

Measure of Truck Delay and Reliability at the Corridor Level

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LIST OF ABBREVIATIONS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AHTD	Annual Hours of Truck Delay
ATRI	American Transportation Research Institute
BFFS	Base Free Flow Speed
CEGE	Civil Environmental and Geo Engineering
CTS	Center for Transportation Study
DOT	Department of Transportation
FAST	Fixing America's Surface Transportation
FHWA	Federal Highway Administration
FPM	Freight Performance Measurement
GIS	Geographic Information System
GPS	Global Positioning System
HCAADT	Heavy Commercial Annual Average Daily Traffic
HOV	High Occupancy Vehicle
LBR	Localized Bottleneck Reduction
MAP-21	Moving Ahead for Progress in the 21 st Century
MnDOT	Minnesota Department of Transportation
MPO	Metropolitan Planning Organization
MTO	Minnesota Traffic Observatory
NHS	National Highway System
NPMRDS	National Performance Management Research Data Set
RI	Reliability Index
RTMC	Regional Traffic Management Center

TAP	Technical Advisory Panel
TCMA	Twin Cities Metro Area
TMC	Traffic Message Channel or Traffic Management Center
TTI	Texas Transportation Institute
TTTR	Truck Travel Time Reliability
TTR	Travel Time Ratio
UMN	University of Minnesota
USDOT	United States Department of Transportation
VOD	Value of Delay
WIM	Weight In Motion

EXECUTIVE SUMMARY

Freight transportation provides a significant contribution to our nation's economy. A reliable and accessible surface freight network enables business in the Twin Cities to be competitive in the Upper Midwest region. Many urban roadways are facing challenges with traffic volumes being over capacity during peak periods. As a result, time and money are lost due to traffic congestion. Operational and design constraints such as, interchange, steep grade, signalized intersection, work zone, merging, lane drop and others, could contribute additional delays for commercial vehicles.

The Minnesota Department of Transportation (MnDOT) freight office published a statewide freight system plan in November 2017. The statewide freight plan identified significant freight system trends, needs and issues. The multi-model plan provided a framework that included recommended freight policies, strategies and performance measures to guide decision making on future investments. The new plan will serve as a policy, project development and investment strategy to comply with Moving Ahead for Progress in the 21st Century (MAP-21) and Fixing America's Surface Transportation (FAST) Act requirements.

This project focuses on measuring the freight efficiency of the surface transportation network using available data from heavy commercial vehicles. The research team previously used private probe vehicle data to measure truck mobility on interstate highways in the Twin Cities Metropolitan Area (TCMA). Since July 2013, the Federal Highway Administration (FHWA) has procured a National Performance Management Research Data Set (NPMRDS) to support its Freight Performance Measurement (FPM) and urban congestion report programs. The NPMRDS includes probe vehicle based travel time data (for both passenger and freight vehicles) at 5-minute intervals for all National Highway System (NHS) facilities. The NPMRDS data is available for public agencies such as state Department of Transportations (DOT) and Metropolitan Planning Organizations (MPO).

This study leveraged our previous effort to measure freight mobility, reliability, and congestion measures by using 24-month of NPMRDS data in the TCMA. Key freight corridors were selected based on the *"Twin Cities Metropolitan Region Freight Study"* [1] jointly published by MnDOT and the Metropolitan Council. A data analysis framework was developed to process the NPMRDS data and generate performance measures. Truck mobility, travel time reliability and congestion measures were computed and analyzed.

Truck mobility analysis was performed by comparing the truck travel time with the passenger vehicle travel in each Traffic Message Channel (TMC) segment. Three reliability measures were also analyzed to evaluate the truck travel time reliability at both the TMC and corridor levels. Furthermore, truck delay during rush hours was computed on a GIS network by fusing truck volume, posted speed limit, and NPMRDS data. Truck bottlenecks were then identified based on the processed performance measures.

On average, roadways with signalized or un-signalized intersections have a higher percentage of truck-to-car travel time ratio (TTR). In general, trucks travel an average of 10% more slowly than cars on freeways. As listed in Table ES.1, trucks on the US and interstate highways have about a 10% longer

travel time than cars. On state highways, the TTR reaches 1.2 and 1.4 in the AM and PM peak periods, respectively. Trucks travel significantly slower than cars on county roads. The TTR on county roads is around 1.5 during mid-day and spikes to 1.7 and 1.9 in the AM and PM peak periods, respectively. The increase of TTR on county roads may largely be due to number of intersections in a TMC segment and delays at signalized intersections.

Table ES.1 Average Median Travel Time Ratio by Roadway Type

AVG of Median TTR	Time Period		
	Roadway Type	AM Peak	Mid-Day
U.S. Highway	1.07	1.06	1.09
Interstate Highway	1.09	1.08	1.13
MN State Highway	1.19	1.13	1.37
County Road	1.68	1.49	1.85
Others	1.28	1.20	1.29

Three truck travel time reliability metrics were selected by the Technical Advisory Panel (TAP) for analysis and comparison. All reliability measures indicated that the truck travel time in the PM peak period was less reliable than the travel time in the AM peak period. Similar to the TTR measure, roadways with signalized or un-signalized intersections were generally less reliable than freeways. At the corridor level, the TTTR95 measure was much higher than the RI95 measure. The variability of TTTR95 was also higher than the RI95 measure. This was mostly caused by the long-tail distribution of truck travel time from the NPMRDS data.

A truck congestion measure was computed by comparing the travel time with a target travel time at base free-flow speed (BFFS) in each TMC segment. Table ES.2 lists the top 5 corridors with significant truck delays in the studied area. I-35W, I-94, US-169, I-494, and MN-55 have an average total truck delay of over 3,000 hours in the AM peak period. And, I-94, I-35W, I-494, US-169, I-694 and MN-55 have an average total truck delay of over 3,000 hours in the PM peak period. Overall, the truck delay during the PM peak was more significant than the delay in the AM peak.

Table ES.2 Top 5 Most Congested Freight Corridors in TCMA

AM Peak		PM Peak	
Corridor	Delay (Hours)	Corridor	Delay (Hours)
I-35W	5,464	I-94	7,519
I-94	4,659	I-35W	6,804
US-169	4,532	I-494	6,741
I-494	3,719	US-169	6,117
MN-55	3,589	I-694	3,693

In the AM Peak, interchanges at I-694 & US-169, I-394 & US-169, I-35W & I-494, I-394 & I-94, I-35E & I-94, I-35E & I-694, and US-52 & I-94 were congested. In addition, roadway segments at I-35W NB between MN-13 and CR-42 had an average truck delay of over 300 hours per mile in the AM peak.

In the PM peak, the major truck congestions occurred at I-394 & US-169, I-494 & MN-100, I-35W & I-494, I-394 & I-94, I-35W & I-94, I-35W & I-694, I-35E & I-694, I-94 & I-35E and US-52 & I-94 interchanges. In addition, segments at I-94 WB between US-169 and I-494, I-394 EB between MN-100 & I-94, I-35W NB S of Downtown Minneapolis, I-35W SB N of I-94, I-94 WB between MN-280 and I-394, I-35W NB between MN-36 and I-694, I-94 EB W of Downtown St. Paul, and I-494 EB between US-169 and I-35W, had significant truck delay.

Table ES.3 presents a list of TMC segments (non-interchange locations) with recurring truck delays in the PM peak period on an average weekday. Among the 6 congested locations, TMC 118P04198 & TMC 118P04199 segments (I-94 WB at I-35W in Minneapolis) had the highest truck delay per mile in the PM peak on an average weekday. Average truck delay in the PM peak in this segment was 570 hours per mile, or 775 hours in total. TMC 118P04237 (I-35W NB south of Downtown Minneapolis) had the second highest truck delay in the PM peak on an average weekday. Average truck delay in the PM peak in this segment was 523 hours per mile. TMC 118N04188 (I-94 EB west of Downtown St. Paul) has the third highest truck delay in the PM peak on a regular weekday. Average truck delay in the PM peak in this segment was 495 hours per mile, or 366 hours in total.

After individual congestion evaluation at each location, the research team found that insufficient capacity, increasing demand, roadway geometry (e.g., horizontal or vertical curves, lane configuration changes), and density of weaving points were the key causes of delays among the 6 investigated truck bottlenecks. Future research will leverage this effort to develop mitigation strategies on significant freight corridors in the TCMA.

Table ES.3 Top Congested TMC Segments in the PM Peak on a Weekday

Ranking	TMC	Location Description	Length (Miles)	Average Hours of Delay Per Mile (Hours)	Total Segment Delay (Hours)
1	118P04198 118P04199	I-94 WB at I-35W	1.36	570	775
2	118P04237	I-35W NB South of Downtown Minneapolis	1.00	523	523
3	118N04188	I-94 EB at Marion Street	0.74	495	366
4	118N04131 118N04133	I-494 EB at MN-100	2.33	480	1,118
5	118P04153	I-694/94 WB West of US-169	1.17	321	376
6	118P04354	I-394 EB West of I-94	1.23	310	381

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Freight transportation provides a significant contribution to our nation's economy. A reliable and accessible freight network enables business in the Twin Cities Metropolitan Area (TCMA) to be competitive in the Upper Midwest region. Many urban roadways are facing challenges with traffic volumes being over capacity during peak periods. As a result, time and money are lost due to traffic congestion. Operational and design constraints such as, interchange, steep grade, signalized intersection, work zone, merging, lane drop and others, could contribute additional delays for commercial vehicles.

MnDOT and the Metropolitan Council conducted a study in 2012 to evaluate the regional freight transportation system. A joint report, titled "*Twin Cities Metropolitan Region Freight Study*" [1] published in August 2013, suggested a need to understand where and when trucks are most affected by highway congestion. Development of a framework for truck data collection and analysis is necessary to better understand the relationships between peak hour truck traffic and peak congestion. In addition, the report recognized the concerns of increasing freight shipping costs caused by congestion delays. Cost-effective and operationally focused solutions are needed to improve travel time reliability. Performance measures derived from this study can also be used to calibrate truck model parameters in Met Council's transportation planning and forecasting model.

A framework for truck data collection and analysis was recommended to better understand the relationships between truck traffic and congestion in peak periods. Building on our previous study to measure freight mobility and reliability along key freight corridors in the TCMA, this study leveraged our previous development to calculate the truck mobility measures using the National Performance Measurement Research Dataset (NPMRDS) from the US Department of Transportation (USDOT).

In July 2013, the Federal Highway Administration (FHWA) announced the NPMRDS to support its Freight Performance Measurement (FPM) and urban congestion report programs. The NPMRDS includes probe vehicle based travel time data (for both passenger and freight vehicles) at 5-minute intervals for all National Highway System (NHS) facilities. NPMRDS travel time is reported based on Traffic Message Channel (TMC) segments with link length varying from less than a mile to several miles. NPMRDS is intended for state agencies to measure system performance in meeting new federal performance management requirements. However, it may be difficult to extract information from the average travel time at 5-minute intervals for analyzing traffic dynamic at the per vehicle level and assessing the impact of signal delay within a relatively long TMC segment.

The NPMRDS data contains a static GIS file and a database file. The GIS shapefile containing static roadway information was used to relate the travel time information to each roadway segment. The GIS shapefile was provided for visualizing and geo-referencing the NPMRDS data to different maps. The TMC file contains TMC segment geometry information. A database file set includes average travel times of

passenger, freight and the two combined for identified roadways geo-referenced to TMC segment IDs. In addition, a lookup table that relates the TMC ID to the link ID in the shapefile was also provided to analyze NPMRDS data by geographic location.

The TMC static data file is a point data file that describes one end of a TMC roadway segment. The static file includes the following information. A sample data is displayed in Table 1.1.

- TMC ID
- Country
- State
- County
- Distance (length of TMC in miles)
- Road number
- Road name
- Latitude
- Longitude
- Road direction

Table 1.1 Sample TMC static data

TMC	Country	State	County	Distance	Road Number	Road Name	Latitude	Longitude	Road Direction
118N04099	USA	Minnesota	Hennepin	1.28431	I-494		44.86872	-93.43246	Southbound
118N04111	USA	Minnesota	Ramsey	1.8147	I-494		44.91665	-92.97905	Eastbound
118N04112	USA	Minnesota	Washington	1.12039	I-494		44.89216	-92.99921	Eastbound
118N04113	USA	Minnesota	Dakota	0.21498	I-494		44.88339	-93.01437	Eastbound

The NPMRDS travel time data file includes the following information. A sample NPMRDS data is listed in Table 1.2.

- TMC ID
- Date (MMDDYYYY)
- Epoch (5-minute increment, in the range 0-287)
- Travel time – all vehicles (seconds)
- Travel time – passenger vehicles (seconds)
- Travel time – freight vehicles (seconds)

Table 1.2 Sample NPMRDS Data

TMC	DATE	EPOCH	Travel TIME ALL VEHICLES	Travel TIME PASSENGER VEHICLES	Travel TIME FREIGHT TRUCKS
118N04099	12012016	61	73	70	75
118N04099	12012016	62	70	70	
118N04099	12012016	63	72	70	73
118N04099	12012016	64	74	74	
118N04099	12012016	66	72	72	72

1.2 OBJECTIVE

This study uses 24 months of NPMRDS data to compute and compare truck mobility and reliability measures at the corridor level. In addition, average daily truck delays are calculated to assess impact of truck congestions and identify any operational bottlenecks or physical constraints. Trucking activity nearby a congested area is further examined to analyze traffic pattern and investigate possible causes of recurring congestions.

1.3 LITERATURE REVIEW

The MnDOT freight office released the statewide freight system plan in November 2017 [2]. The statewide freight plan identified significant freight system trends, needs and issues. The multi-model plan provided a framework that includes recommended freight policies, strategies and performance measures to guide decision making on future investments. The new plan will be developed as a policy, project development and investment strategy, in compliance with Moving Ahead for Progress in the 21st Century (MAP-21), highlighting best practices, Minnesota initiatives, cooperative partnership and associations [3].

One of the key elements of the MAP-21 act is to focus on performance and outcome-based programs. American Association of State Highway and Transportation Officials (AASHTO) is working on recommendations of performance measures in 6 areas (safety, pavement condition, bridges, freight, system performance, and congestion mitigation and air quality) to help state agencies meet new federal performance management requirements. Performance measures in categories such as, safety, maintenance, mobility, reliability, congestion, accessibility, and environment, are recommended for the freight.

Travel time reliability is one of the key measures of freight performance along interstates or interregional corridors in the nation [4, 5]. Pu examines several reliability measures and recommended a median-based buffer index or a failure rate estimate as more appropriate to handle heavily skewed travel time distributions [6].

FHWA has established a partnership with the American Transportation Research Institute (ATRI) and the trucking industry since 2002 to measure average truck travel speed on major freight-significant corridors in North America [7]. A spatial data processing methodology has been evaluated, refined, and assisted by Liao [8] to improve the effectiveness of generating freight performance measures (FPM). Analyses of truck speed, volume and travel time by location help identify network impediments and variations of seasonal flow changes [9]. Derived vehicle speed and travel time from GPS and/or terrestrial wireless systems used by the trucking industry provide potential opportunities to support freight planning and operations on the surface transportation system.

In Washington state, McCormack and Hallenbeck used 25 portable GPS data collection units with a 1-second polling rate to gather truck positioning data for measuring freight movements along freight significant corridors [10]. 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 [11].

FHWA is leading the effort to assess 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 Freight Performance Measurement (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 [12]

In July 2013, the FHWA announced the NPMRDS to support its FPM and urban congestion report programs. The NPMRDS includes probe vehicle based travel time data (for both passenger and freight vehicles) for every 5-minute interval 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 the U.S.

Liao conducted a study to generate and analyze freight performance measures along 38 key freight corridors in the TCMA and four major freight corridors that connect the Twin Cities to three regional freight centers (St. Cloud, Mankato, and Rochester) outside the TCMA [13]. 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). Truck bottlenecks were also identified and ranked based on hours of truck delay and the number of hours with speeds less than the target speeds (set by MnDOT) during the peak periods.

For congestion mitigation, FHWA has initiated a localized bottleneck reduction (LBR) program to focus on the causes, impacts, and potential solutions for recurring congestions. Several studies have been conducted to help agencies reduce localized bottleneck congestion [14-17].

The cost of traffic mobility deficiencies can be estimated as a means of expressing the financial impact of congestion. The congestion cost measures can have utility to both transportation decision-makers and system users when they accurately reflect the tangible costs of transportation use on congested facilities. Adams et al. evaluated the value of delay (VOD) to commercial vehicle operators due to

highway congestion by including factors such as direct operational cost, travel length, travel time variation, inventory holding, and warehouse management [18].

The annual Urban Mobility Scorecard [19] produced by Texas Transportation Institute (TTI) measures the costs of congestion at both the national and local levels. The 2015 report estimated that the overall cost of congestion in the US was \$160 billion (using 2014 data) based on wasted fuel and lost productivity. In the Minneapolis-St. Paul, Minnesota, area, the cost of annual truck congestion was \$327 million and the total congestion cost was \$2.196 billion in 2014. The estimated cost of truck congestion in 2014 was \$94 per hour.

In addition, the ATRI has conducted an analysis to assess the operational costs of truck delays since 2008. Its recent update [20], *An Analysis of the Operational Costs of Trucking: 2017 Update*, reported that the total marginal costs for the industry across all sectors, fleet sizes and regions were \$1.592 per mile and \$63.66 per hour based on 2016 data.

1.4 REPORT ORGANIZATION

This report is organized as follows. Key freight corridors are identified and presented in Chapter 2. Chapter 3 defines the performance measures for truck mobility, travel time reliability, and congestion. Results from a performance measure analysis are presented and discussed in Chapter 4. Potential causes of truck congestion at 6 locations in the TCMA are further investigated and discussed in Chapter 5. Finally, summary and discussion of this study are presented in Chapter 6. Additional analyses of truck travel time reliability comparison at both the TMC and corridor levels are included in Appendix A and hourly truck volume distribution is included in Appendix B.

CHAPTER 2: IDENTIFY KEY FREIGHT CORRIDORS

The research team worked with MnDOT staff and TAP members to prioritize a list of key truck corridors with recurring congestion in peak periods in the Twin Cities Metro Area (TCMA). Monthly NPMRDS data were analyzed to measure travel time reliability and estimate truck delay at the corridor level, and then to identify system impediments during peak hours. A TAP meeting was held to finalize a list of key freight corridors to measure truck delay and reliability.

Met Council provided a GIS map (see Figure 2.1) of a tiered based freight corridor in the Twin Cities 7-county metro area [21]. Weighted score of each corridor was computed by applying weights to average daily truck volumes (60%), truck percent of total traffic (20%), proximity to freight clusters (10%), and proximity to freight facilities (10%). Freight Clusters identified through analysis of intensity of freight-generating establishments in four sectors including consumer goods, natural resources, manufacturing, and transportation / logistics [21].

The research team compared the Met Council's regional truck corridor map with the NPMRDS map where truck travel time data is available. As displayed in Figure 2.2, the blue lines represent the tiered based truck corridors with NPMRDS data and the red lines are the tiered based corridors where NPMRDS data is not available. The green lines represent the other (non-freight significant) corridors with NPMRDS data in the Twin Cities metro area.

Figure 2.3 display the regional corridors (Tier 1 to 3) where NPMRDS data is available. A list of the corridors is included in Table 2.1. After the approval from the TAP, truck performance measures of the corridors listed in Table 2.1 were processed and analyzed using NPMRDS data from 2015 and 2016.

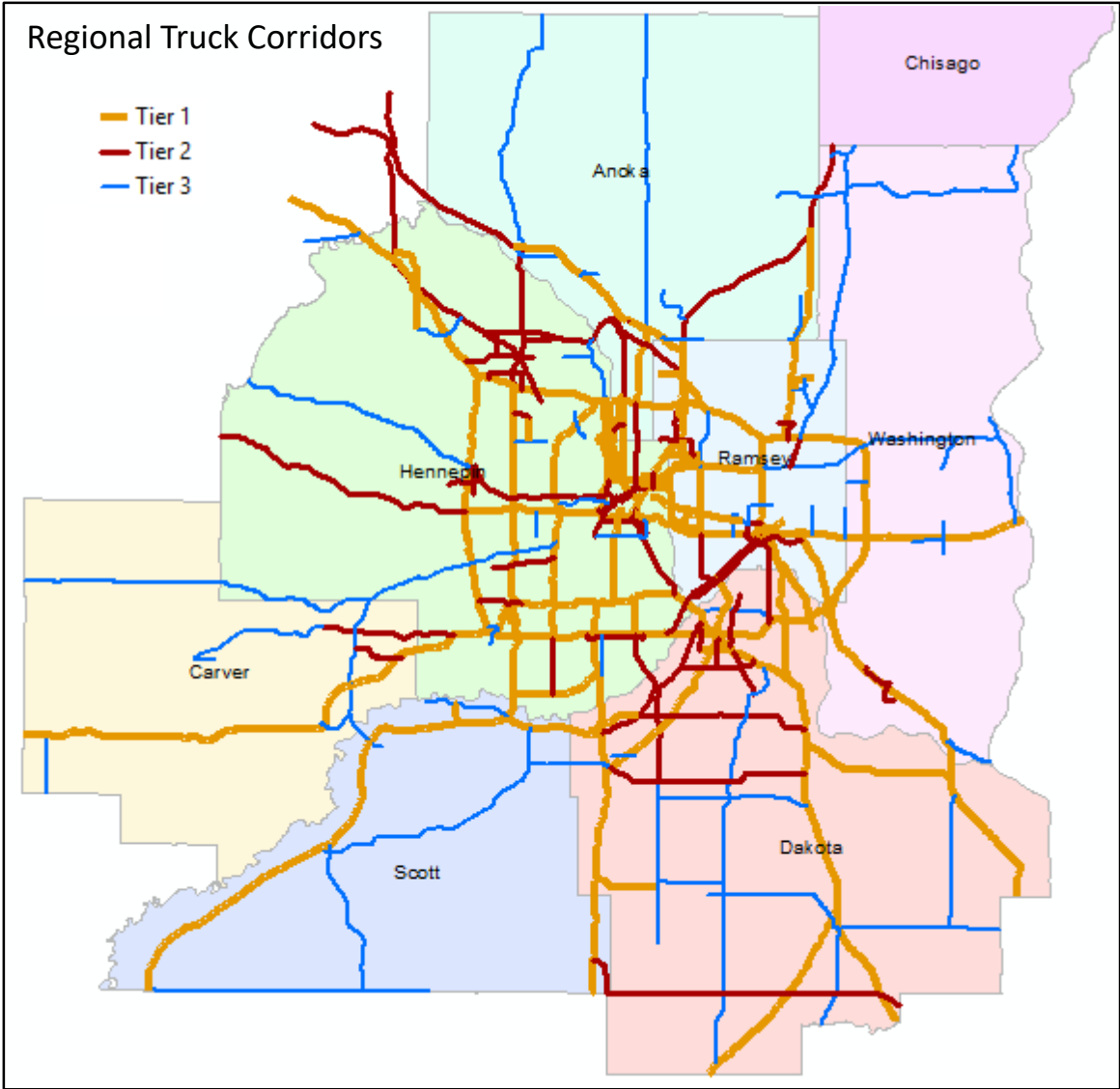


Figure 2.1 Tiered Based Regional Truck Corridors from the Met Council Truck Study.

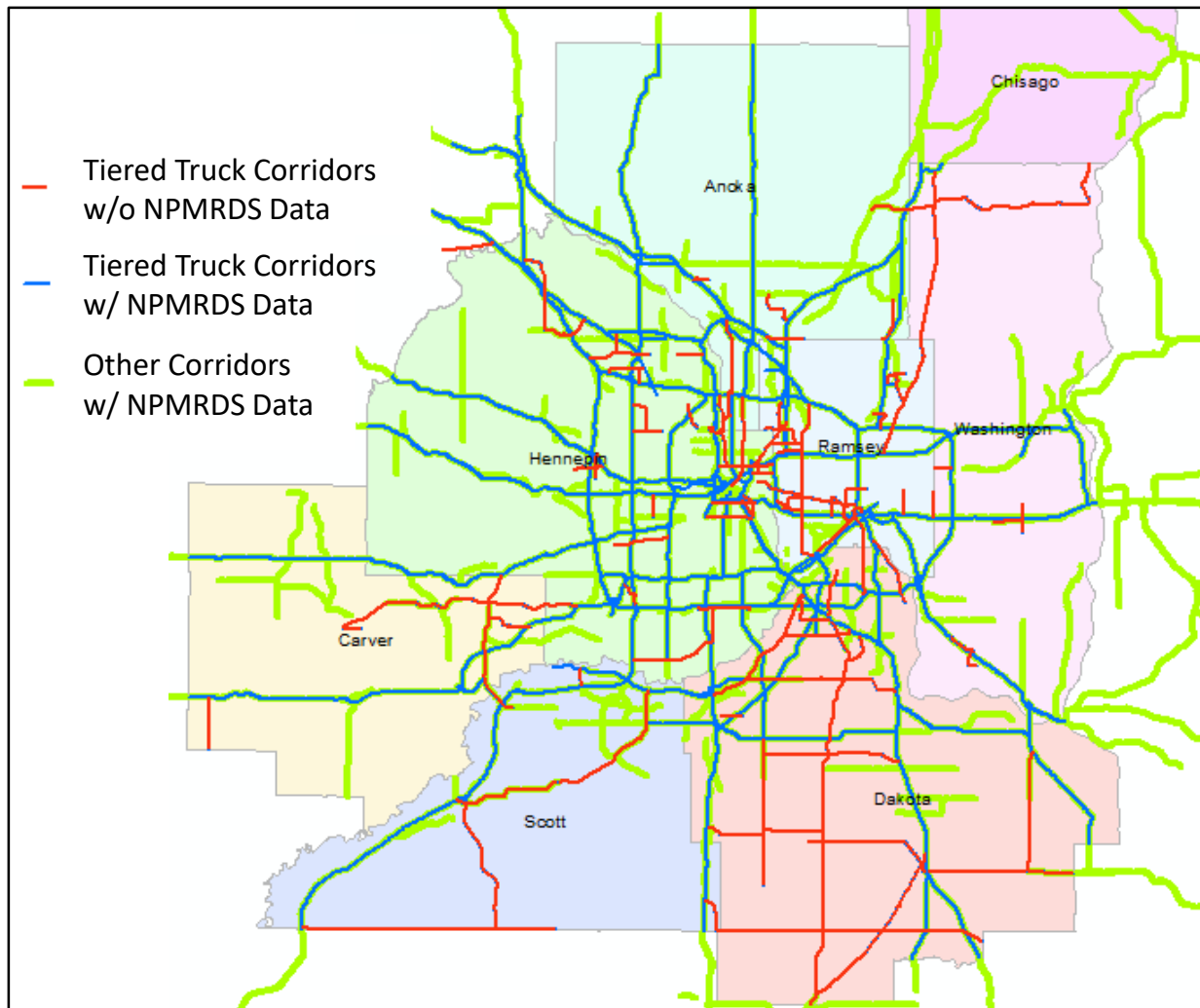


Figure 2.2 Comparison of Truck Corridors with or without NPMRDS Data.

