
hcadt int,
hourly_count int,
total_count bigint,
vol_prop double precision,
dir int,
day_type varchar)

-- speed by segment, hr, dir
create view v1 as
```

```
select routeid, segmentid, hour_of_day, avg(speed) as spd_avg, count(speed) as cnt from
temp1 where day_of_week>0 and day_of_week<6
and dir=1
group by routeid, segmentid, hour_of_day;

-- sement length
create view v2 as
select a.gid as routeid, b.segment_id as segmentid,b.length
from tcma_final4 a
right join tcma_segments b
on a.name=b.route_name ;

-- join v1 & v2
create view v3 as
select a.*,b.length from v1 a
left join v2 b
on a.routeid=b.routeid and
a.segmentid=b.segmentid ;

-- join v3 with HCADT
Create view v4 as
select a.*, c.hcaadt from v3 a
left join hcaadt_2012 c
on a.routeid=c.routeid and a.segmentid=c.segmentid ;

-- join v4 with hourly_vol_percentage
create view v5 as
select a.*, b.hourly_count, b.total_count, b.vol_prop,b.dir,b.day_type from v4 a
left join hourly_vol_percentage b
on a.routeid=b.routeid and
a.segmentid=b.segmentid
and a.hour_of_day = b.hour_of_day
where b.dir=1 and b.day_type='weekday' ;

insert into truck_delay_para
select * from v5

-- group by segment - daily delay for 45MPH target speed
select routeid, segmentid, sum((length/spd_avg-length/45)/1609.344*vol_prop*hcadt/2) as
daily_delay_hr from truck_delay_para
where spd_avg>0 and spd_avg<45 and dir=1 and day_type='weekday'
group by routeid, segmentid
order by routeid, segmentid
```