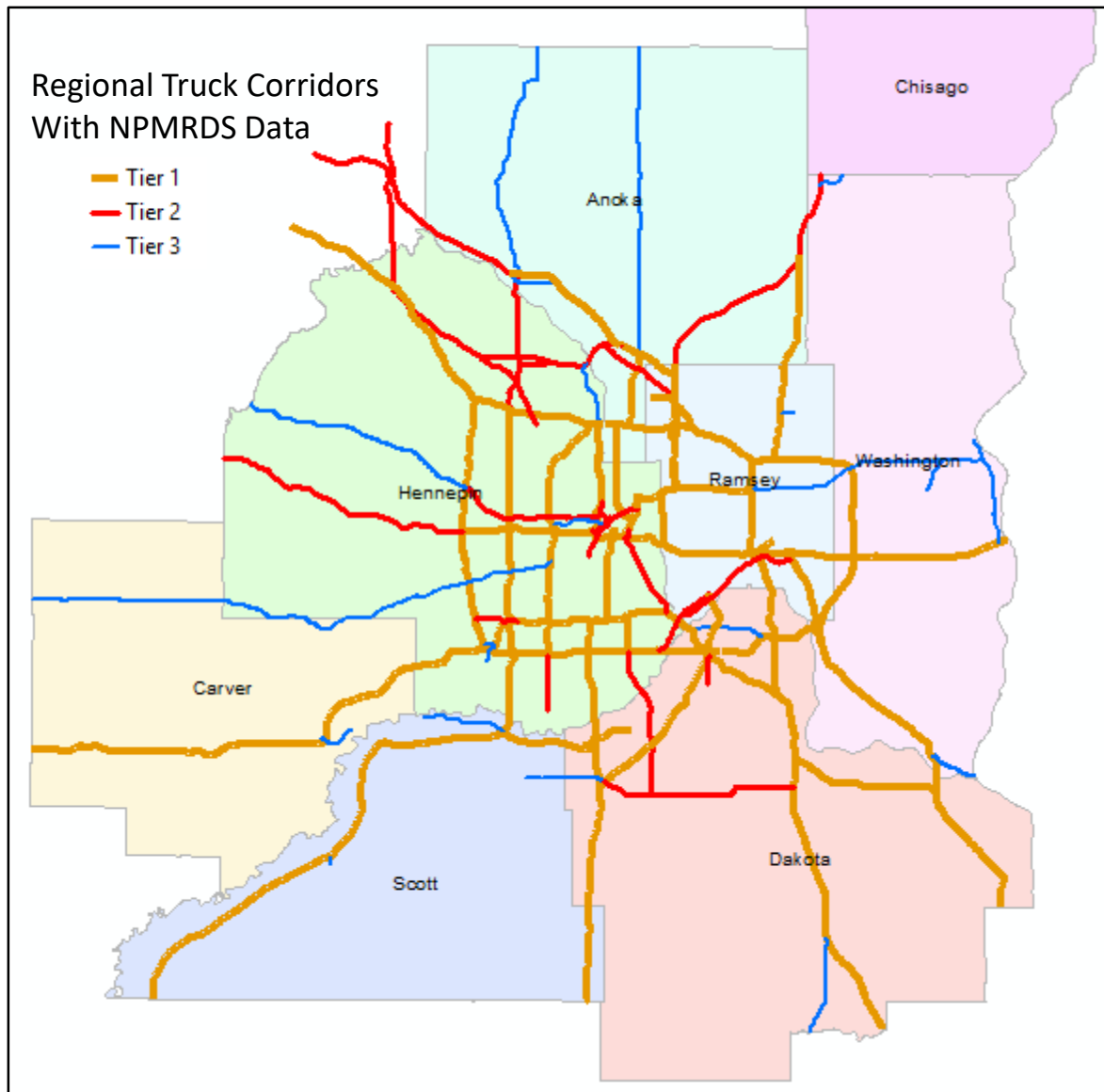


Figure 2.3 Tiered Based Truck Corridors with NPMRDS Data Coverage.

Table 2.1 List of Tiered Corridors with NPMRDS Data

Tier	Road Class	Route Number	Route Name
Tier 1	Interstates	94	
Tier 1	Interstates	35	
Tier 1	Interstates	694	
Tier 1	Interstates	494	
Tier 1	Interstates	394	
Tier 1	Other NHS	10	
Tier 1	Other NHS	65	
Tier 1	Other NHS	169	

Tier 1	Other NHS	100	
Tier 1	Other NHS	280	
Tier 1	Other NHS	36	
Tier 1	Other NHS	62	
Tier 1	Other NHS	212	
Tier 1	Other NHS	13	
Tier 1	Other NHS	77	
Tier 1	Other NHS	52	
Tier 1	Other NHS	55	
Tier 1	Other NHS	61	
Tier 1	A-Minor Arterials	47	University Ave NE
Tier 1	A-Minor Arterials	77	Old Hwy 8
Tier 1	A-Minor Arterials		Lyndale Ave N
Tier 1	A-Minor Arterials		Fort Rd
Tier 1	A-Minor Arterials	32	Cliff Rd
Tier 1	A-Minor Arterials	46	Cleveland Ave
Tier 1	A-Minor Arterials		7th Ave
Tier 1	A-Minor Arterials		Johnson St NE
Tier 2	Other NHS	101	
Tier 2	Other NHS	610	
Tier 2	Other NHS	5	
Tier 2	Other NHS	12	
Tier 2	Other NHS	37	Shepard Rd, Warner Rd
Tier 2	Other NHS	42	County Rd 42
Tier 2	A-Minor Arterials	81	Bottineau Blvd
Tier 2	A-Minor Arterials		E Hennepin Ave
Tier 2	A-Minor Arterials		Hennepin Ave S
Tier 2	A-Minor Arterials		Lexington Ave S
Tier 2	A-Minor Arterials	34	Normandale Blvd
Tier 2	A-Minor Arterials		Cedar Ave
Tier 2	A-Minor Arterials	30	93rd Ave N
Tier 3	Other NHS	252	
Tier 3	Other NHS	36	
Tier 3	Other NHS	7	
Tier 3	Other NHS	42	Eagan Dr.
Tier 3	Other NHS	8	
Tier 3	A-Minor Arterials	110	
Tier 3	A-Minor Arterials		Main St
Tier 3	A-Minor Arterials	96	Hwy 96 E
Tier 3	A-Minor Arterials	56	
Tier 3	A-Minor Arterials	40	Glenwood Ave
Tier 3	A-Minor Arterials	95	
Tier 3	A-Minor Arterials	5	Stillwater Blvd N
Tier 3	A-Minor Arterials		Flying Cloud Dr., Valley View Rd
Tier 3	A-Minor Arterials		Chaska Blvd

Table 2.2 Roadway Mileage by Road Class for Tiered Corridors with NPMRDS Data

Road Type	Centerline Length (Mile)
Interstates	224.0
Other NHS	438.0
A-Minor Arterials	127.5
Total	789.5

CHAPTER 3: PERFORMANCE MEASURES

3.1 PROCESS NPMRDS DATA

The 2015 and 2016 (24 months) FHWA National Performance Management Research Data Set (NPMRDS) was received from MnDOT. The travel time data (in 5-min intervals) and truck volume data have been imported to our database in order to compute performance measures on the selected truck highway corridors. A GIS shapefile containing static roadway information was used to relate the travel time information to each roadway segment. A Traffic Message Channel (TMC) file contains TMC segment geometry information. A database file set includes average travel times of passenger, freight and combined for identified roadways geo-referenced to TMC segment IDs.

The research team processed 24 months of NPMRDS data and generated monthly mobility and reliability measures for each TMC segment in the study area. Truck travel time reliability measures and delay were processed using the following steps.

1. Load NPMRDS data to SQL database
2. Joint NPMRDS travel time data to TMC links in GIS
3. Process truck speed in mid-day and AM/PM peak periods by roadway segment
4. Process truck reliability by time period and by roadway segment
5. Estimate truck delay by roadway segment for AM and PM peak hours
6. Data aggregation

Based on the feedback from the TAP, truck reliability and delay measures were computed for each time period as listed in Table 3.1.

Table 3.1 Time Periods

Time Period	Duration
Weekday AM Peak	6AM – 10AM
Weekday Mid-Day Peak	10AM – 4PM
Weekday PM Peak	4PM – 8PM
Weekend	6AM - 8PM

3.2 PERFORMANCE MEASURES

Truck to car travel time ratio, truck travel time reliability and truck delay were defined and presented as follows.

3.2.1 Mobility Measure

The travel time ratio (TTR) is defined as the truck travel time divided by the passenger vehicle travel time (Eq. 3-1). The travel time ratios for each TMC segment in each 5-minute interval were computed in the AM, mid-day, and PM peak periods using the 24-month NPMRDS data.

$$TTR = \frac{\text{Median Truck Travel Time in 5 min.}}{\text{Median Car Travel Time in 5 min.}} \quad (3-1)$$

3.2.2 Truck Travel Time Reliability

Three truck travel time reliability measures, RI95, TTTR80, and TTTR95, were recommended by the TAP to investigate the differences and effectiveness. The RI95 measure is defined as the 95th percentile truck travel time divided by the average truck travel time in each TMC segment, as calculated using Eq. (3-2) for each time period.

$$RI95 = \frac{\text{95th Percentile Truck Travel Time}}{\text{Average Truck Travel Time}} \quad (3-2)$$

The TTTR80 measure is defined as the 80th percentile truck travel time divided by the median truck travel time in each TMC segment, as calculated using Eq. (3-3) for each time period.

$$TTTR_{80} = \frac{\text{80th Percentile Truck Travel Time}}{\text{50th Percentile Truck Travel Time}} \quad (3-3)$$

Similarly, the TTTR95 measure is defined as the 95th percentile truck travel time divided by the median truck travel time in each TMC segment, as calculated using Eq. (3-4) for each time period.

$$TTTR_{95} = \frac{\text{95th Percentile Truck Travel Time}}{\text{50th Percentile Truck Travel Time}} \quad (3-4)$$

3.2.3 Truck Delay

Truck delay was computed by comparing the actual and targeted travel time in each TMC segment, as defined in Eq. (3-5). Truck delays were calculated for AM and PM peak periods on weekdays. The computed monthly delay result contains performance measures for AM and PM peak periods, as listed in Table 3-1. The target speed or threshold speed in Eq. (3-5) is determined using the recommendation from the “*Developing Twin Cities Arterial Mobility Performance Measures Using GPS Speed Data*” report [22] (p.15-19). Roadway speed limit dataset was obtained from MnDOT to determine base free-flow speed (BFFS) for delay computation. The BFFS is determined based on the speed limit and guidance from the highway capacity manual using the following equation [23]. The maximum BFFS is set to 68 MPH for all trucks.

$$Delay_{rte} = \sum_{seg} \sum_{hr} (Truck_Travel_Time - \frac{Segment\ Length}{BFFS}) \times Volume_{hr, seg} \quad (3-5)$$

BFFS	= 40 mph,	for posted speed limits < 40 mph
	= Speed Limit + 7,	for posted speed limits 40 - 45 mph
	= Speed Limit + 5,	for posted speed limits ≥ 50 mph

(3-6)

In addition, the NPMRDS dataset does not include sample size of the probe vehicle information. Truck volume data (HCAADT) and hourly truck volume distribution from our previous study [9] were used to estimate truck delay at each roadway segment in the AM and PM peak periods.

CHAPTER 4: DATA ANALYSES

Truck mobility, travel time reliability and delay analyses were performed and discussed this chapter. Truck mobility analysis was conducted (Chapter 4.1) by comparing the truck travel time with the passenger vehicle travel in the same TMC segment. In addition, 3 reliability measures (RI95, TTTR80, and TTTR95) were analyzed to evaluate the truck travel time reliability at the corridor level (Chapter 4.2). Furthermore, truck delay was computed by using truck volume data and truck bottleneck was identified by using the processed performance measures (Chapter 4.3).

4.1 MOBILITY ANALYSIS

The travel time ratio (TTR) is defined as the truck travel time divided by the passenger vehicle travel time (Eq. 3-1). The travel time ratios for each TMC segment in each 5-minute interval were computed in the AM, mid-day, and PM peak periods using the 24-month NPMRDS data. For example, a TTR value of 1.0 means that, on average, the trucks and the passenger vehicles have the same travel time. Similarly, a TTR value of 1.2 means that, on average, truck travel time is 20% longer than car travel time.

Figure 4.1 displays the average median TTR and the corresponding standard deviation (SD) of TTR in the AM peak period in each month for the entire network. The network-wide monthly TTR in the AM peak period is relatively steady, around 1.3, over the 24-month period with an SD varying from 1 to 2.4. The average network-wide median TTR during mid-day is about 1.2 with an SD varying from 0.7 to 2.2 as shown in Figure 4.2. Similarly, the network-wide monthly median TTR in the PM peak period is around 1.3 over the 24-month period with an SD varying from 1 to 2.9 as displayed in Figure 4.3. The variations of standard deviation of TTR in the PM peak is significantly larger than the variations in the AM and mid-day periods. This is probably caused by increasing trucking activities and dynamic nature of traffic congestion in the PM peak period.

According to studies conducted by Puget Sound Regional Council [24], trucks travel by an average of 10% slower than cars on freeways. Based on the NPMRDS data in the Twin Cities metro area, the 24-month average of median travel time ratio in each epoch (a 5-minute interval) in a month by roadway type and time period is listed in Table 4.1. In general, trucks on the US and interstate highways have about 10% longer travel time than cars. On state highway, the TTR reaches to 1.2 and 1.4 in the AM and PM peak periods, respectively. Trucks travel significantly slower than cars on county roads. The TTR on county road is around 1.5 during mid-day and the TTR spikes to 1.7 and 1.9 in the AM and PM peak periods, respectively. The increase of TTR on county road may largely contributed by number of intersections in a TMC segment and delays at signalized intersections.

It is suggested that a reasonable range of median TTR would be less than 1.2 for trucks traveling on highways. Highway TMC segments with TTR greater than 1.2 require further investigation to understand the possible causes. A reasonable range of TTR for arterials requires additional investigation since it could be affected by number of traffic lights in a TMC segment.

Table 4.1 Average Median Travel Time Ratio by Roadway Type

AVG of Median TTR	Time Period		
	AM Peak	Mid-Day	PM Peak
U.S. Highway	1.07	1.06	1.09
Interstate Highway	1.09	1.08	1.13
MN State Highway	1.19	1.13	1.37
County Road	1.68	1.49	1.85
Others	1.28	1.20	1.29

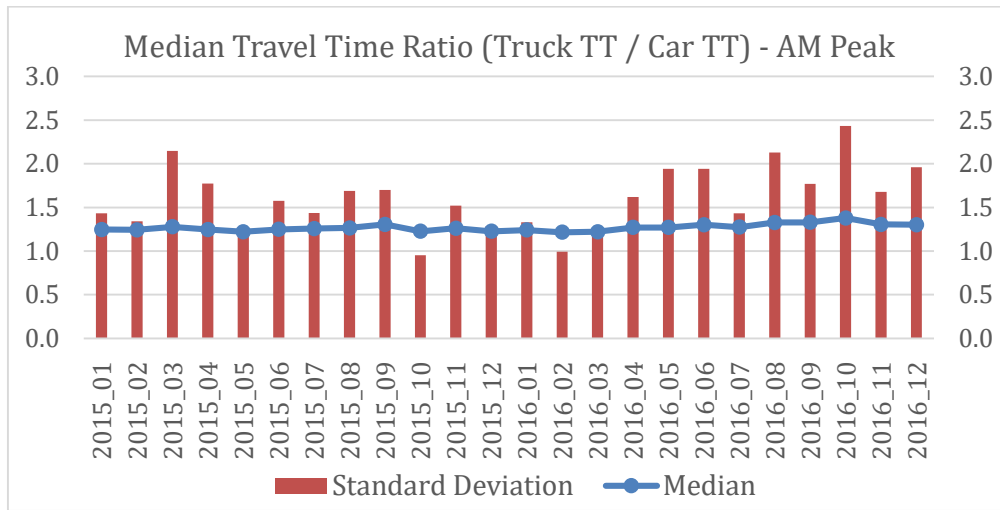


Figure 4.1 Network-wide Monthly Median Travel Time Ratio in the AM Peak Period.

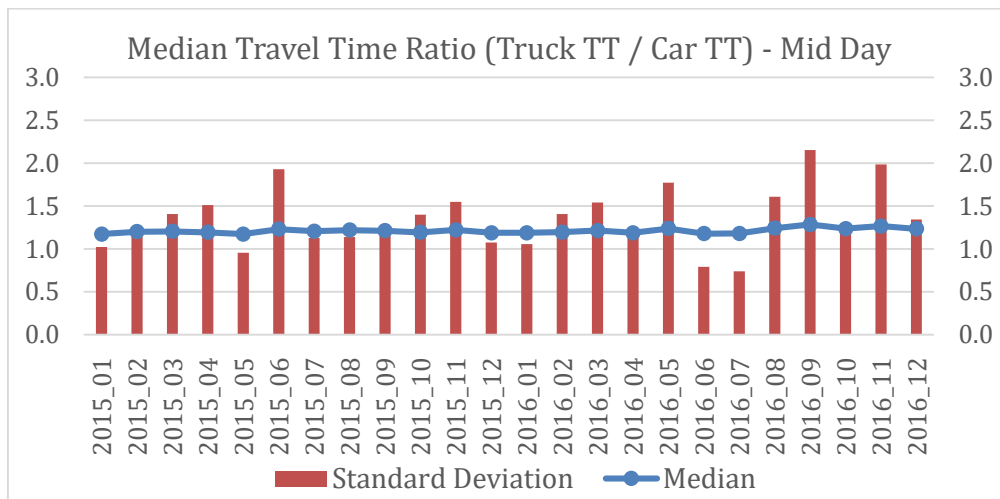


Figure 4.2 Network-wide Monthly Median Travel Time Ratio in Mid-Day.

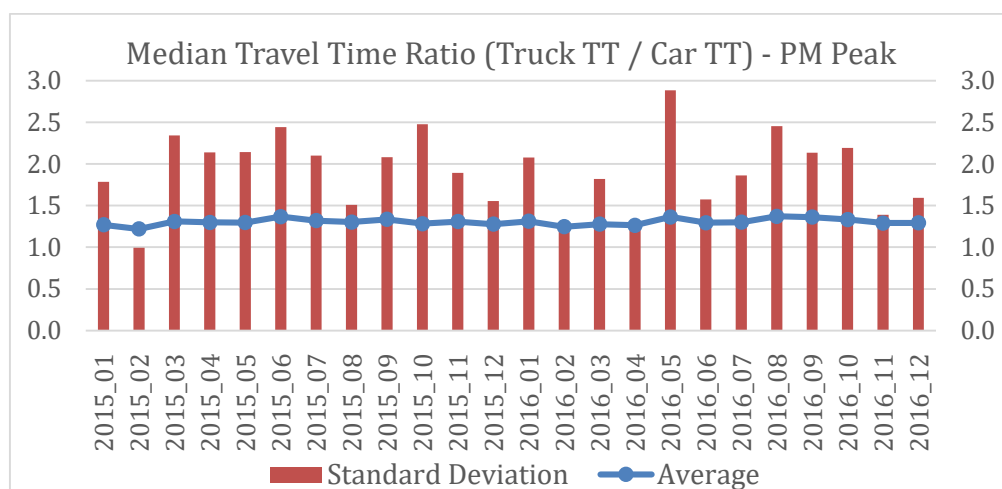


Figure 4.3 Network-wide Monthly Median Travel Time Ratio in the PM Peak Period.

4.1.1 Median TTR in the AM Peak

The TTR at TMC segment level was further analyzed for both AM and PM peak periods. Figure 4.4 displays the roadway segments with median TTR greater than 1.1 (i.e., median truck travel time is over 10% longer than the median passenger vehicle travel time) in the AM peak. Many sites with TTR measures greater than 2 are located near the highway interchanges, arterial signalized intersections, or at highway on/off ramps. A few locations with median TTR greater than 2 are listed as follows.

- I35E SB merge to I-694 WB (118N04156)
- MN-36 WB merge to I-35W NB (118P17345, 118P17347)
- I-394 EB at W of I94 (118P04355, 118P04356, 118P17671)
- I-94 EB to I-394 (118P17679)
- I-35E NB at N of I-94 (118P04318)
- I-394 EB at E of US-169 (118P17589)
- MN-100 SB at S of I-394 (118P19036, 118P19038)
- MN-7 EB at W of MN-100 (118P05183, 118P05179)
- US-169 NB to MN-62 EB interchange
- MN-62 WB to MN-100 SB interchange
- MN-77 NB to I-494 WB interchange
- MN-5 EB at MN-55

Analyses of TTR at 2 locations in the AM peak period are presented here. The monthly TTRs of couple TMC segments (118P04355 & 118P04356) on I-394 before merging to I-94 EB in the AM peak period are plotted in Figure 4.5. The average TTRs for both TMC segments are 2.1 and 2.3, respectively. The relatively high TTR in this area is likely to be caused by the merging of traffic. Trucks usually take longer

time to accelerate and decelerate. In a stop-and-go traffic condition, smaller vehicles tend to find gaps in front of trucks and cut off.

Similarly, the monthly TTRs of two TMC segments (118N05115& 118P05116) on MN-165 north of I-694 in the AM peak period are plotted in Figure 4.6. The average TTRs for NB and SB traffic are 1.3 and 1.5, respectively.

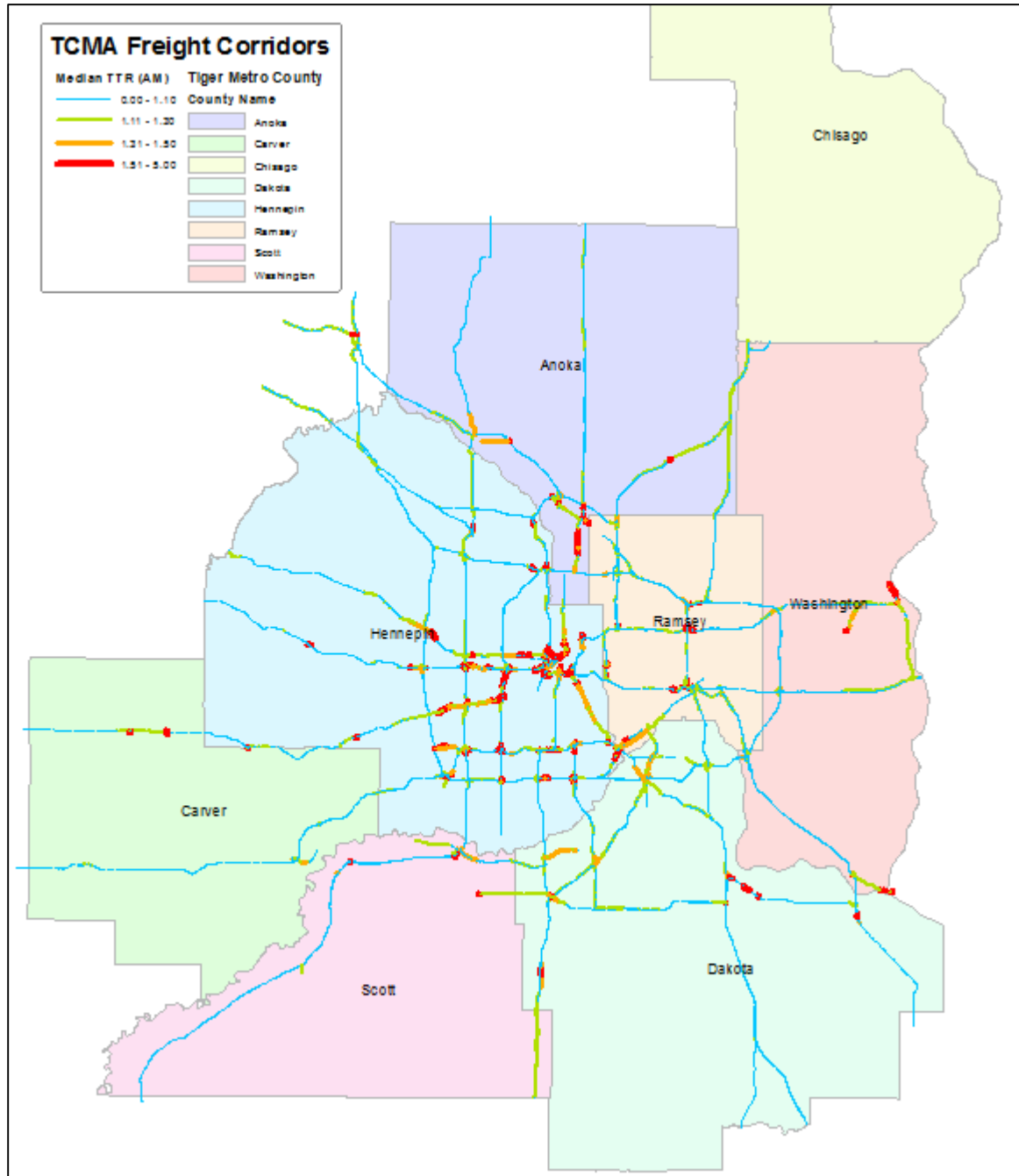


Figure 4.4 Median TTR in the AM Peak.

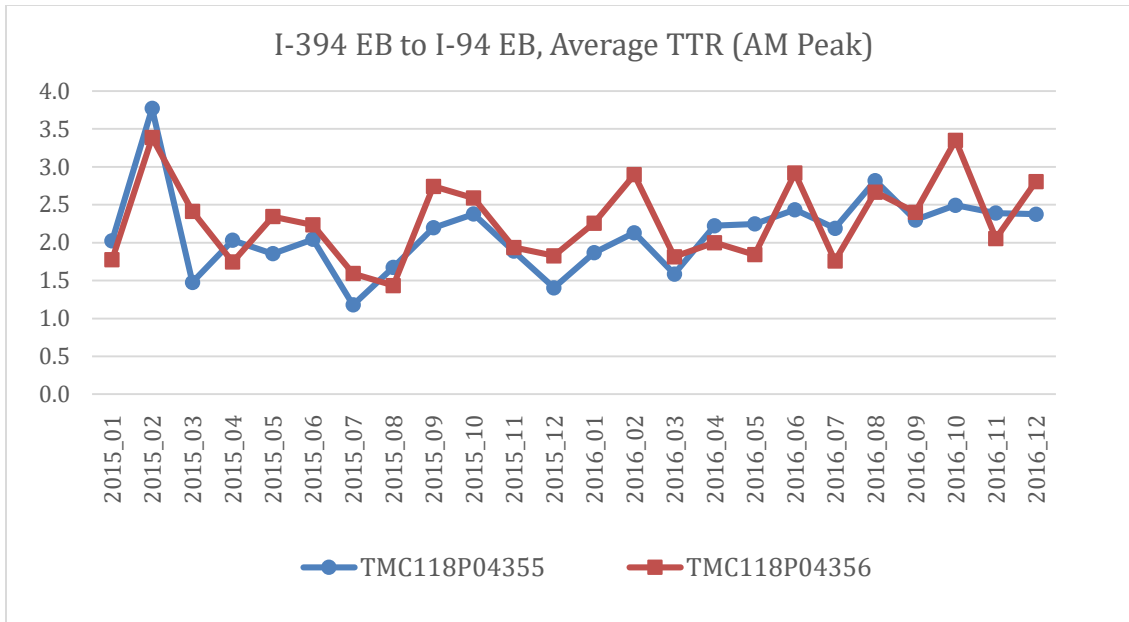


Figure 4.5 TTR of Two TMC Segments on I-394 EB to I-94 EB in the AM Peak.

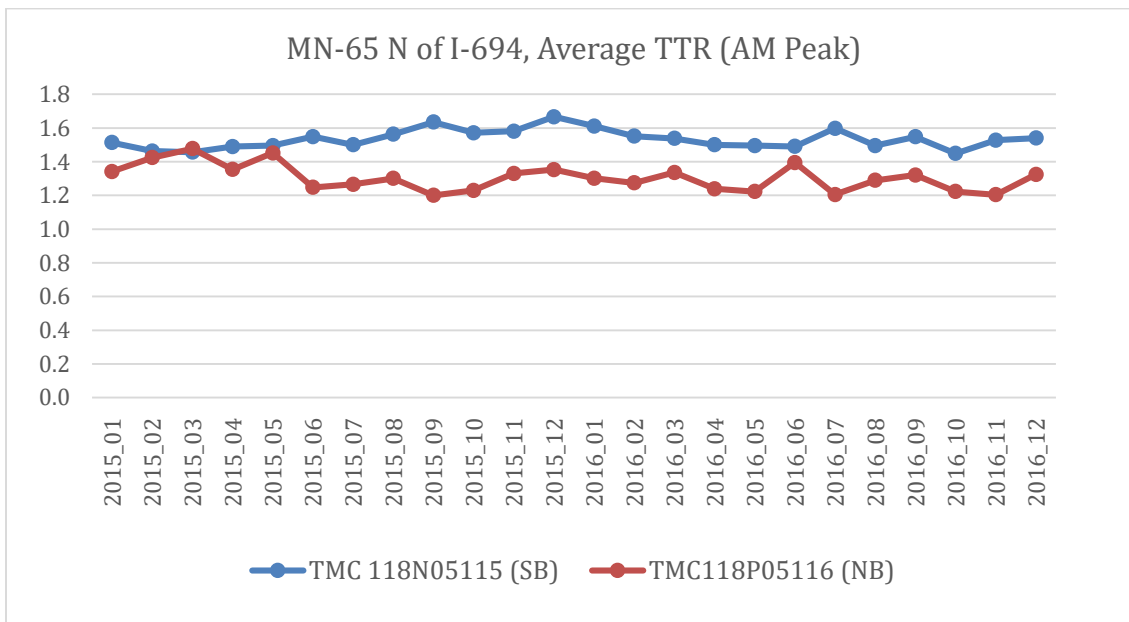


Figure 4.6 TTR of Two TMC Segments on MN-65 N of I-694 in the AM Peak.

4.1.2 Median TTR in the PM Peak

Figure 4.7 displays the roadway segments with median TTR greater than 1.1 (i.e., median truck travel time is over 10% longer than the median passenger vehicle travel time) in the PM peak. As shown in Figure 4.7, most sites with TTR greater than 2 are located near the highway interchanges, arterial signalized intersections, or at highway on/off ramps.

A few locations with median TTR greater than 2 in the PM peak are listed as follows.

- MN-55 WB between MN-100 and Downtown Minneapolis (118P04705)
- MN-55 WB between US-169 and MN-100 (118P04710)
- I-394 EB at W of I94 (118P04355, 118P04356, 118P17671)
- I-94 EB to I-394 (118P17681)
- I-35W SB to I-94 WB (118N04242)
- NE University Ave, N of Minneapolis (118P07704, 118P07705)
- I-94 WB near SE Huron Blvd (118P04195)
- I-94 EB at I-35E in Downtown St. Paul (118N04187, 118N04188)
- MN-7 EB at W of MN-100 (118P05183, 118P05179)
- MN-62 EB E of US-169 (118P04427)
- MN-5 EB at MN-55 (118P04417, 118P04418)
- I-35E NB N of I-494 (118P17219)
- MN-77 SB S of I-494 (118N04451)
- US-169 and MN-62 interchange
- MN-100 and MN-62 interchange
- I-35W and MN-62 interchange
- I-35W and I-494 interchange
- I-35W and MN-36 interchange

Analyses of TTR at 3 locations in the PM peak period are discussed here. The monthly TTRs of couple TMC segments (118P04355 & 118P04356) on I-394 before merging to I-94 EB in the PM peak period are plotted in Figure 4.8. The average TTRs for both TMC segments are 2.8 and 2.5, respectively. The median TTR in May and August 2015 (particularly, the 118P04355 segment) are significantly higher than the TTR in the other months. It is suspected that the spikes of TTR in these months may be caused by the smaller number of truck sample size. In the PM peak, trucks usually avoid the congested I-394 to I-94 area, before the Lowry tunnel.

The monthly TTRs of two TMC segments (118N05115& 118P05116) on MN-165 north of I-694 in the PM peak period are plotted in Figure 4.9. The average TTRs for NB and SB traffic are 1.2 and 1.6, respectively.

The monthly TTRs of two TMC segments (118N04187 & 118N04188) on I-94 EB west of I-35E in Downtown St. Paul during PM peak period are plotted in Figure 4.10. The average TTRs for both TMC segments are 2.2 and 2.0, respectively.

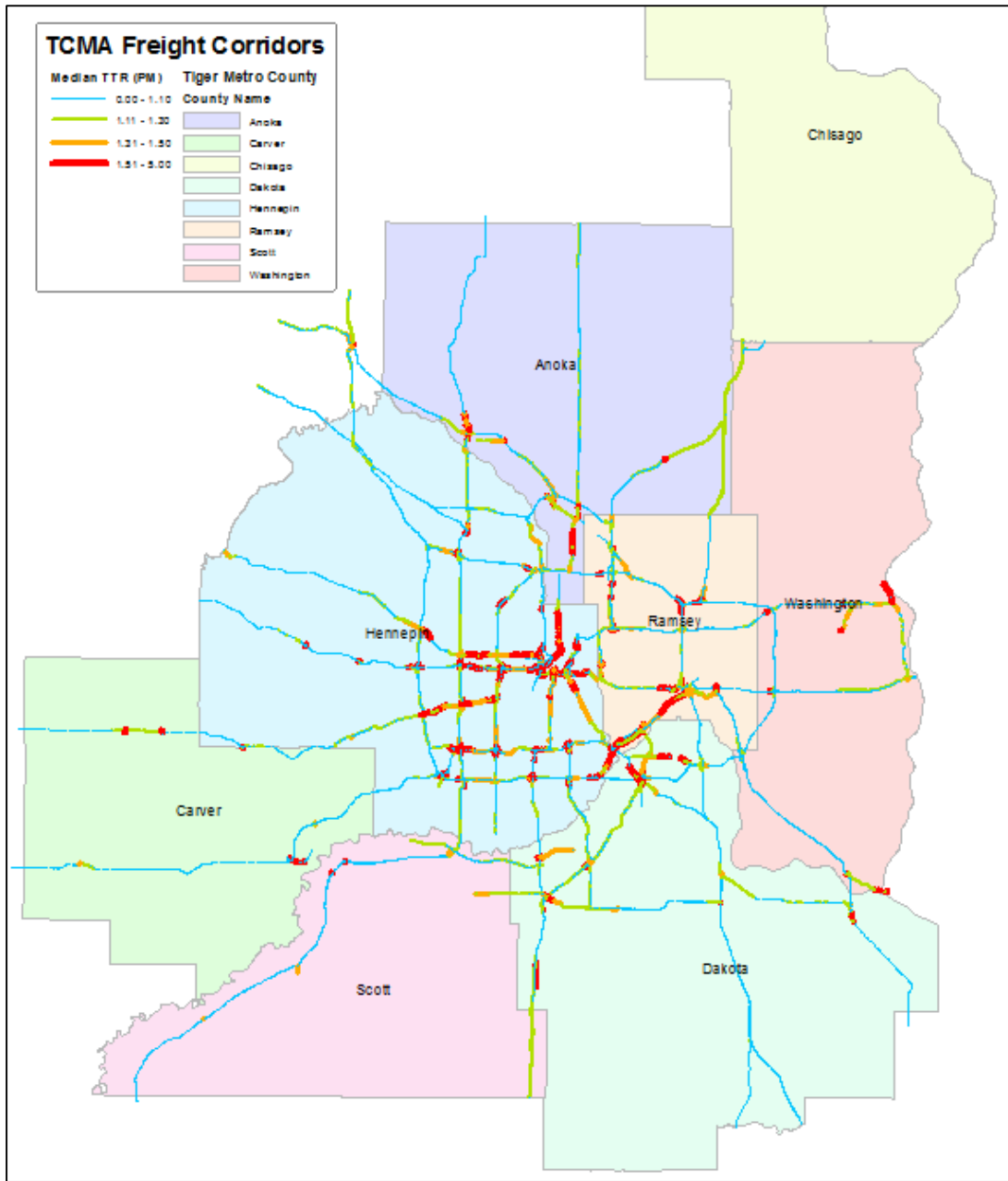


Figure 4.7 Median TTR in the PM Peak.

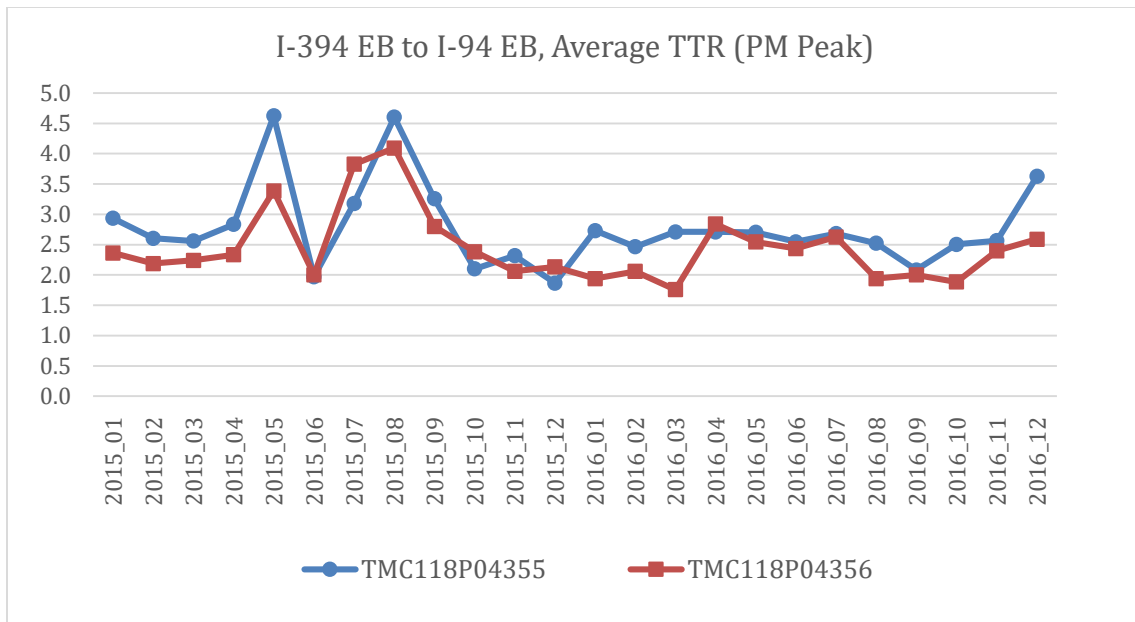


Figure 4.8 TTR of Two TMC Segments on I-394 EB to I-94 EB in the PM Peak.

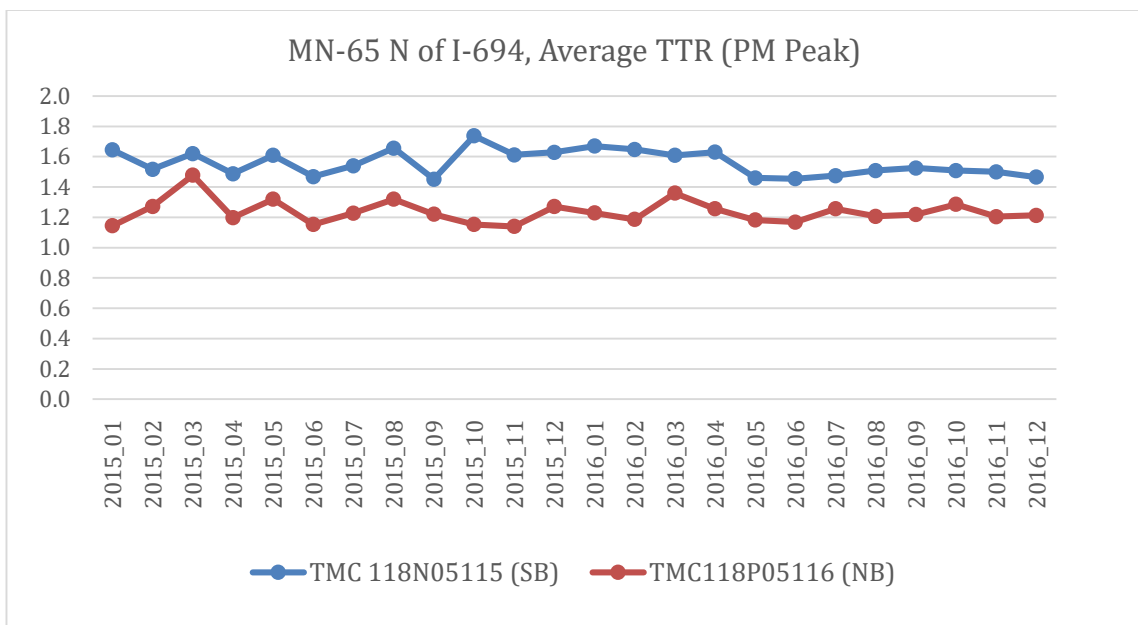


Figure 4.9 TTR of Two TMC Segments on MN-65 N of I-694 in the PM Peak.

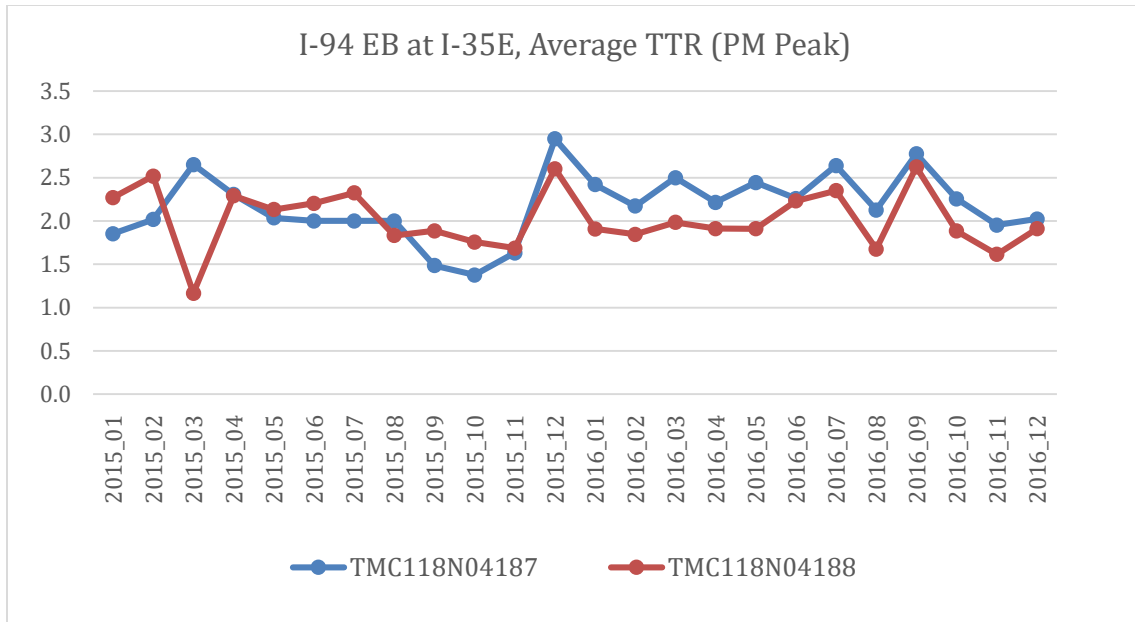


Figure 4.10 TTR of Two TMC Segments on I-94 EB W of I-35E in the PM Peak.

4.1.3 TTR by Route

The travel time ratio measure is further analyzed by route. Figure 4.11 displays the percent of miles with average TTR greater than or equal to 1.5 for AM, mid-day, and PM periods. In general, roadways with signalized or un-signalized intersections have higher percentage of truck to car travel time ratio. For example, the average truck travel time on 34% of county road 30 is over 50% longer than the average passenger vehicle travel time in the PM peak. In the PM peak hours, the average truck travel time on 6.8% of I-94 roadway in the Twin Cities metro area is over 50% longer than the average passenger vehicle travel time. Similarly, the average truck travel time on 6.6% of I-394 roadway is over 50% longer than the average passenger vehicle travel time.

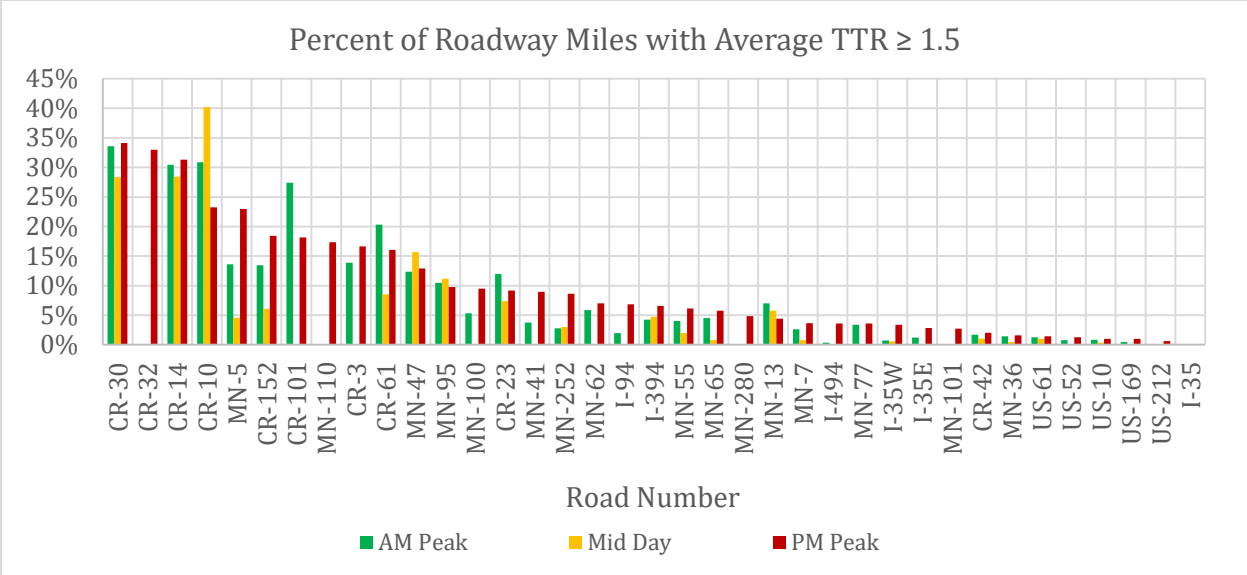


Figure 4.11 Percent of Roadway Miles with TTR ≥ 1.5 by Time Period.

4.2 TRAVEL TIME RELIABILITY ANALYSIS

Three truck travel time reliability measures (RI95, TTTR80, and TTTR95), as defined in Eq. (3-2 to 3-4), were calculated for each TMC segment in each time period. Each reliability measure is discussed in the following sections.

4.2.1 RI95

The RI95 measure is calculated using Eq. (3-2) for each time period. However, only measures in the AM peak, mid-day, and PM peak periods are presented here. Figure 4.12 displays the average RI95 and its corresponding standard deviation (SD) in the AM peak period in each month for the entire network. The network-wide monthly RI95 in the AM peak period is around 1.9 over the 24-month period with an SD ranging from 1 to 1.3. The average network-wide average RI95 in mid-day is about 1.8 with an SD ranging from 1 to 1.2 as shown in Figure 4.13. Similarly, the network-wide monthly median RI95 in the PM peak period, as shown in Figure 4.14, is around 2.1 over the 24-month period with an SD varying from 1.1 to 1.5.

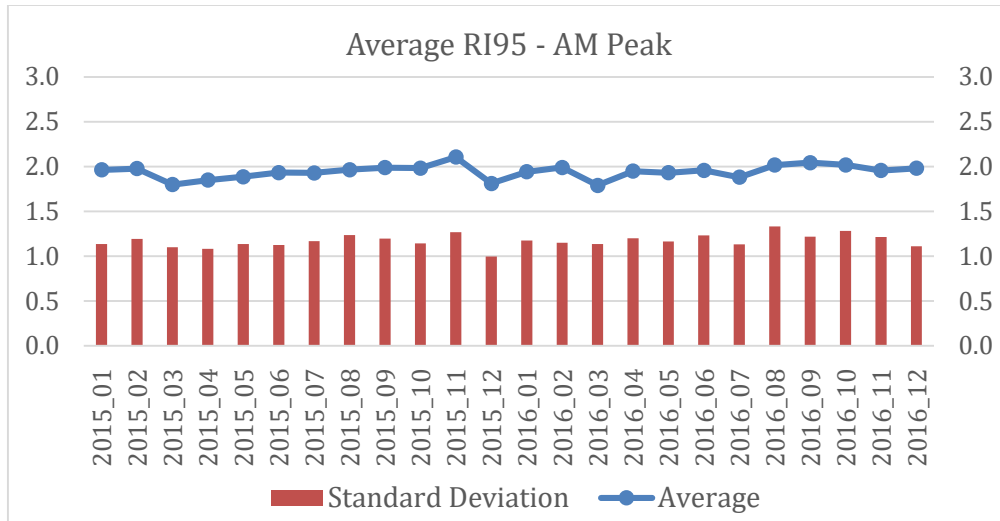


Figure 4.12 Network-wide Monthly Average RI95 in the AM Peak.

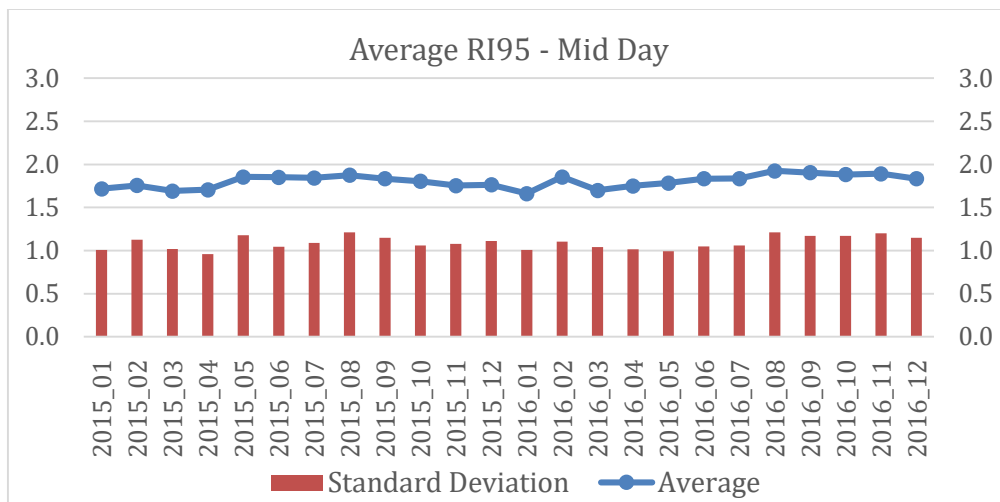


Figure 4.13 Network-wide Monthly Average RI95 in Mid-Day.

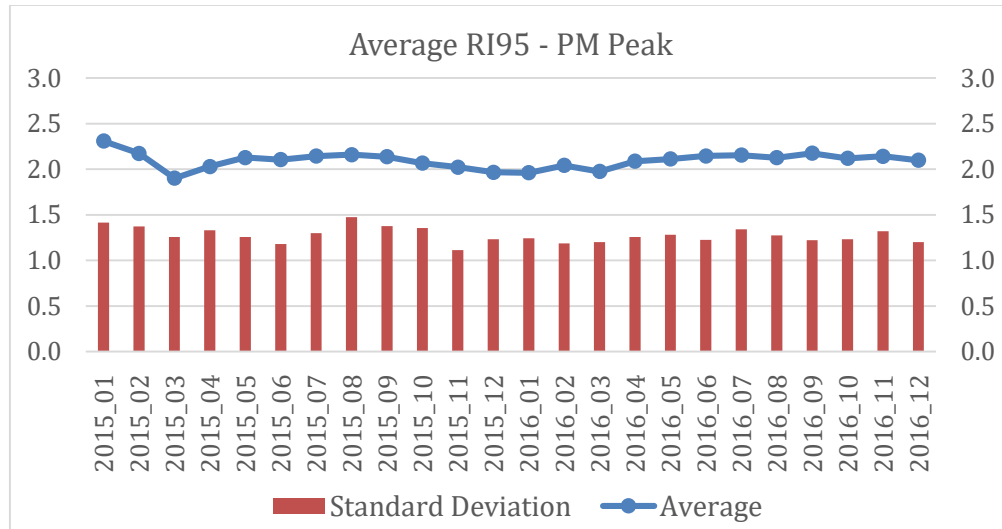


Figure 4.14 Network-wide Monthly Average RI95 in the PM Peak.

4.2.1.1 RI95 in the AM Peak

The RI95 at TMC segment level was analyzed for both AM and PM peak periods. Figure 4.15 displays the roadway segments with average RI95 greater than 1.5 in the AM peak. Many sites with RI95 measures greater than 2.5 are located near the highway interchanges, arterial signalized intersections, or at highway on/off ramps. A few routes with average RI95 greater than 2.5 (segments in red color displayed in Figure 4.15) are listed as follows.

- MN-55 between Loretto and Downtown Minneapolis
- Hiawatha Ave between E 26th street and MN-62
- MN-7 between MN-101 and MN-100
- US-10 EB between US-169 and MN-101, and NB from I-494 to I-94
- CR-42 near I-35W & I-35E junction
- US-169 between 36 Ave. N and I-394
- I-35W NB from CR-42 to MN-13
- MN-62 between I-494 and I-35W
- MN-47 between Hennepin Ave and St Anthony Parkway

Analyses of RI95 measures at 2 locations in the AM peak period are presented as follows. The monthly RI95 measures of couple TMC segments (118P04690 & 118P04691) on MN-55 south of Lake St. in the AM peak period are plotted in Figure 4.16. The average RI95 measures for both TMC segments are 2.9 and 3.3, respectively.

Similarly, the monthly RI95 measures of two TMC segments (118P05178 & 118P05181) on MN-7 west and east of US-169 in the AM peak period are plotted in Figure 4.17. The average RI95 measures for EB

traffic for both TMC segments are 3.0 and 3.1, respectively. The spike of RI95 at TMC 118P05178 in September 2015 during AM peak period, as shown in Figure 4.17, is probably an outlier.

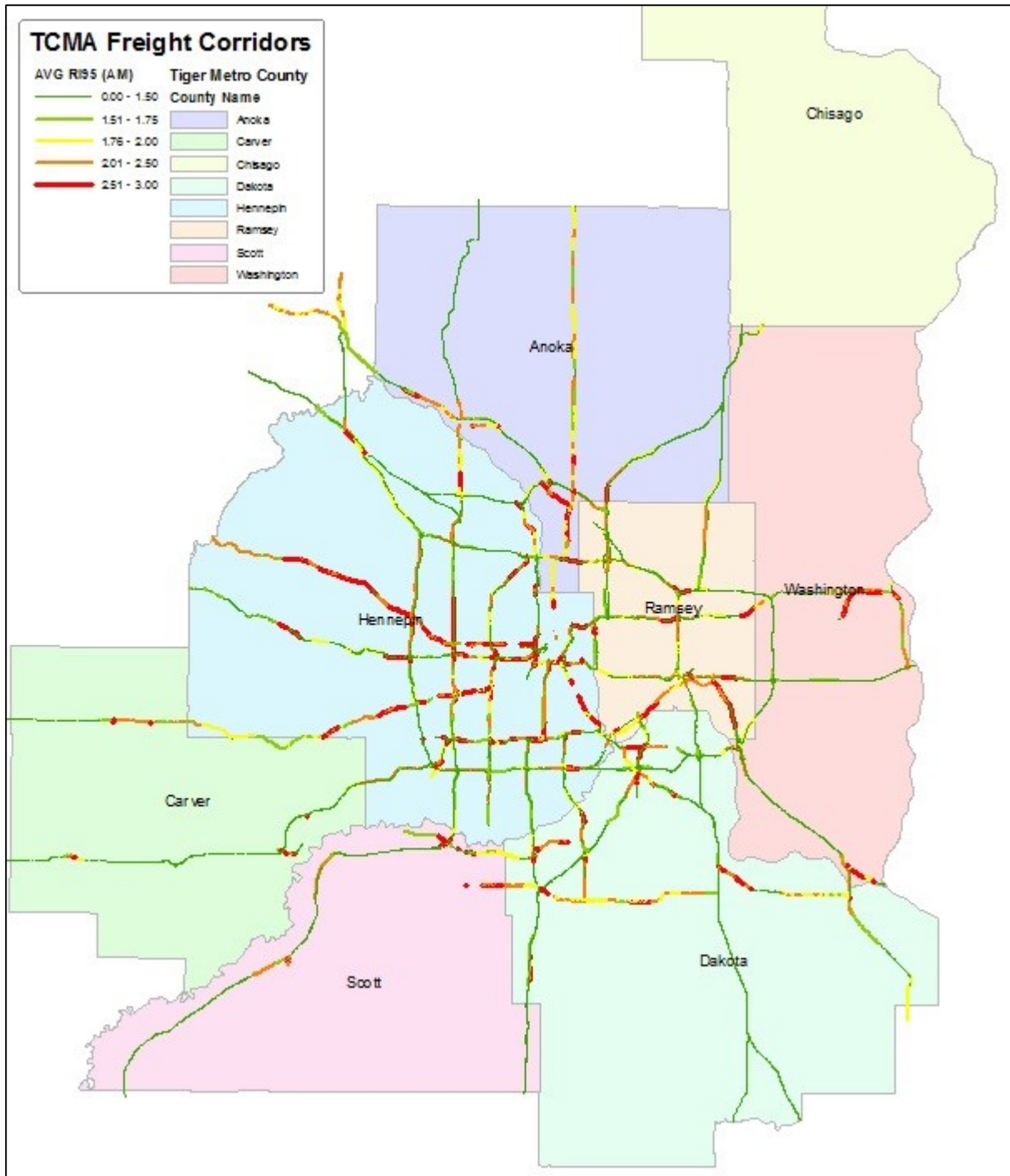


Figure 4.15 Average RI95 Measure in the AM Peak.

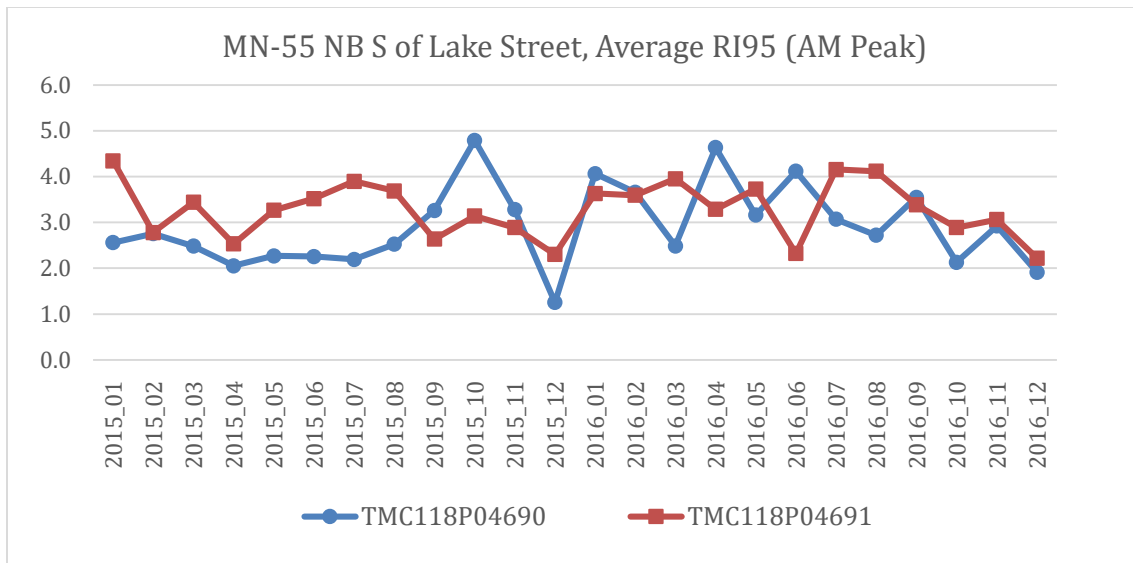


Figure 4.16 RI95 of Two TMC Segments on MN-55 South of Lake St. in the AM Peak.

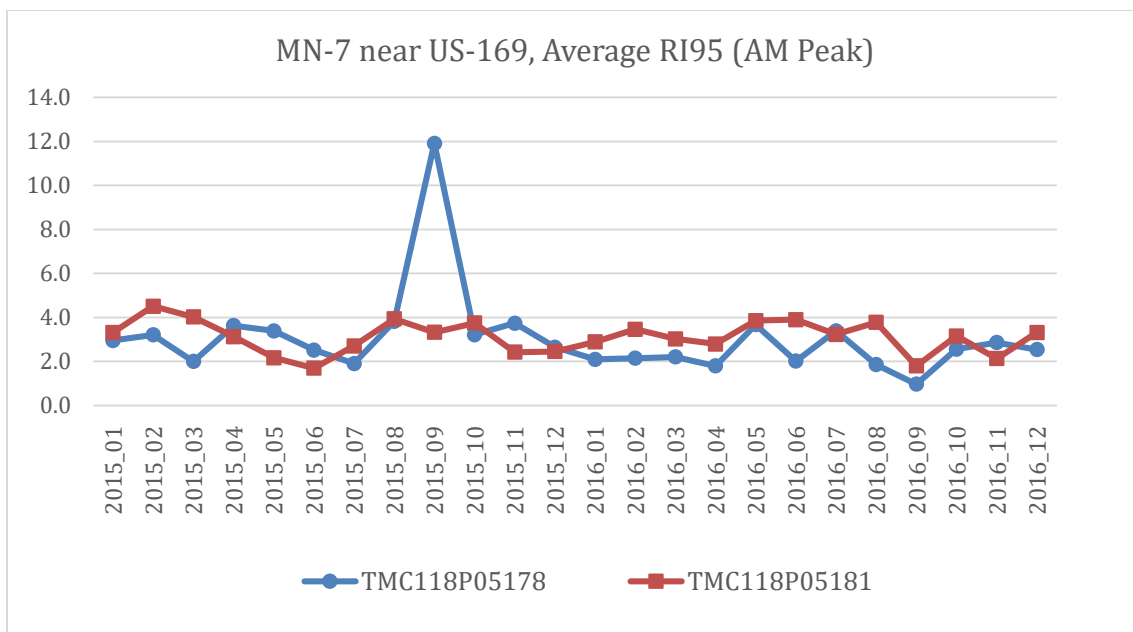


Figure 4.17 RI95 of Two TMC Segments on MN-7 near US-169 in the AM Peak.

4.2.1.2 RI95 in the PM Peak

Figure 4.18 displays the roadway segments with average RI95 greater than 1.5 in the PM peak. RI95 greater than 4.0 are displayed in red, RI95 value between 2.5 and 4.0 are shown in orange color, and RI95 value between 1.5 and 2.5 are displayed in green). As shown in Figure 4.18, many sites with RI95 measures greater than 2.5 are located near the highway interchanges, arterial signalized intersections,

or at highway on/off ramps. A few locations with average RI95 greater than 4 in the PM peak are listed as follows.

- MN-55 E of US-169 and MN-100
- MN-7 E of US-169
- MN-62 W of US-169
- US-169 and US-10 junction area
- I-35W and I-494 interchange
- Hennepin Ave in Downtown Minneapolis
- Warner Rd. in St. Paul
- Stillwater Blvd S of MN-36

Analyses of RI95 measures at 2 locations in the PM peak period are presented as follows. The monthly RI95 measures of couple TMC segments (118N04706 & 118N04710) on MN-55 EB between US-169 and MN-100 in the PM peak period are plotted in Figure 4.19. The average RI95 measures for both TMC segments are 4.4 and 4.2, respectively. TMC segment 118N04710 is on MN-55 EB from US-169 off-ramp to Boone Ave. It includes a signalized intersection at MN-55 and Boone Ave. TMC segment 118N04706 is located on MN-55 from Douglas Dr. to MN-100. It includes 2 signalized intersections at Douglas Dr. and MN-100. The spikes of RI95 at these locations (see Figure 4.19) are mostly likely contributed by the signal delays.

Similarly, the monthly RI95 measures of two TMC segments (118P05181 & 118N05181) on MN-7 east of US-169 in the PM peak period are plotted in Figure 4.20. The average RI95 measures for both EB and WB traffic are 3.5 and 4.7, respectively. TME segment 118P05181 is located on MN-7 WB from Louisiana Ave. to Aquila Ave. (about 0.9 miles). It includes 3 signalized intersections at Louisiana Ave., Texas Ave., and Aquila Ave. The spikes of RI95 at this segment (see Figure 4.20) are mostly likely contributed by the signal delays.

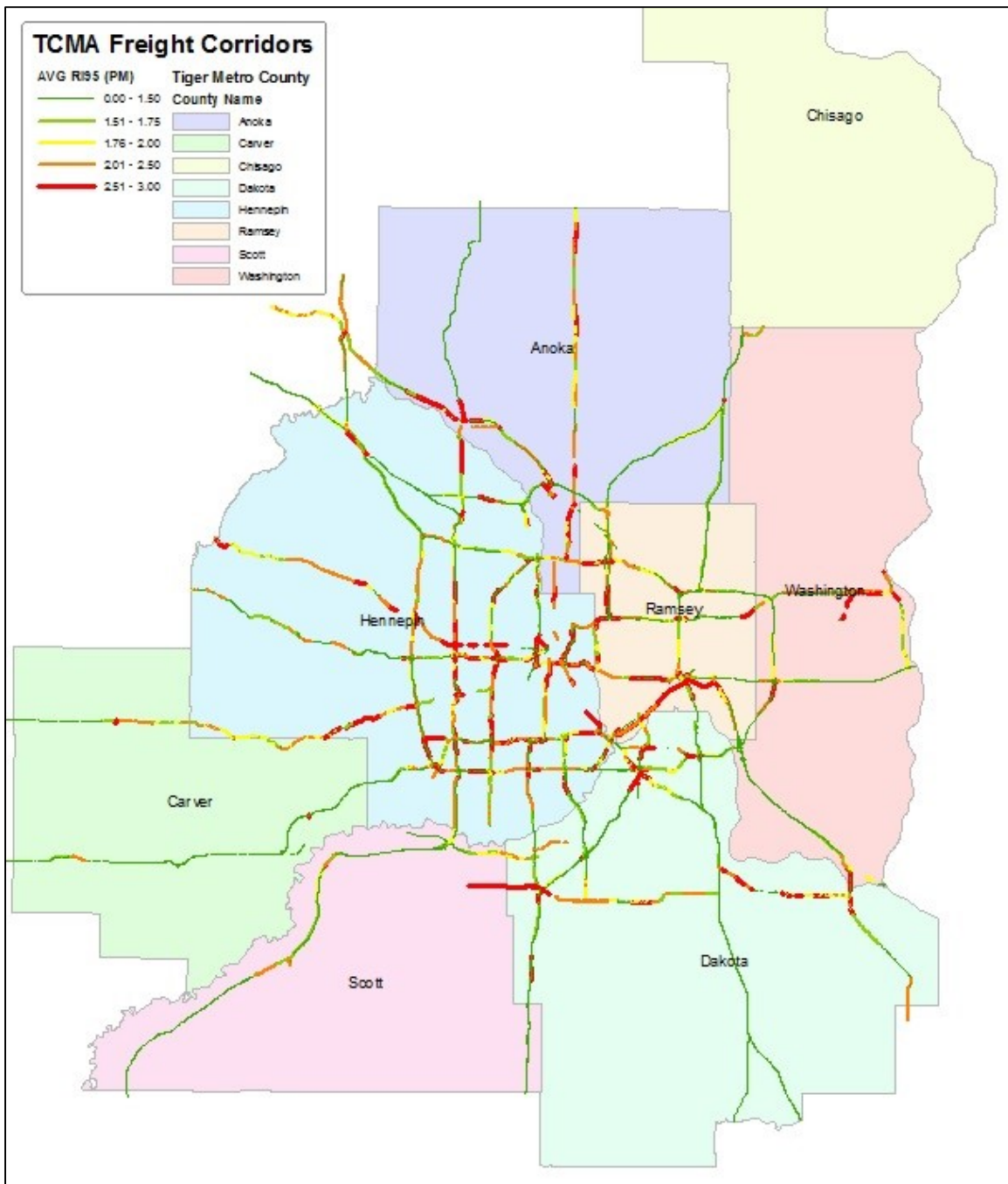


Figure 4.18 Average RI95 Measure in the PM Peak.

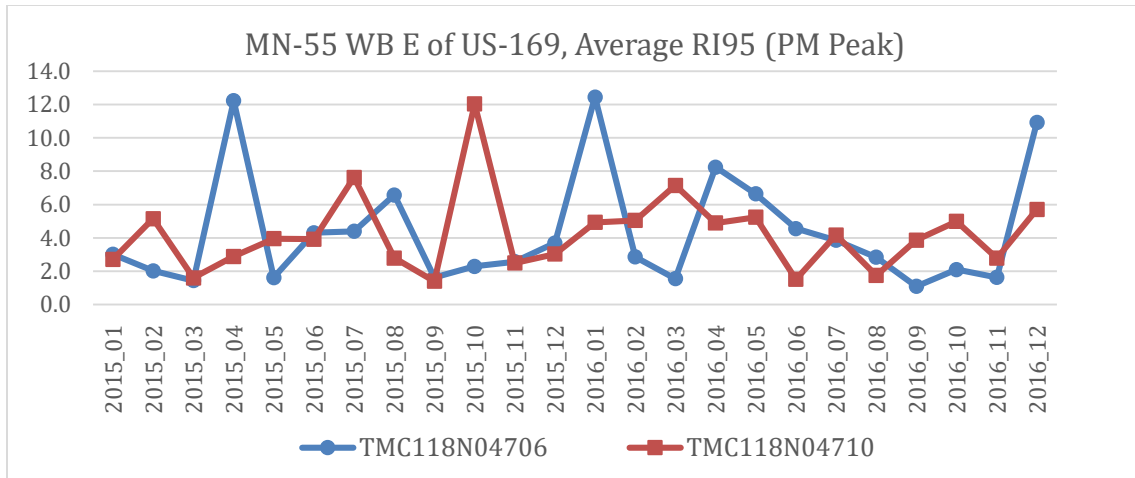


Figure 4.19 RI95 of Two TMC Segments on MN-55 EB between US-169 and MN-100 in the PM Peak.

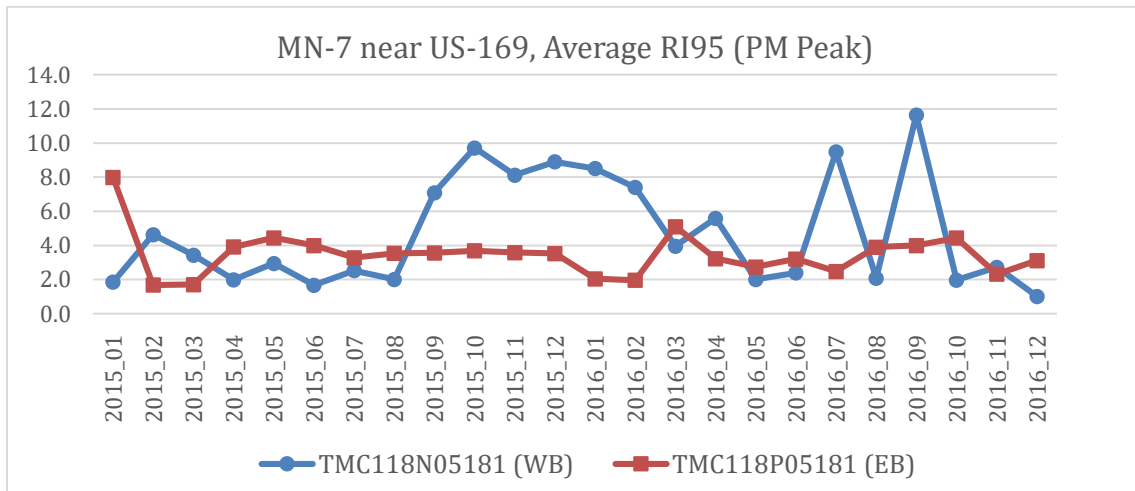


Figure 4.20 RI95 of Two TMC Segments on MN-7 East of US-169 in the PM Peak.

4.2.1.3 RI95 by Route

The RI95 measure is further analyzed by route. Figure 4.21 displays the percent of miles with average RI95 greater than 2.0 for AM, mid-day, and PM periods. In general, roadways with signalized or un-signalized intersections are less reliable than freeways. For example, the 95th percentile truck travel time on 68% of MN-252 is over twice as long as the average truck travel time in the PM peak. In the PM peak hours, the 95th percentile truck travel time on 22.3% of I-94 roadway in the Twin Cities metro area is over twice as long as the average truck travel time. Similarly, the 95th percentile truck travel time on 40% of I-394 roadway is over twice as long as the average truck vehicle travel time.

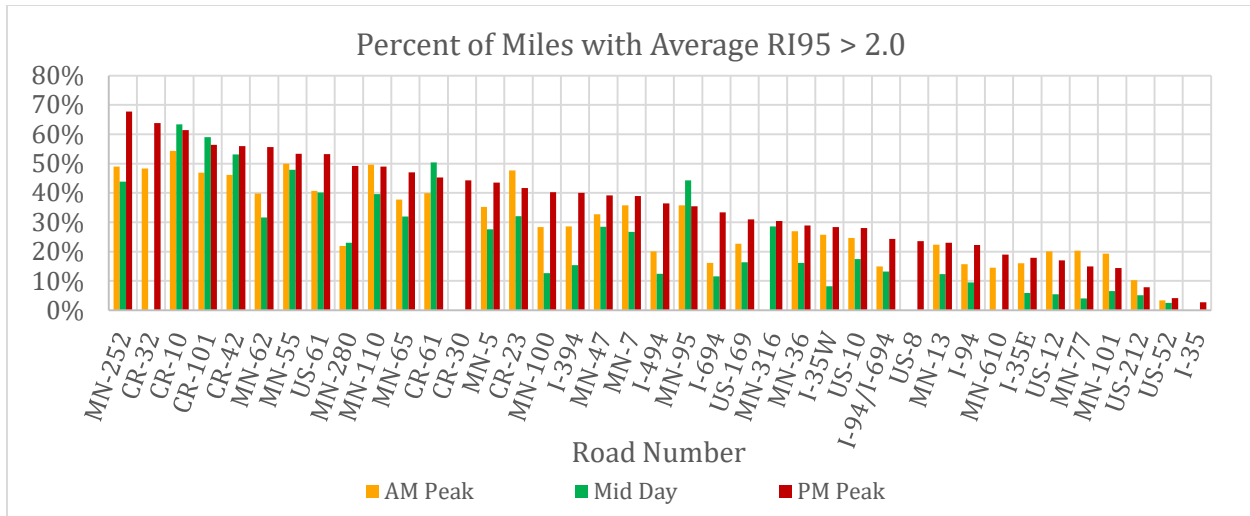


Figure 4.21 Percent of Roadway Miles with RI95 ≥ 2.0 by Time Period.

4.2.2 TTTR80

The TTTR80 measure is calculated using Eq. (3-3) for each time period. However, only measures in the AM peak, mid-day, and PM peak periods are presented here. Figure 4.22 displays the average TTTR80 and its corresponding standard deviation (SD) in the AM peak period in each month for the entire network. The network-wide monthly TTTR80 in the AM peak period is around 1.5 over the 24-month period with an SD ranging from 0.7 to 2.3. The average network-wide average TTTR80 in mid-day is about 1.4 with an SD ranging from 0.5 to 1.7 as shown in Figure 4.23. Similarly, the network-wide monthly median TTTR80 in the PM peak period, as shown in Figure 4.24, is around 1.6 over the 24-month period with an SD varying from 0.8 to 2.4.

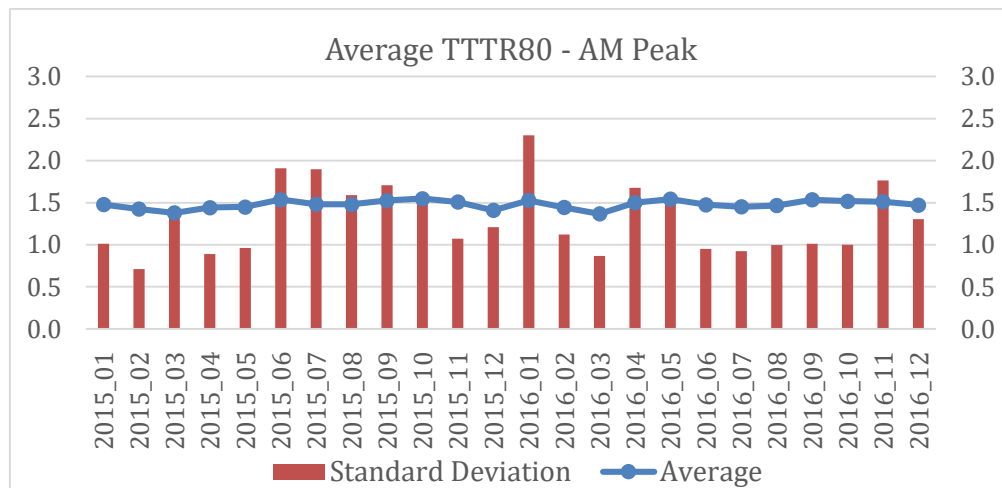


Figure 4.22 Network-wide Monthly Average TTTR80 in the AM Peak.

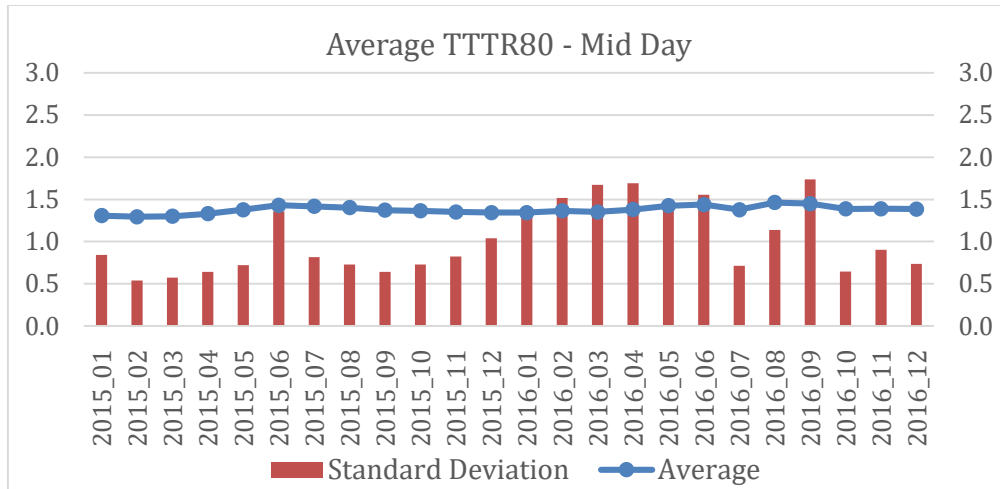


Figure 4.23 Network-wide Monthly Average TTTR80 in Mid-Day.

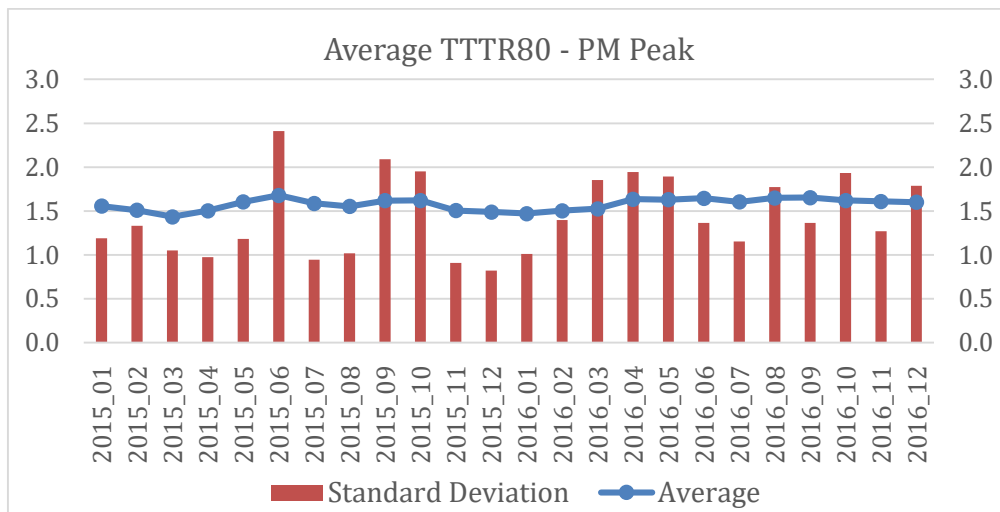


Figure 4.24 Network-wide Monthly Average TTTR80 in the PM Peak.

4.2.2.1 TTTR80 in the AM Peak

TTTR80 at TMC segment level was analyzed for both AM and PM peak periods. Figure 4.25 displays the roadway segments with average TTTR80 greater than 1.5 in the AM peak. Many sites with TTTR80 measures greater than 2.0 are located near the highway interchanges, arterial signalized intersections, or at highway on/off ramps.

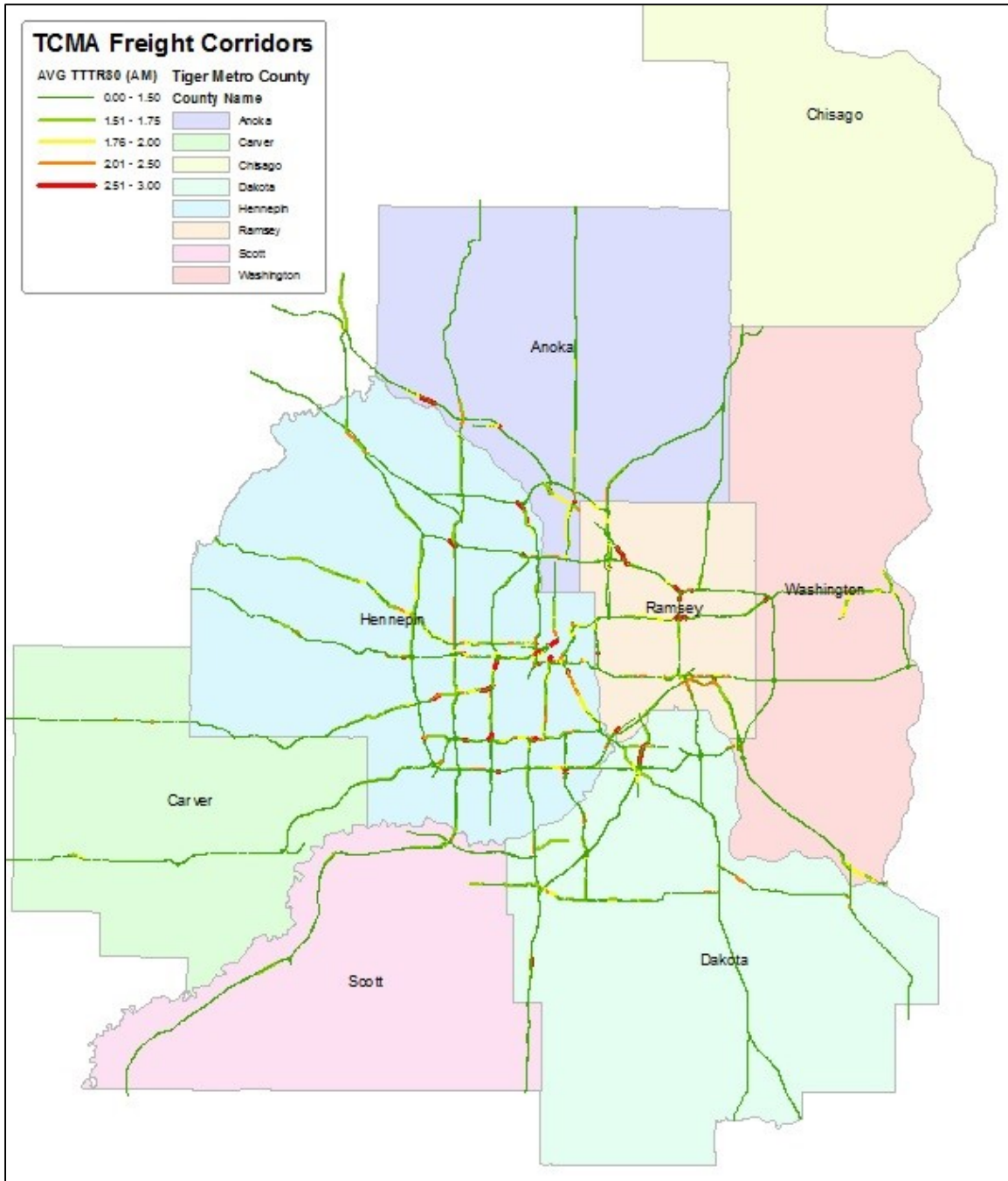


Figure 4.25 Average TTTR80 measure in the AM peak period.

A few routes with average TTTR80 greater than 2.0 (segments in orange or red color displayed in Figure 4.25) are listed as follows.

- MN-55 WB near I-494 in Plymouth area
- US-169 SB N of I-394
- I-394 EB between US-160 and Downtown Minneapolis
- I-94 between I-394 and I-35W

- MN-62 and I-35W common area
- I-494 between US-169 and MN-100
- I-35W between MN-13 and CR-42
- MN-55 (Hiawatha Ave) S of I-94
- Warner Rd. between US-52 and US-10

Analyses of TTTR80 measures at 2 locations in the AM peak period are presented as follows. The monthly TTTR80 measures of five TMC segments (118N04302, 118N04303, 118N04304, 118N04305 & 118N04306) on US-169 SB north of I-394 in the AM peak period are plotted in Figure 4.26. The average TTTR80 measures for TMC segments 118N04302 to 118N04306 are 2.2, 2.1, 2.1, 2.1 and 2.0, respectively.

Similarly, the monthly TTR80 measures of three TMC segments (118P04714, 118P04716 & 118P04717) on MN-55 west of I-494 in the AM peak period are plotted in Figure 4.27. The average TTTR80 measures for these TMC segments are 2.2, 2.5, and 2.0, respectively.

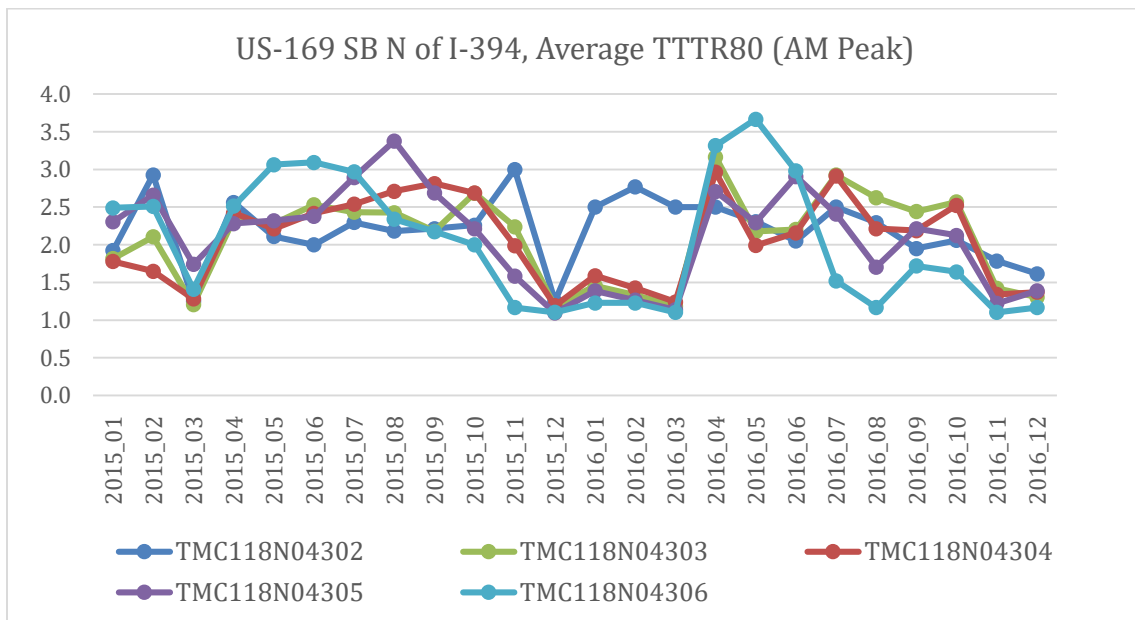


Figure 4.26 TTTR80 of 5 TMC Segments on US-169 SB North of I-394 in the AM Peak.

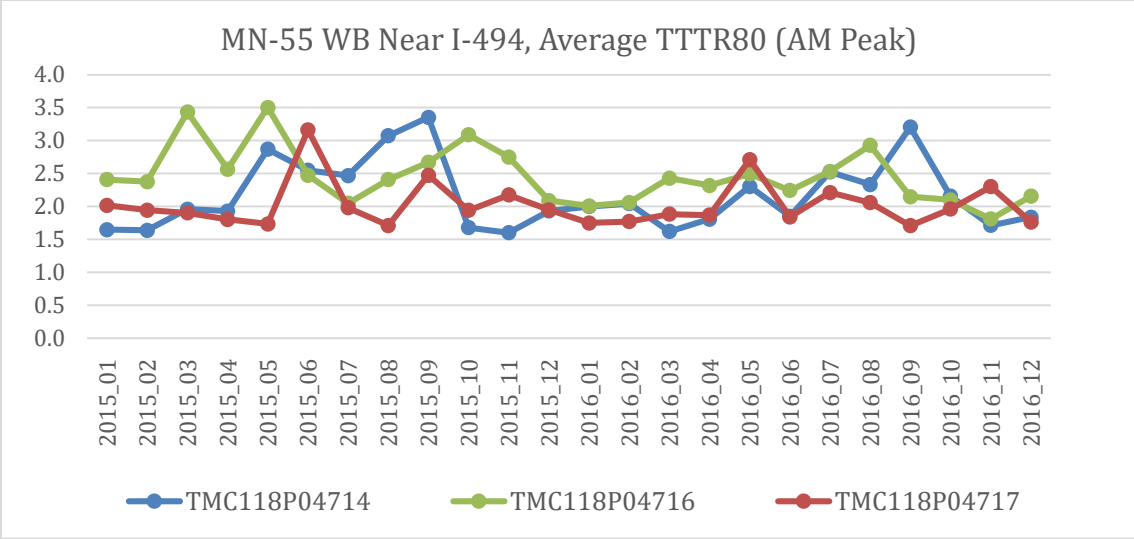


Figure 4.27 TTTR80 of 3 TMC Segments on MN-55 WB near I-494 in the AM Peak.

4.2.2.2 TTTR80 in the PM Peak

Figure 4.28 displays the roadway segments with average TTTR80 greater than 1.5 in the PM peak. TTTR80 measure greater than 2,5 are displayed in red, TTTR80 value between 2.0 and 2.5 are shown in orange color, and TTTR80 value between 1.75 and 2.0 are displayed in yellow). As shown in Figure 4.28, many sites with TTTR80 measures greater than 2.0 in the PM peak are located near the highway interchanges, arterial signalized intersections, or at highway on/off ramps. A few locations with average TTTR80 greater than 2.0 in the PM peak are listed as follows.

- US-169 N of CR-81
- MN-252
- US-169 N of I-394
- MN-55 between MN-100 and US-169
- MN-55 (Hiawatha Ave) between I-94 and MN-62
- MN-7 between I-494 and MN-100
- MN-62 between MN-77 and MN-55
- I-35W between MN-36 and I-694
- I-694 between I-94 and US-10
- I-35E between MN-110 and I-494
- I-494 between US-169 and MN-100
- Warner Rd. between US-52 and US-10

Analyses of TTTR80 measures at 2 locations in the PM peak period are presented as follows. The monthly TTTR80 measures of five TMC segments (118N04302, 118N04303, 118N04304, 118N04305 & 118N04306) on US-169 SB north of I-394 in the PM peak period are plotted in Figure 4.29. The average TTTR80 measures for these TMC segments are 2.2, 2.2, 2.5, 1.8 and 1.6, respectively. In January 2015,

the TTTR80 measures for 118N04304, 118N04305 & 118N04306 segments are over 7.8 in the PM peak periods. As compared to the 24-month average TTTR80, there might be weather related causes to the significantly unreliable travel time in Jan. 2015.

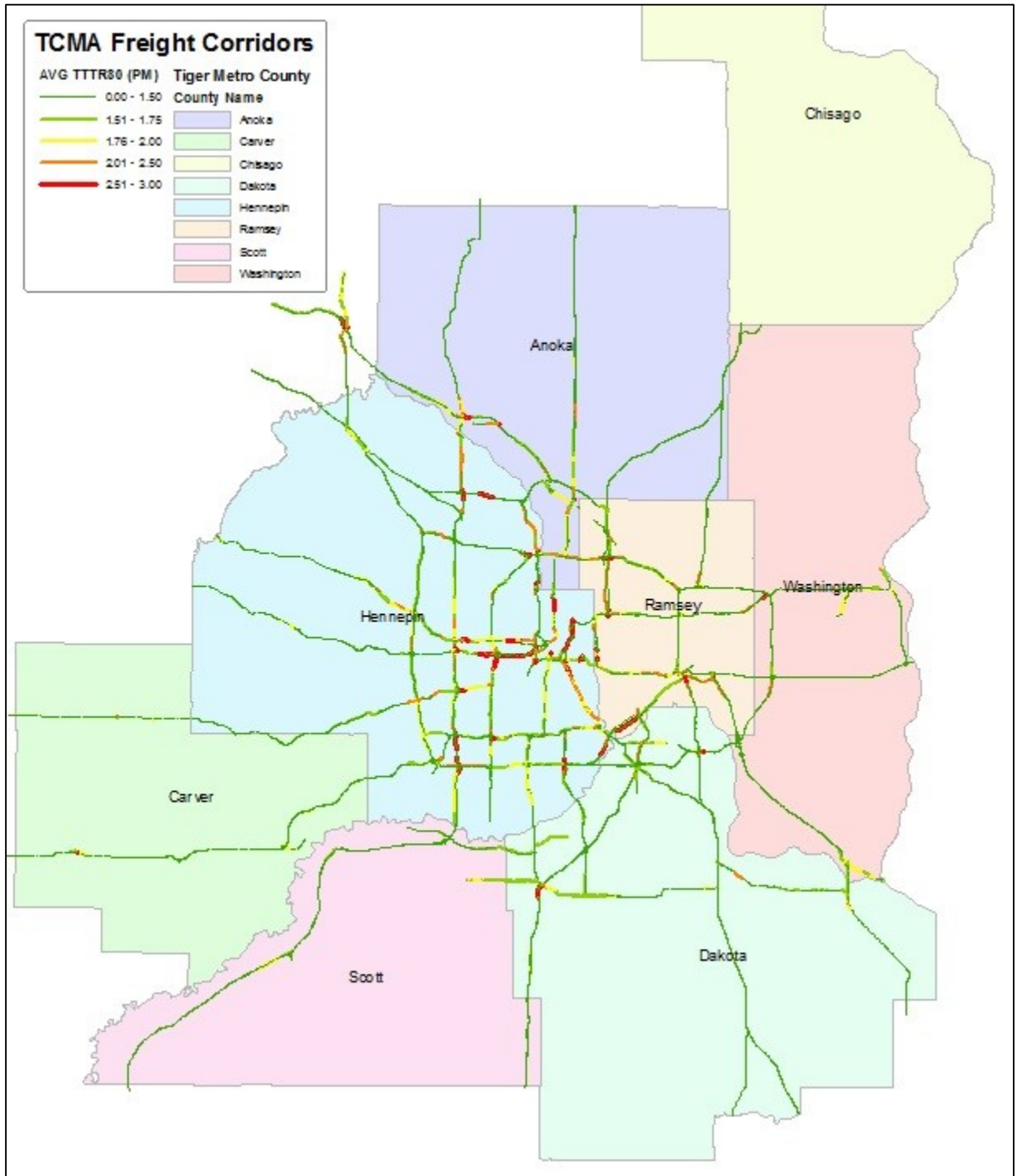


Figure 4.28 Average TTTR80 measure in the PM peak period.

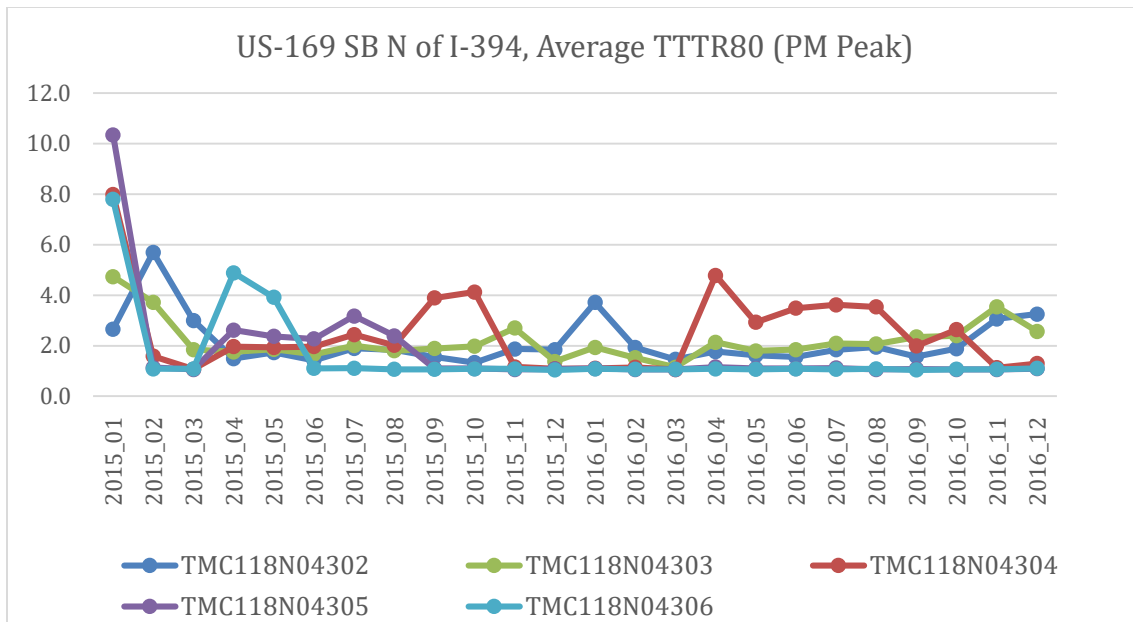


Figure 4.29 TTTR80 of 5 TMC Segments on US-169 SB North of I-394 in the PM Peak.

Similarly, the monthly TTTR80 measures of three TMC segments (118P04714, 118P04716 & 118P04717) on MN-55 west of I-494 in the PM peak period are plotted in Figure 4.30. The average TTTR80 measures for these TMC segments are 2.5, 2.3, and 2.1, respectively.

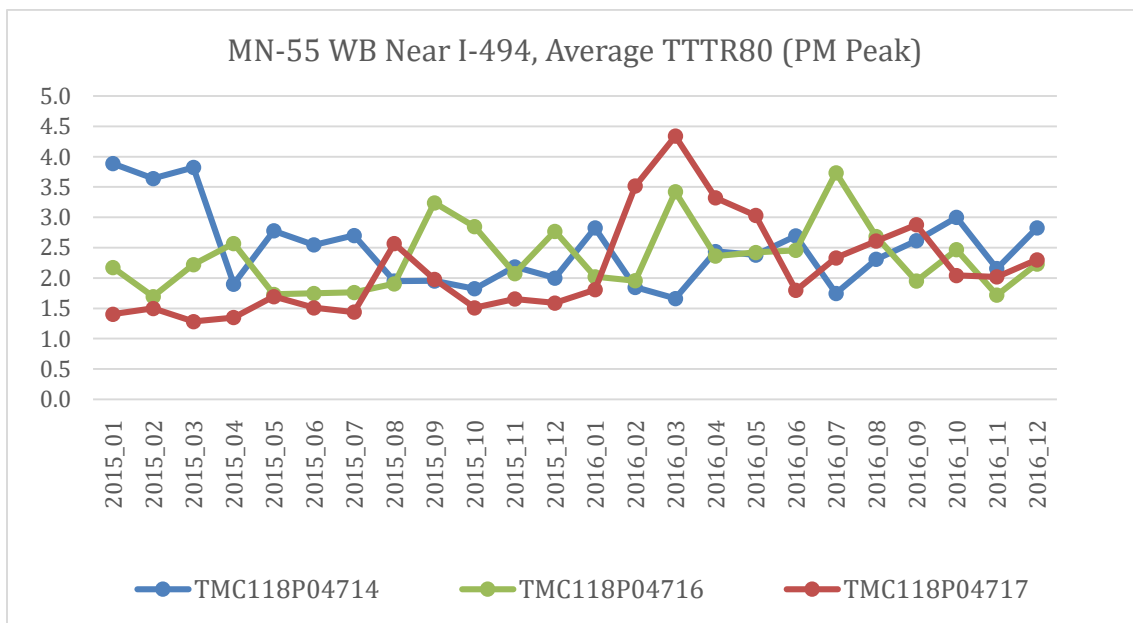


Figure 4.30 TTTR80 of 3 TMC Segments on MN-55 WB near I-494 in the PM Peak.

4.2.2.3 TTTR80 by Route

The TTTR80 measure is further analyzed by route. Figure 4.31 displays the percent of miles with average TTTR80 greater than 2.0 for AM, mid-day, and PM periods. In general, roadways with signalized or unsignalized intersections are less reliable than freeways. For example, the 80th percentile truck travel time on 35% of MN-41 is over twice as long as the average truck travel time in the PM peak. In the PM peak hours, the 80th percentile truck travel time on 29.8% of MN-252 roadway in the Twin Cities metro area is over twice as long as the average truck travel time. Similarly, the 80th percentile truck travel time on 19.3% of I-394 roadway is over twice as long as the average truck vehicle travel time.

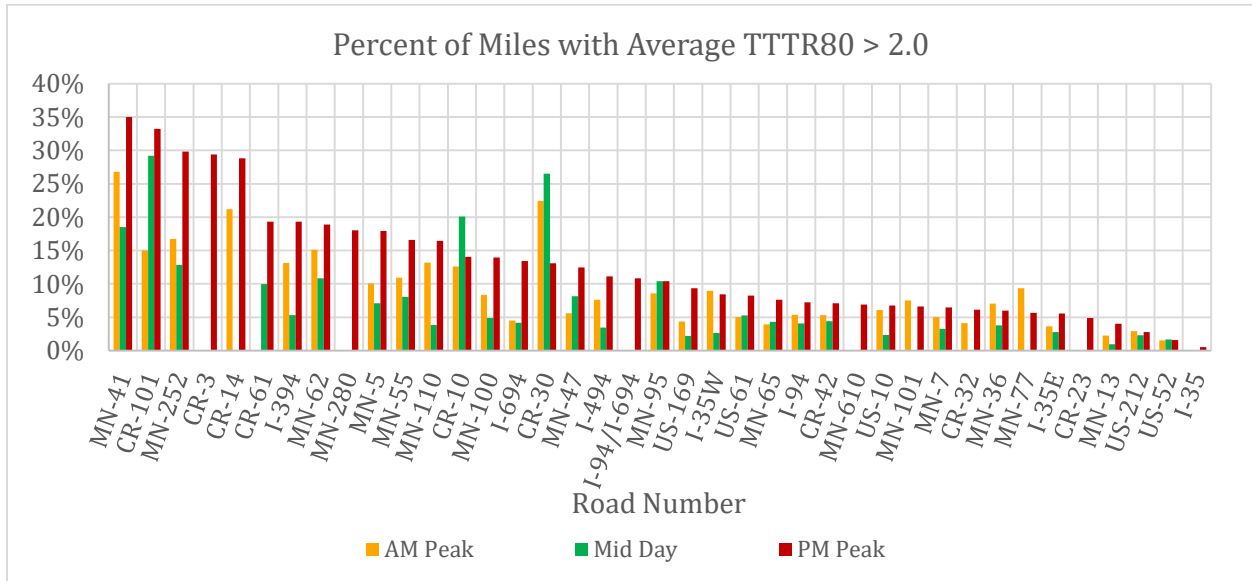


Figure 4.31 Percent of Roadway Miles with TTTR80 ≥ 2.0 by Time Period.

4.2.3 TTTR95

The TTTR95 measure is calculated using Eq. (3-4) for each time period. However, only measures in the AM peak, mid-day, and PM peak hours are discussed here. Figure 4.32 displays the average TTTR95 and its corresponding standard deviation (SD) in the AM peak period in each month for the entire network. The network-wide monthly TTTR95 in the AM peak period is around 3.2 over the 24-month period with an SD ranging from 3.8 to 5.6. The average network-wide average TTTR95 in mid-day is about 2.9 with an SD ranging from 3.5 to 4.9 as shown in Figure 4.33. Similarly, the network-wide monthly median TTTR95 in the PM peak period, as shown in Figure 4.34, is around 3.6 over the 24-month period with an SD varying from 3.9 to 6.7.

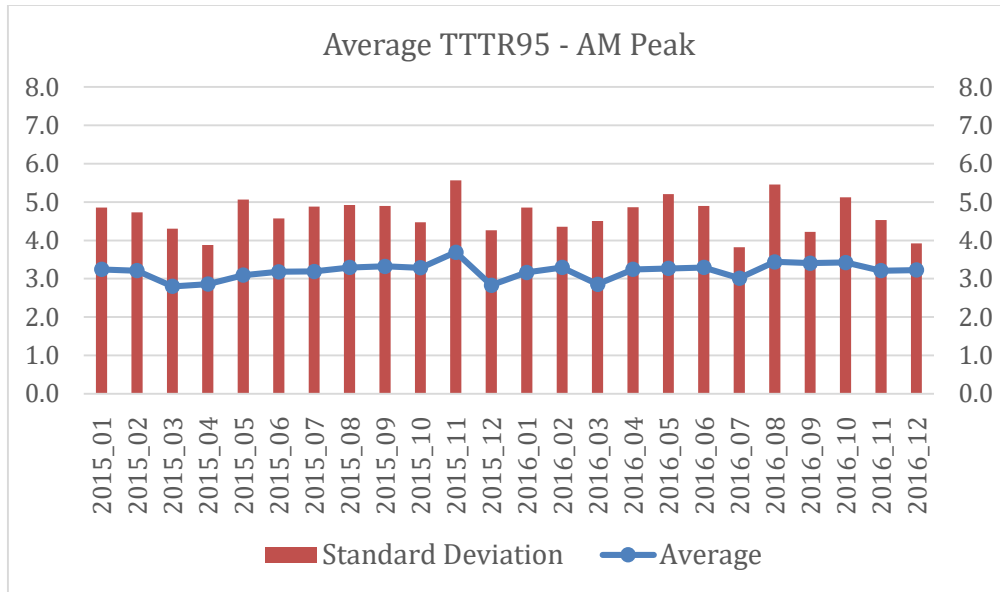


Figure 4.32 Network-wide Monthly Average TTTR95 in the AM Peak.

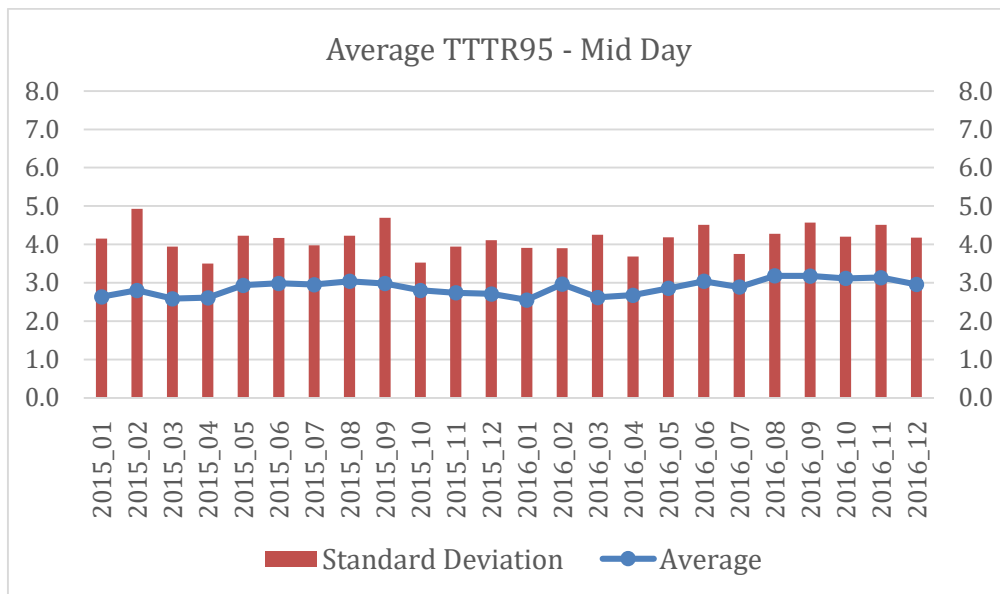


Figure 4.33 Network-wide Monthly Average TTTR95 in Mid-Day.

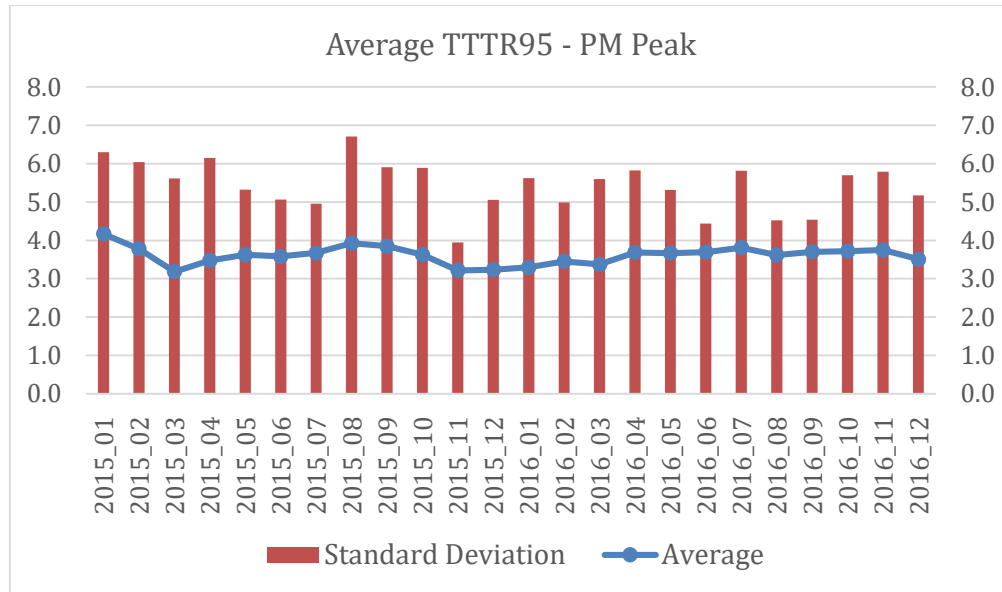


Figure 4.34 Network-wide Monthly Average TTTR95 in the PM Peak.

4.2.3.1 TTTR95 in the AM Peak

The TTTR95 at TMC segment level was analyzed for both AM and PM peak periods. Figure 4.35 displays the roadway segments with average TTTR95 greater than 1.5 in the AM peak. Many sites with TTTR95 measures greater than 2.0 are located near the highway interchanges, arterial signalized intersections, or at highway on/off ramps. A few locations with average TTTR95 greater than 5.0 (segments in red color displayed in Figure 4.35) are listed as follows.

- MN-55 between I-494 and Downtown Minneapolis
- US-169 SB N of I-394
- I-394 between US-169 and MN-100
- I-94 between I-394 and I-35W
- MN-7 between I-494 and MN-100
- MN-62 and I-35W common area
- MN-62 between I-494 and US-169
- MN-55 (Hiawatha Ave) S of I-94
- Warner Rd. between US-52 and US-10
- I-35W between MN-13 and CR-42
- MN-36 E of Stillwater Blvd

Analyses of TTTR95 measures at 2 locations in the AM peak period are presented as follows. The monthly TTTR95 measures of five TMC segments (118N04302, 118N04303, 118N04304, 118N04305 & 118N04306) on US-169 SB north of I-394 in the AM peak period are plotted in Figure 4.36. The average TTTR95 measures for TMC segments 118N04302 to 118N04306 are 5.5, 5.3, 5.2, 5.4 and 5.6, respectively.

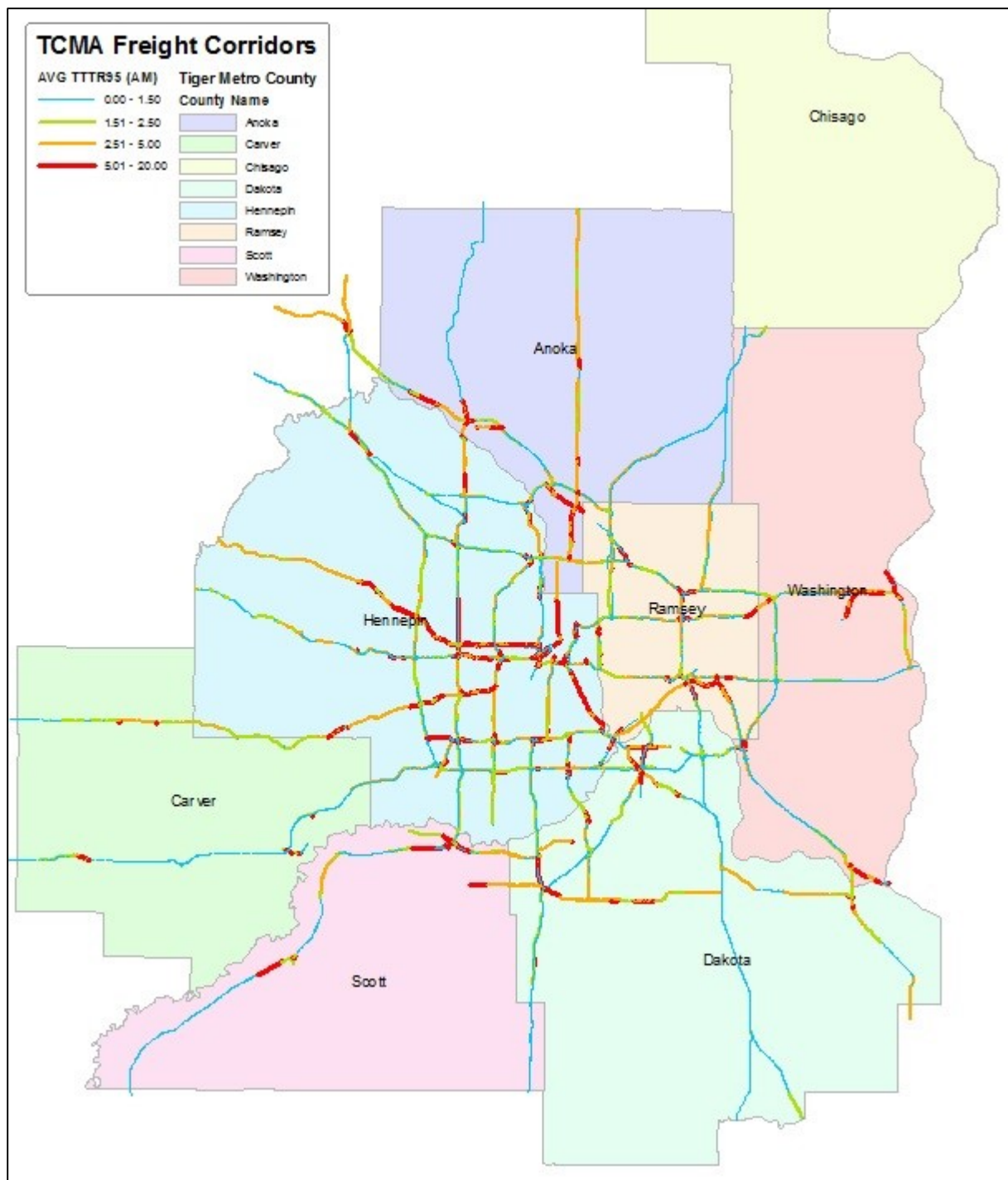


Figure 4.35 Average TTR95 measure in the AM peak period.

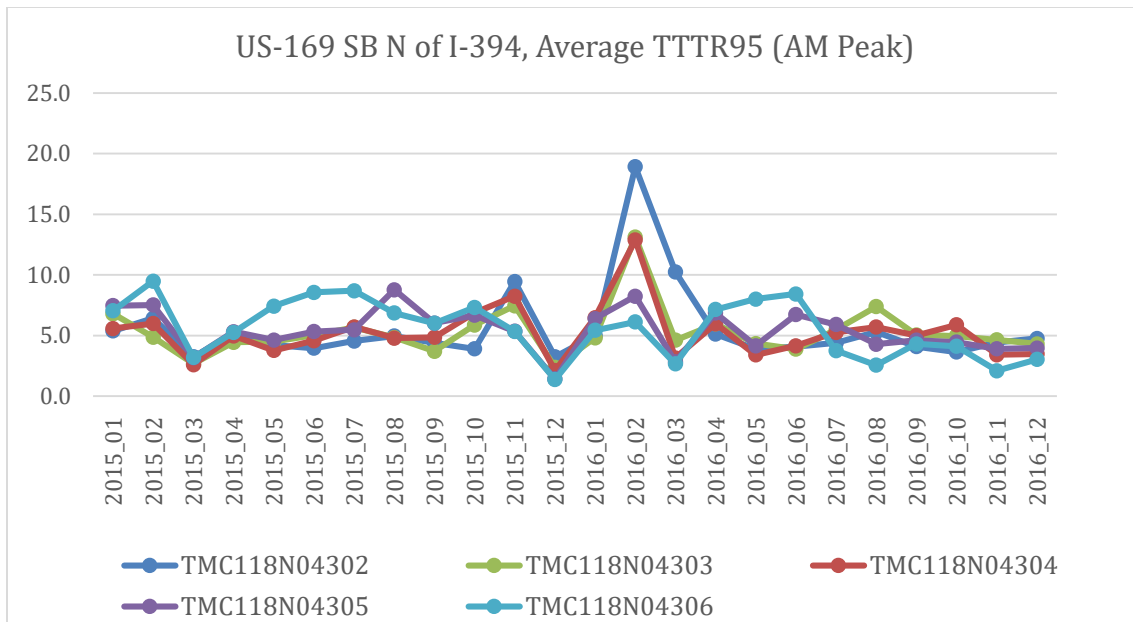


Figure 4.36 TTTR95 of 5 TMC Segments on US-169 SB North of I-394 in the AM Peak.

Similarly, the monthly TTTR95 measures of three TMC segments (118P04714, 118P04716 & 118P04717) on MN-55 west of I-494 in the AM peak period are plotted in Figure 4.37. The average TTTR95 measures for these TMC segments are 8.6, 8.1, and 7.6, respectively.

The variation of TTTR95 measures of 5 TMC segments on US-169 are smaller as compared to the variation on MN-55 nearby I-494 area. The travel time variations on MN-55 is largely contributed by the traffic signal delays.

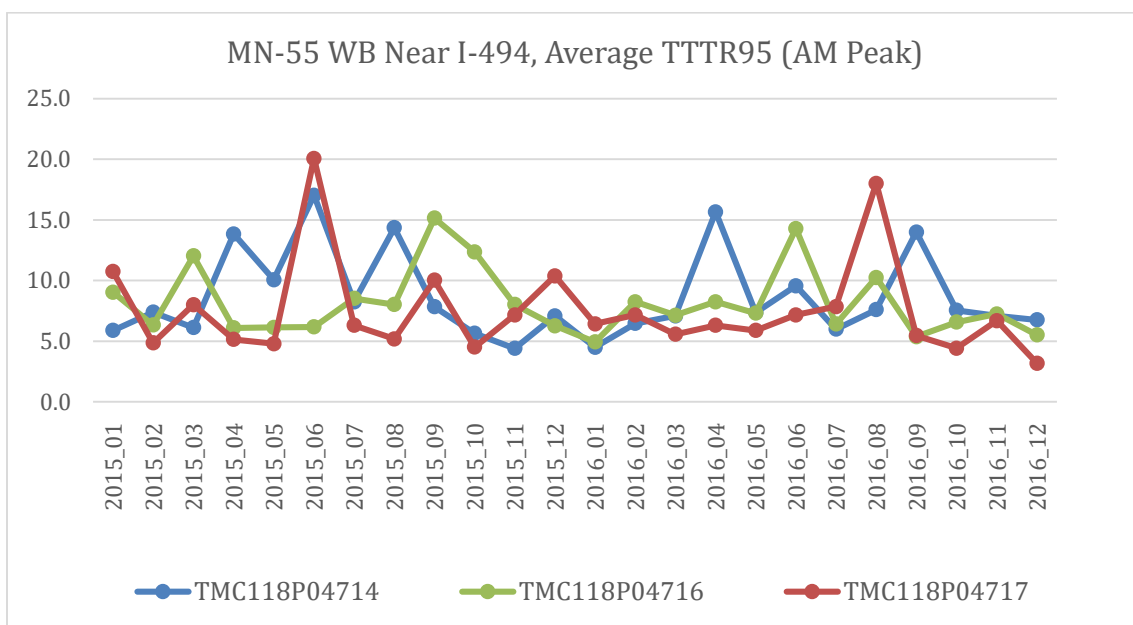


Figure 4.37 TTTR95 of 3 TMC Segments on MN-55 WB near I-494 in the AM Peak.

4.2.3.2 TTTR95 in the PM Peak

Figure 4.38 displays the roadway segments with average TTTR95 greater than 1.5 in the PM peak. TTTR95 measure greater than 5 are displayed in red, TTTR95 value between 2.5 and 5.0 are shown in orange color, and TTTR95 value between 1.5 and 2.5 are displayed in light green). As shown in Figure 4.38, many sites with TTTR95 measures greater than 5.0 in the PM peak are located near the highway interchanges, arterial signalized intersections, or at highway on/off ramps. A few locations with average TTTR95 greater than 5.0 in the PM peak are listed as follows.

- US-169 N of CR-81
- MN-252
- US-169 N of I-394
- US-169 between MN-62 and I-494
- MN-55 between I-494 and Downtown Minneapolis
- MN-55 (Hiawatha Ave) between I-94 and MN-62
- MN-7 between I-494 and MN-100
- MN-62 between I-494 and US-169
- I-35W between MN-36 and I-694
- MN-65 N of I-694
- Warner Rd. between US-52 and US-10

Analyses of TTTR95 measures at 2 locations in the PM peak period are presented as follows. The monthly TTTR95 measures of four TMC segments (118N04302, 118N04303, 118N04304, & 118N04305) on US-169 SB north of I-394 (from 36th Ave. to Betty Crocker Dr., about 2.9 miles) in the PM peak period are plotted in Figure 4.39. The average TTTR95 measures for these TMC segments are 4.9, 5.6, 6.3, and 4.8, respectively. In February 2015, the TTTR95 measures for 118N04304, 118N04305 & 118N04306 segments are higher than 12 in the PM peak periods. As compared to the 24-month average TTTR95, there might be weather related causes to the significantly unreliable travel time in Feb. 2015.

Similarly, the monthly TTTR95 measures of three TMC segments (118P04714, 118P04716 & 118P04717) on MN-55 WB from County Road 6 to Rockford Rd. (about 3 miles) in the PM peak period are plotted in Figure 4.40. There are 7 traffic signals on MN-55 between County Road 6 and Rockford Rd. Signal timing and coordination will affect the truck travel time on roadway with signalized intersections. The average TTTR95 measures for these TMC segments are 8.0, 10.5, and 9.4, respectively. There are two spikes for segment 118P04716 in September 2015 and for 118P04717 in August 2016 with TTTR95 higher than 50. It is suspected that both spikes are likely to be outliers.

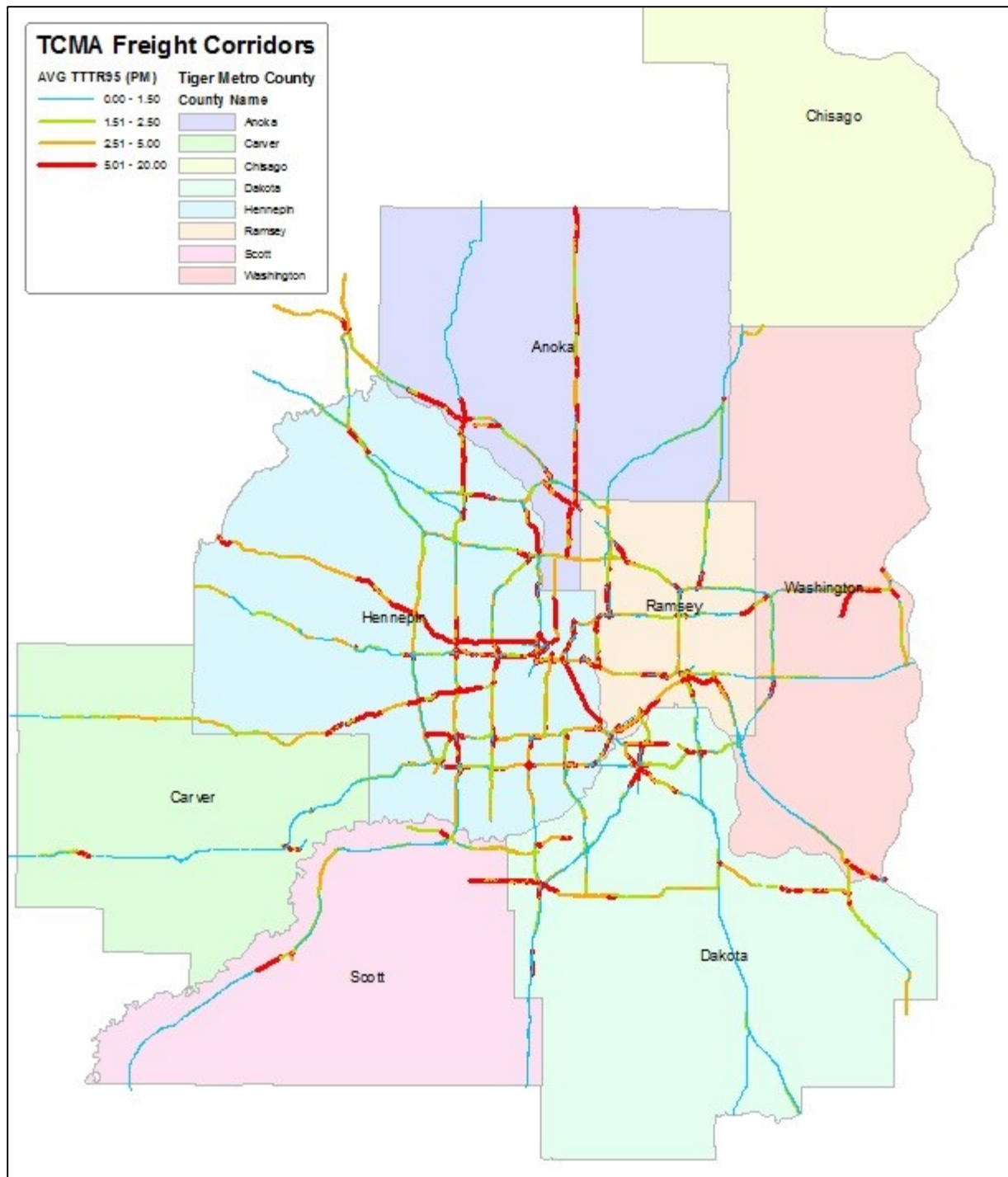


Figure 4.38 Average TTTR95 measure in the PM peak period.

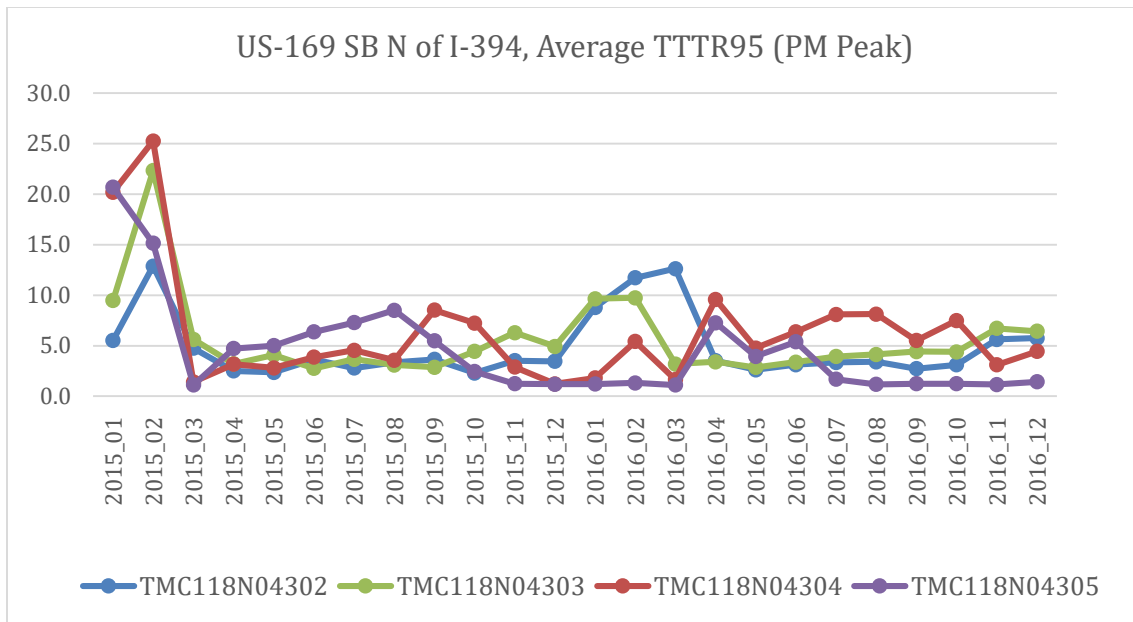


Figure 4.39 TTTR95 of 4 TMC Segments on US-169 SB North of I-394 in the PM Peak.

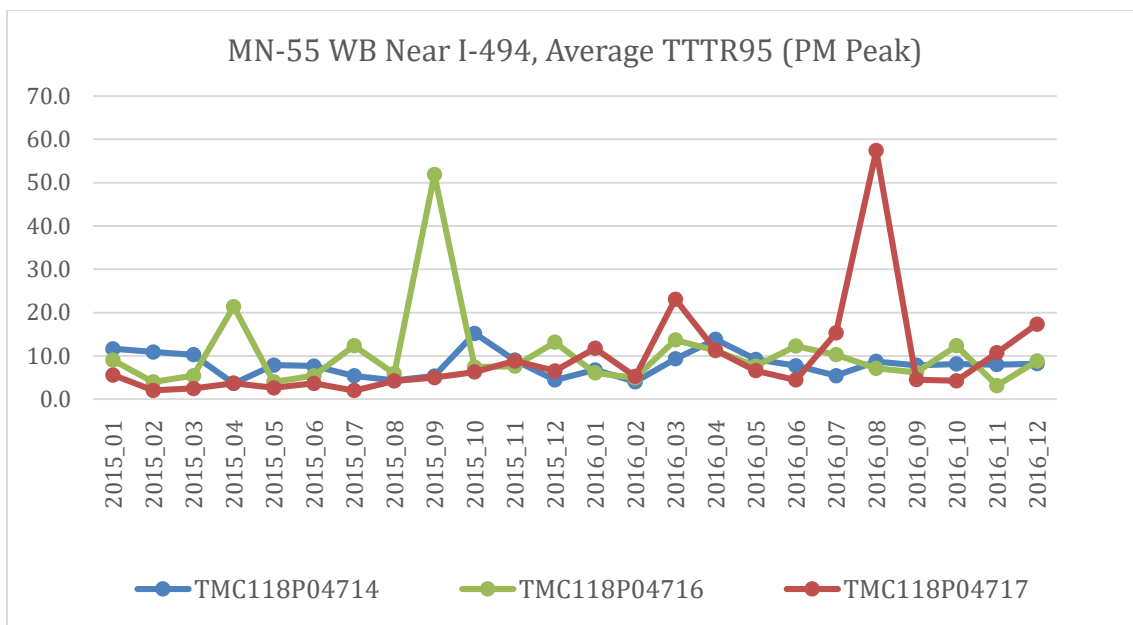


Figure 4.40 TTTR95 of 3 TMC Segments on MN-55 WB near I-494 in the PM Peak.

4.2.3.3 TTTR95 by Route

The TTTR95 measure is further analyzed by route. Figure 4.41 displays the percent of miles with average TTTR95 greater than 2.0 for AM, mid-day, and PM periods. In general, roadways with signalized or unsignalized intersections are less reliable than freeways. For example, the 95th percentile truck travel time on 80% of CR-42 is over twice as long as the average truck travel time in the PM peak. In the PM peak hours, the 95th percentile truck travel time on 75.5% of MN-65 roadway in the Twin Cities metro area is over twice as long as the average truck travel time. Similarly, the 95th percentile truck travel time on 52.7% of I-394 roadway is over twice as long as the average truck vehicle travel time.

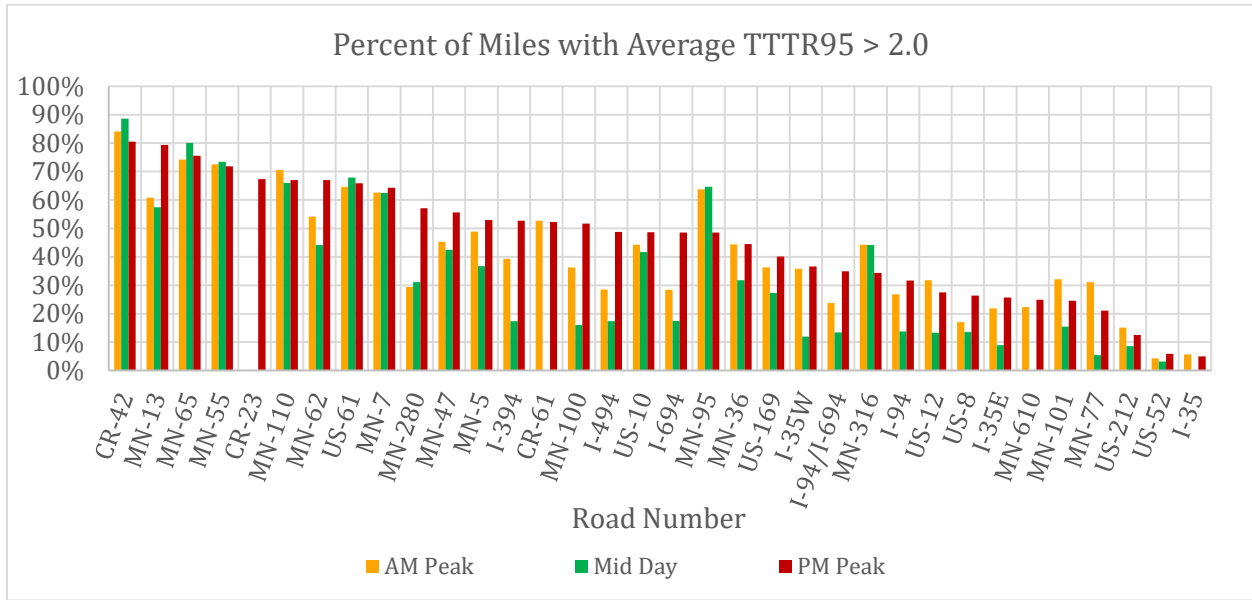


Figure 4.41 Percent of Roadway Miles with TTTR95 \geq 2.0 by Time Period.

4.2.4 Summary of Reliability Measures

Table 4.2 summarizes the RI95, TTTR80, and TTTR95 measures for truck travel time in the Twin Cities NHS network. All measures indicate that the truck travel time in the PM peak period is less reliable than in the AM peak period.

Table 4.2 Percent of roadway segments with reliability measure < 1.5

Percent of Roadway	Weekday			Weekend
	AM	Mid-Day	PM	
RI95	54.8%	63.9%	50.0%	72.5%
TTTR80	80.3%	85.9%	75.3%	89.9%
TTTR95	46.7%	56.3%	42.4%	65.4%

Based on the RI95 measures (see Figure 4.21), the 3 most unreliable corridors in the PM peak hours are MN-252, CR-32 and CR-10. According to the TTTR80 measure (see Figure 4.31), the 3 most unreliable corridors in the PM peak are MN-41, CR-101, and MN-252. Based on the TTTR95 measures (see Figure 4.41), the 3 most unreliable corridors in the PM peak hours are CR-42, MN-65 and MN-55.

Additional analyses of truck travel time reliability comparison at both the TMC and corridor levels are included in Appendix A.

4.3 TRUCK DELAY ANALYSIS

Truck delay, as defined in Eq. (3-5), was computed for each TMC segment in both AM and PM peak periods. Base free flow speed (BFFS) for commercial heavy vehicles, as defined in Eq. (3-6), was used to determine free flow truck travel time in each roadway segment. Observed truck travel time (from NPMRDS data) was compared to the free flow truck travel time to determine delay in each segment. Hourly truck volume distributions from our previous study [9] were used to estimate total truck delay at each TMC in peak periods. Hourly truck volume distribution is included in Appendix B.

4.3.1 Truck Delay in the AM Peak

Truck delays in the AM peak period in Mar. and Sep. 2016 were presented as examples to evaluate the truck delays at the corridor level. Figure 4.42 displays the estimated daily truck delay in the AM peak period in Mar. 2016 for each corridor with total delay greater than 1,000 hours. MN-55, I-35W and I-94 have a total truck delay over 3,000 hours in the AM peak period.

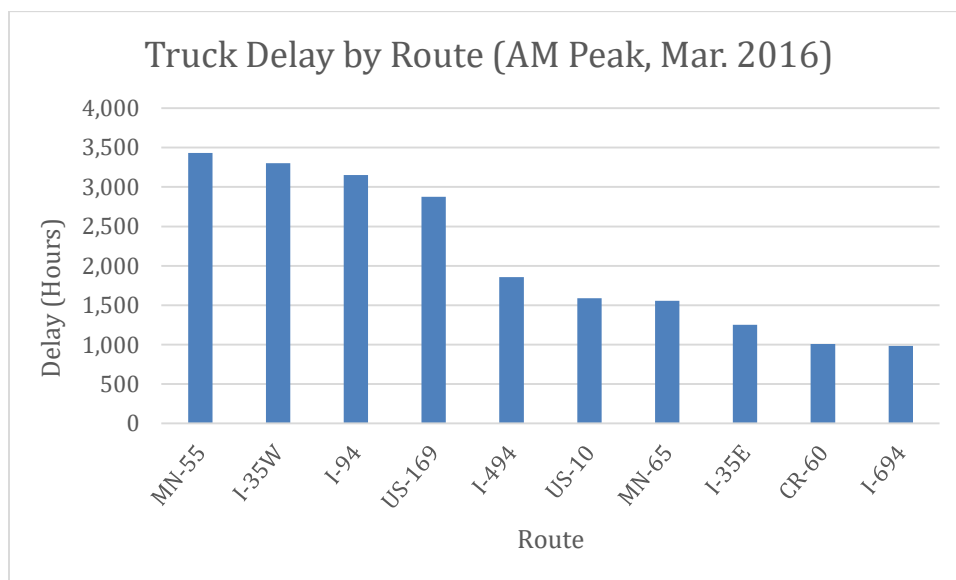


Figure 4.42 Daily Truck Delay (Over 1,000 hours) by Corridor in the AM Peak in Mar. 2016.

Figure 4.43 displays the estimated daily truck delay for each corridor with total delay greater than 1,000 hours. I-35W, I-94, US-169, I-494, and MN-55 have total truck delay over 3,000 hours in the AM peak period in September 2016.

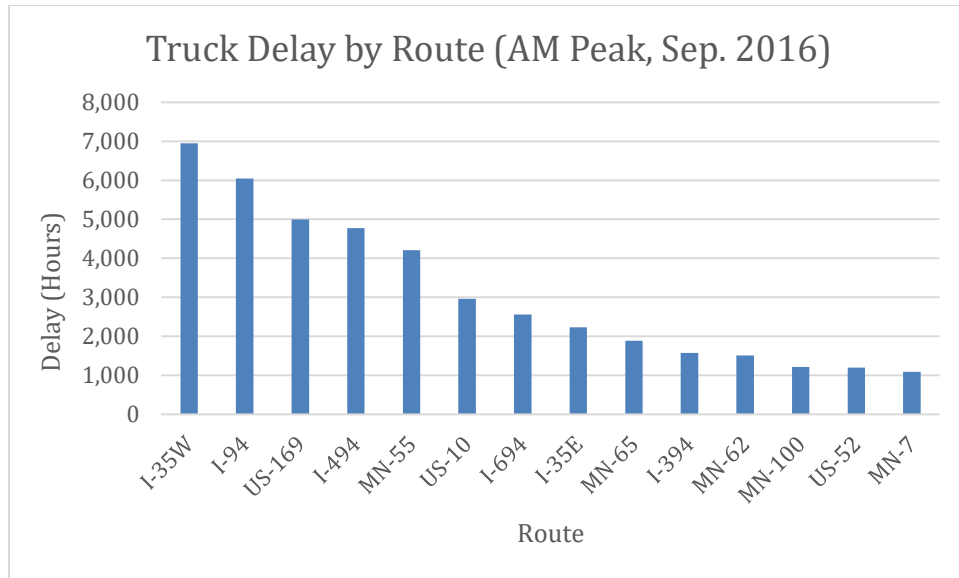


Figure 4.43 Daily Truck Delay (Over 1,000 hours) by Corridor in the AM Peak in Sep. 2016.

Average daily truck delay in the AM peak at the corridor level during the 24-month period was further analyzed. Figure 4.44 displays the average daily truck delay for each corridor with total delay greater than 1,000 hours. I-35W, I-94, US-169, I-494, and MN-55 have an average total truck delay over 3,000 hours in the AM peak period.

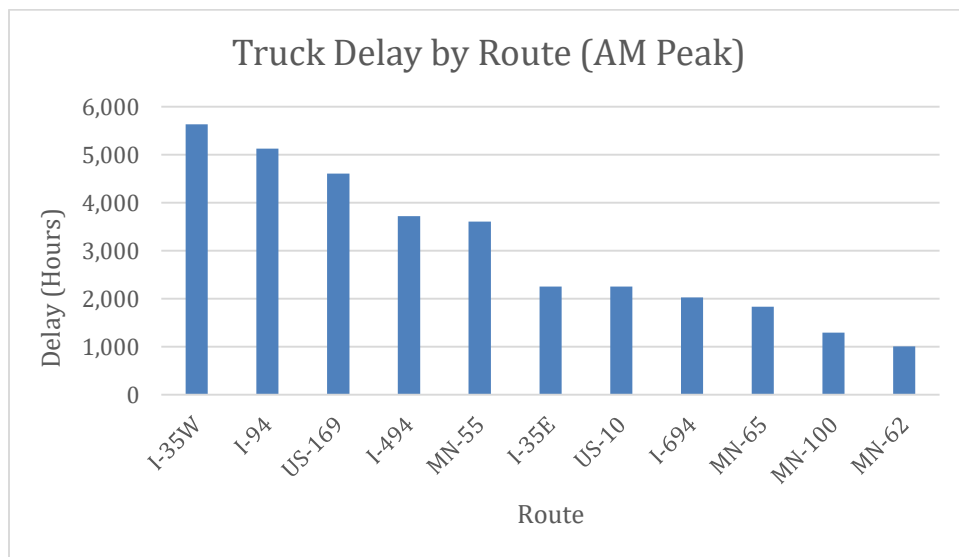


Figure 4.44 Average Daily Truck Delay (Over 1,000 hours) by Corridor in the AM Peak.

Figure 4.45 display the average truck delay per mile in the Twin Cities in the AM peak based on the 24-month of NPMRDS data. Interchanges at I-694 & US-169, I-394 & US-169, I-35W & I-494, I-394 & I-94, I-35E & I-94, I-35E & I-694, and US-52 & I-94 were congested during AM peak hours. In addition, roadway segments at I-35W NB between MN-13 and CR-42 has an average truck delay over 300 hours per mile in the AM peak.

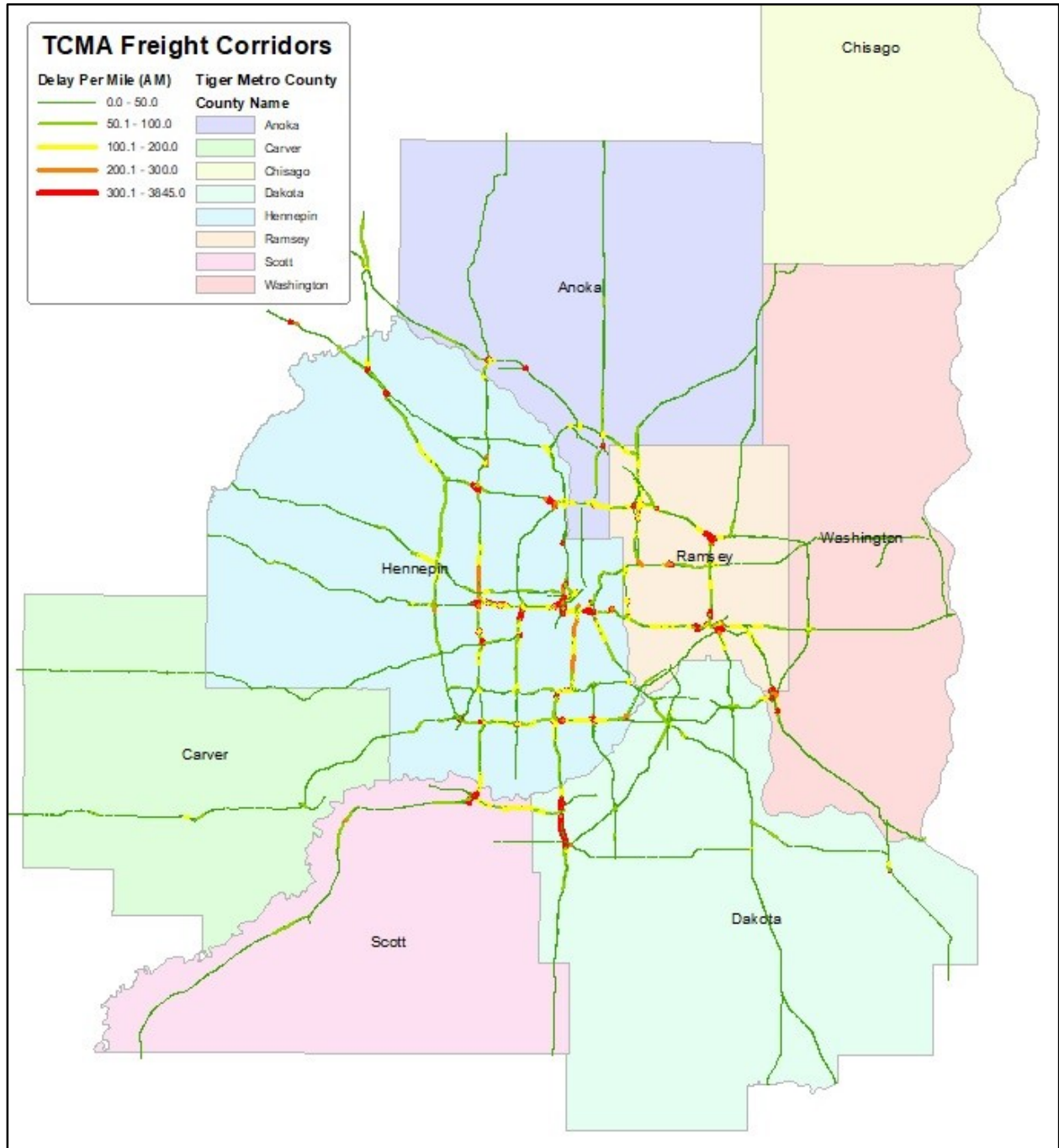


Figure 4.45 Visualization of Average Truck Delay per Mile by TMC Segment in the AM Peak.

4.3.2 Truck Delay in the PM Peak

Truck delays in the PM peak period in Mar. and Sep. 2016 were presented as examples to evaluate the truck delays at the corridor level. Figure 4.46 displays the estimated daily truck delay in the PM peak period in Mar. 2016 for each corridor with total delay greater than 1,000 hours. I-94, I-35W, US-169, I-494 and MN-55 have a total truck delay over 3,000 hours in the PM peak period.

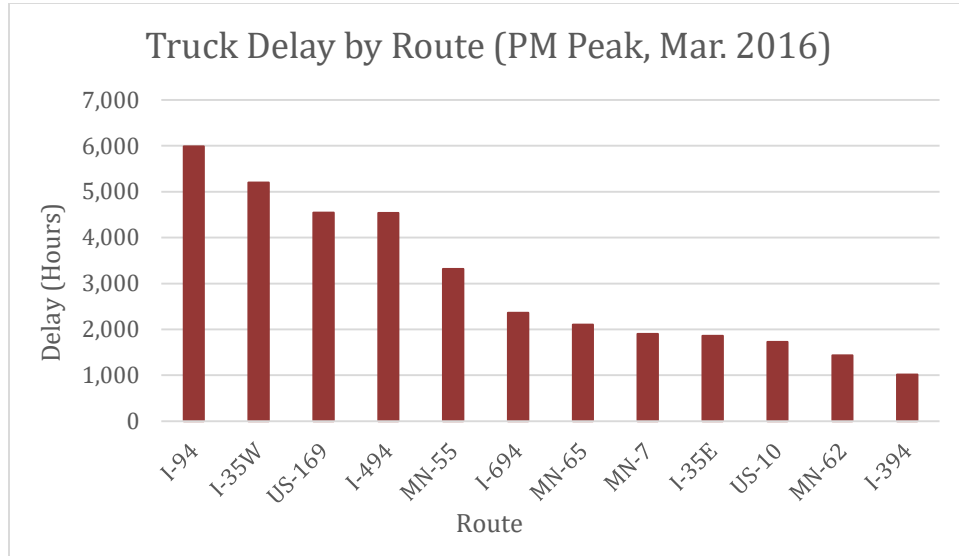


Figure 4.46 Daily Truck Delay (Over 1,000 hours) by Corridor in the PM Peak in Mar. 2016.

Figure 4.47 displays the estimated daily truck delay for each corridor with total delay greater than 1,000 hours. I-35W, I-94, US-169, I-494, I-696, and MN-55 have a total truck delay over 3,000 hours in the PM peak period in September 2016.

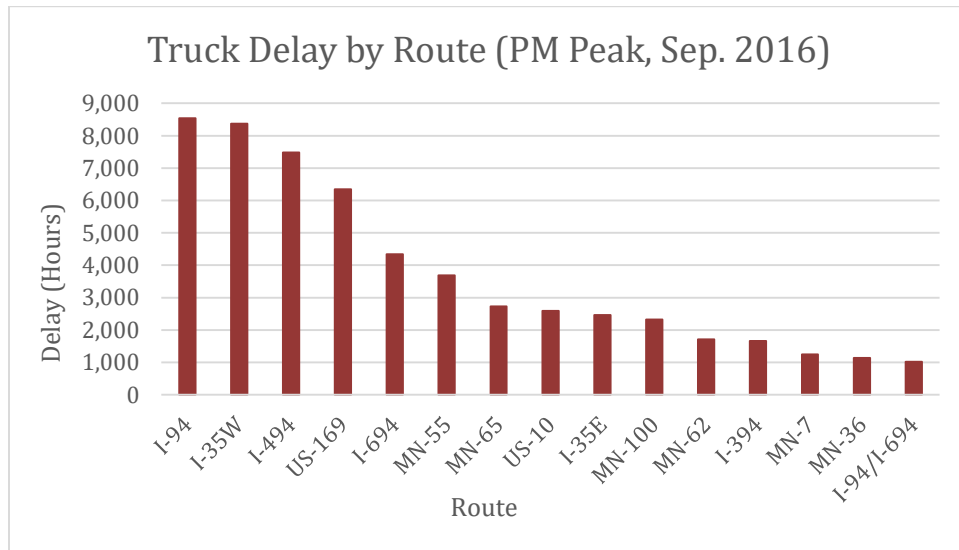


Figure 4.47 Daily Truck Delay (Over 1,000 hours) by Corridor in the PM Peak in Sep. 2016.

Average daily truck delay in the PM peak at the corridor level during the 24-month period was further analyzed. Figure 4.48 displays the average daily truck delay for each corridor with total delay greater than 1,000 hours. I-94, I-35W, I-494, US-169, I-694, and MN-55 have an average total truck delay over 3,000 hours in the PM peak period.

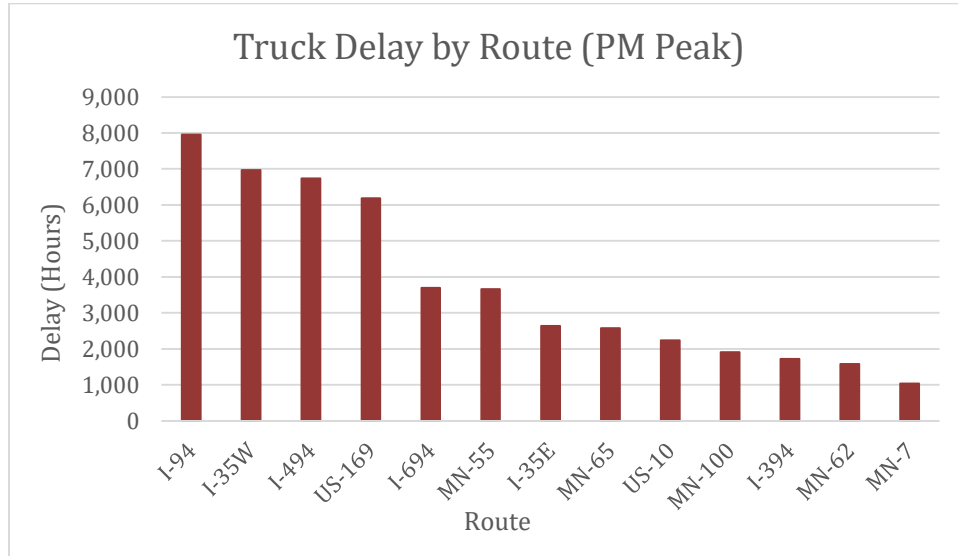


Figure 4.48 Average Daily Truck Delay (Over 1,000 hours) by Corridor in the PM Peak.

Figure 4.49 display the average truck delay per mile in the Twin Cities in the PM peak based on the 24-month of NPMRDS data. Interchanges at I-394 & US-169, I-494 & MN-100, I-35W & I-494, I-394 & I-94, I-35W & I-94, I-35W & I-694, I-35E & I-694, I-94 & I-35E, and US-52 & I-94 were congested during PM peak hours. In addition, segments at I-94 WB between US-169 and I-494, I-394 EB between MN-100 & I-94, I-35W NB S of Downtown Minneapolis, I-35W SB N of I-94, I-94 WB between MN-280 and I-394, I-35W NB between MN-36 and I-694, and I-94 EB W of Downtown St. Paul, and I-494 EB between US-169 and I-35W, have an average truck delay over 300 hours per mile in the PM peak hours.

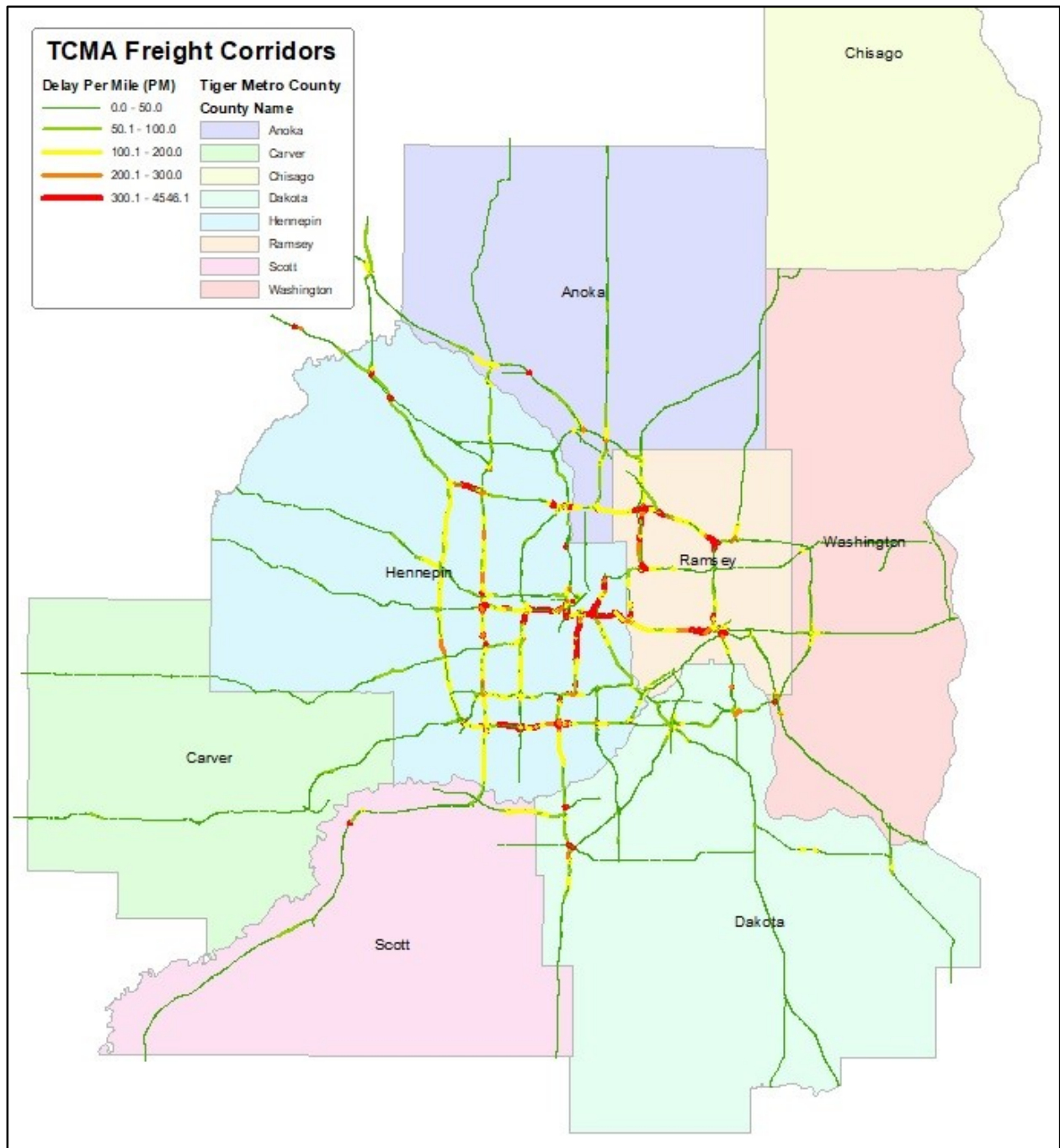


Figure 4.49 Visualization of Average Truck Delay per Mile by TMC in the PM Peak.

4.3.3 Truck Delay at TMC Segment Level

Average daily truck delays were examined at 6 locations in the PM peak hours as listed below. Figure 4.50 to Figure 4.55 displays the average daily truck delay in the PM peak period by month. Truck delays at these locations indicated some seasonal variations. Overall, the recurring truck delays at these locations are consistent throughout the 24-month study period.

- I-494 EB E & W MN-100 – TMC 118N04131 & TMC 118N04133
- I-94 WB W of US-169 – TMC 118P04153
- I-394 EB W of I-94 – TMC 118P04354
- I-35W NB S of Downtown Minneapolis – TMC 118P04237
- I-94 WB at I-35W – TMC 118P04198 & TMC 118P04199
- I-94 EB at Marion Street – TMC 118N04188

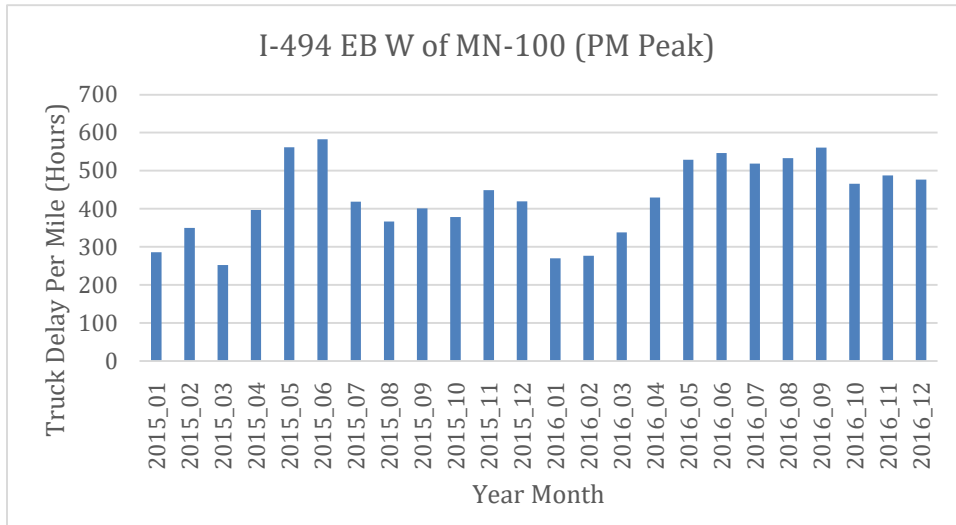


Figure 4.50 Average truck delay at I-494 EB W of MN-100 during the PM peak.

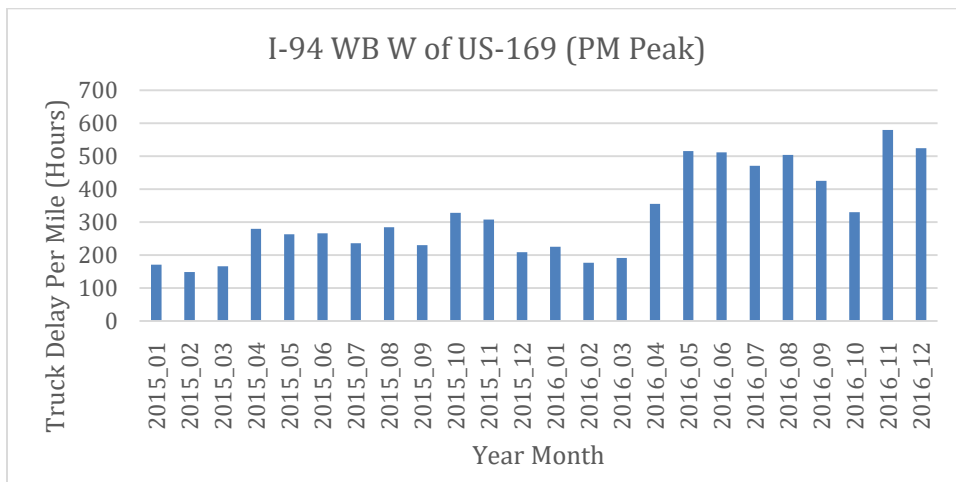


Figure 4.51 Average truck delay at I-94 WB W of US-169 during the PM peak.

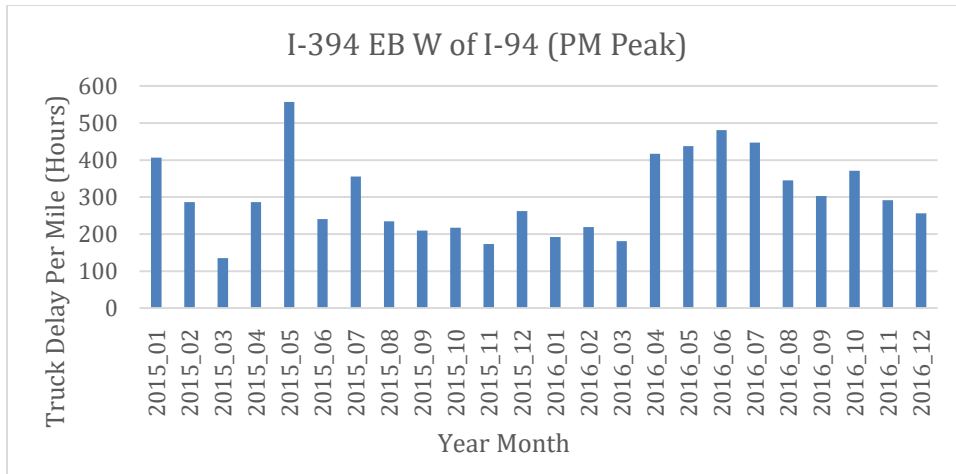


Figure 4.52 Average truck delay at I-394 EB W of I-94 during the PM peak.

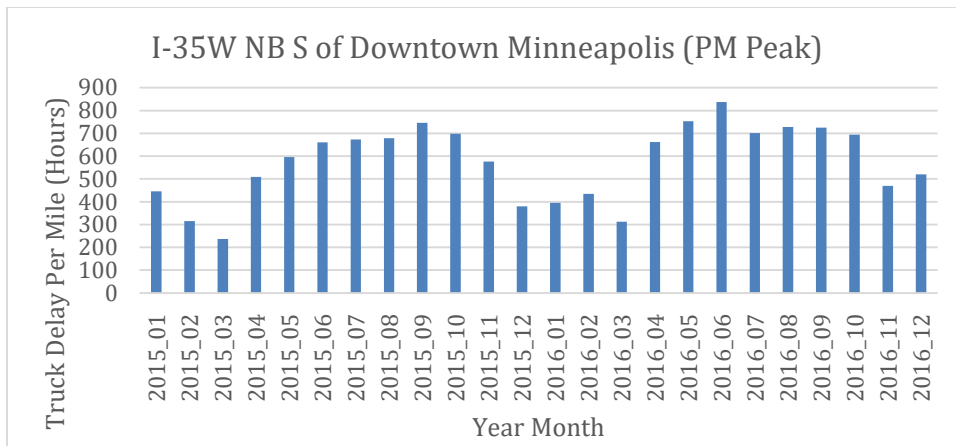


Figure 4.53 Average truck delay at I-35W NB S of Downtown Minneapolis during the PM peak.

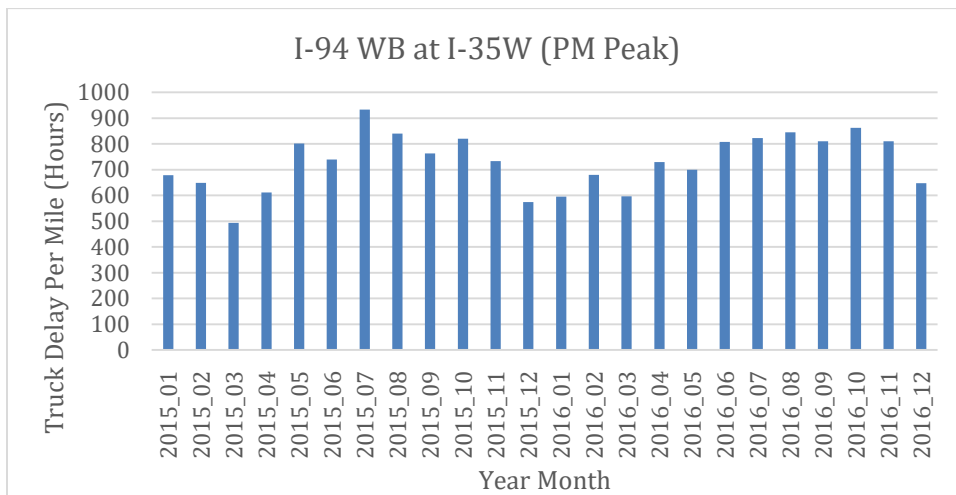


Figure 4.54 Average truck delay at I-94 WB & I-35W SB during the PM peak.

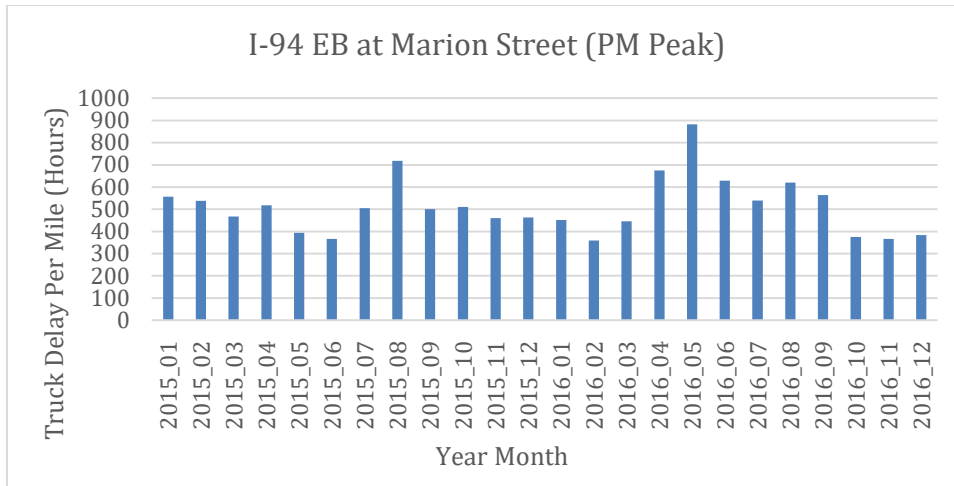


Figure 4.55 Average daily truck delay at I-94 EB at Marion Street W of Downtown St. Paul.

A list of TMC segments (non-interchange locations) with recurring truck delays in the PM peak hours are listed in Table 4.3 as follows. TMC 118P04198 & TMC 118P04199 segments (I-94 WB at I-35W in Minneapolis) has the highest truck delay per mile in the PM peak on an average weekday. Average truck delay in the PM peak in this segment is 570 hours per mile, or 775 hours in total. TMC 118P04237 (I-35W NB south of Downtown Minneapolis) has the second highest truck delay in the PM peak on an average weekday. Average truck delay in the PM peak in this segment is 523 hours per mile. TMC 118N04188 (I-94 EB west of Downtown St. Paul) has the third highest truck delay in the PM peak on a regular weekday. Average truck delay in the PM peak in this segment is 495 hours per mile, or 366 hours in total.

Table 4.3 Top Congested TMC Segment in the PM Peak

Ranking	TMC	Description	Length (Miles)	Average Hours of Delay Per Mile (Hours)	Total Segment Delay (Hours)
1	118P04198 118P04199	I-94 WB at I-35W	1.36	570	775
2	118P04237	I-35W NB South of Downtown Minneapolis	1.00	523	523
3	118N04188	I-94 EB at Marion Street	0.74	495	366
4	118N04131 118N04133	I-494 EB East & West of MN-100	2.33	480	1,118
5	118P04153	I-694/94 WB West of US-169	1.17	321	376
6	118P04354	I-394 EB West of I-94	1.23	310	381

CHAPTER 5: POTENTIAL CAUSES OF TRUCK DELAY

This chapter focuses on examining and evaluating the potential causes of truck congestion at 6 selected bottlenecks in the PM peak hours. The examination and evaluation were conducted by driving through the congested locations and reviewing video from MnDOT traffic cameras [25] during PM peak. Table 5.1 lists the annual average daily truck and all traffic volume in 2016 at 6 locations where recurring truck congestion occurred during PM peak period. On average, heavy commercial vehicles consist of 5% of overall traffic at the selected sites. Among the 6 locations, the I-694/94 WB west of US-169 has the highest HCAADT volume and truck volume percentage. I-394 EB west of I-94 has the lowest HCAADT volume and truck volume percentage in the PM peak period.

Table 5.1 Truck Volume Percentage at Selected TMC Segments

#	TMC	Location Description	Length (Miles)	HCAADT 2016	AADT 2016	Heavy Truck %
1	118P04198 118P04199	I-94 WB at I-35W	1.36	6,800	155,000	4.4%
2	118P04237	I-35W NB South of Downtown Minneapolis	1	7,500	193,000	3.9%
3	118N04188	I-94 EB at West of Downtown St. Paul	0.74	7,500	142,500	5.3%
4	118N04131 118N04133	I-494 EB at MN-100	2.33	8,750	164,500	5.3%
5	118P04153	I-694/94 WB West of US-169	1.17	10,000	118,000	8.5%
6	118P04354	I-394 EB West of I-94	1.23	3,400	134,000	2.5%

5.1 I-94 WB AT I-35W

The location of I-94 and I-35W interchange in Minneapolis is illustrated in Figure 5.1. The 2016 HCAADT and AADT for I-94 WB traffic at this location (TMC 118P04198 & TMC 118P04199) were 6,800 and 155,000, respectively. Commercial trucks make up 4.4% of all vehicles traveling through this location. Recurring traffic congestion occurred in peak hours on a daily basis. Speed limit in the Lowry tunnel (A) in the west was reduced to 40 MPH due to horizontal and vertical curves. In addition, multiple paths of traffic weaving in (from I-35W NB and Downtown Minneapolis) and out (to local streets in Downtown Minneapolis) generate several potential points of disruption in this area (between point A and B as illustrated in Figure 5.1). Traffic congestion queue on I-94 WB often goes couple miles from the tunnel to the Mississippi River.

In addition, heavy traffic going from I-94 WB to I-35W SB through a single lane off-ramp (B) often generates delays when I-35W SB is already congested. Insufficient capacity, roadway geometry, and density of on/off-ramps are the key causes of the congestion in this location. The truck mobility (TTR), reliability (TTTR95) and delays are plotted in Figure 5.2. The average TTR at this location is 1.36 with a

standard deviation of 0.19. The average TTTR95 is 3.19 with a standard deviation of 0.3. The column chart in Figure 5.2 displays the daily average truck delay in the PM peak by month at this location. In 2015 & 2016, the average truck delay in the PM peak at this location ranges from 374 to 625 hours on a daily basis.



Figure 5.1 Aerial Map of I-94 and I-35W Interchange in Minneapolis, MN.

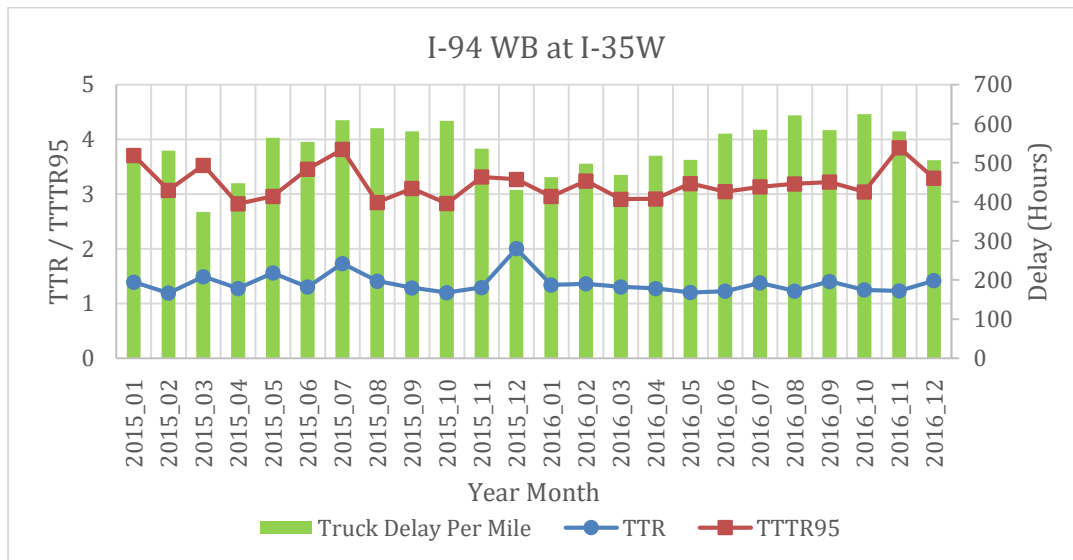


Figure 5.2 Average TTR, TTTR95, and Delay per Mile at I-94 WB & I-35W.

Figure 5.3 is a photo from MnDOT RTMC camera at I-94 and Cedar Ave in Minneapolis in the PM peak period. The I-94 WB and I-35W SB interchange is less than 1 mile downstream.



Figure 5.3 Screenshot of MnDOT RTMC Camera at I-94 and Cedar Ave.

5.2 I-35W NB SOUTH OF DOWNTOWN MINNEAPOLIS

The location of I-35W NB and I-94 interchange in south of Downtown Minneapolis is illustrated in Figure 5.4. The 2016 HCAADT and AADT for I-35W NB traffic at this location (TMC 118P04237) were 7,500 and 193,000, respectively. Commercial trucks make up 3.9% of all vehicles traveling through this location. Recurring traffic congestion occurred in peak hours on a daily basis. Point A (as illustrated in Figure 5.4) is a weaving location for traffic coming from I-94 EB to I-35W NB and leaving I-35W NB to I-94 EB. Another weaving point (I-35W NB & MN-55/Hiawatha Ave.) with horizontal and vertical curves ahead of point A creates additional frictions to the traffic flow in this area. Speed limit on I-35W NB at the 90-degree turn (B) was reduced from 55 to 35 MPH due to the sharp horizontal curve. In addition, multiple paths of traffic weaving in (from 33rd and 38th Street) and out (to I-94 WB and Downtown Minneapolis) generate several potential points of disruption in this area (between C and D as illustrated in Figure 5.4). Traffic congestion queue on I-35W NB often grows beyond point D.

Insufficient capacity, roadway geometry, and multiple weaving points at this location are the key causes of recurring congestion. The truck mobility (TTR), reliability (TTTR95) and delays are plotted in Figure 5.5. The average TTR at this location is 1.42 with a standard deviation of 0.17. The average TTTR95 is 3.91 with a standard deviation of 1.34. The truck travel time reliability measures in Jan. & Feb. 2015 were significantly higher (8.0 & 7.8) than the TTTR95 in the other months (see Figure 5.5). The unreliable truck travel time may be caused by winter weather or roadway incidents in Jan. & Feb. 2015. The column chart in Figure 5.5 indicates a seasonal pattern in the daily average truck delay in the PM peak by month at this roadway segment. In 2015 & 2016, the average truck delay in the PM peak at this location ranges from 208 to 735 hours on a daily basis. In general, trucks traveling through the location in non-winter months (Apr. to Nov.) have longer travel time delay than traveling in winter months.



Figure 5.4 Aerial Map of I-35W and I-94 Interchange in Minneapolis, MN.

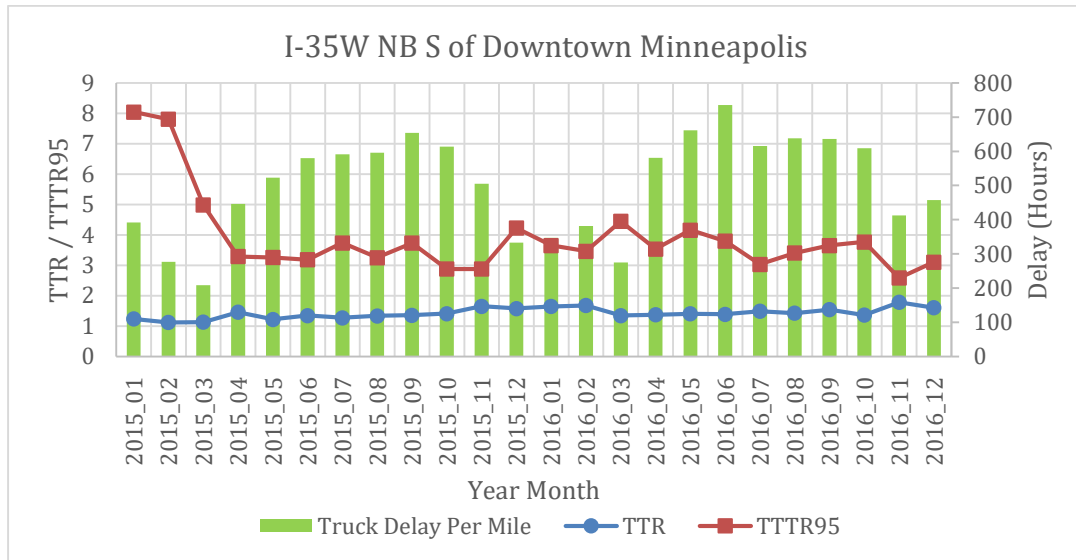


Figure 5.5 Average TTR, TTR95, and Delay per Mile at I-35W NB & I-94.

5.3 I-94 EB WEST OF DOWNTOWN ST. PAUL

The location of I-94 EB and I-35E interchange in west of Downtown St. Paul is illustrated in Figure 5.6. The 2016 HCAADT and AADT for I-94 EB traffic at this location (TMC 118N04188) were 7,500 and 142,500, respectively. Commercial trucks make up 5.3% of all vehicles traveling through this location. Recurring traffic congestion occurred in peak hours on a daily basis. Point A (as illustrated in Figure 5.6) is a weaving location for traffic coming from I-94 EB to US-52. Horizontal and vertical curves between point A & B also slow down the traffic flow in this area in rush hours. Speed limit between point A and C is reduced to 50 MPH due to multiple horizontal and vertical curves. In addition, multiple paths of traffic weaving in (from I-35E and Downtown St. Paul) and out (to I-35E NB, 7th Street and US-52) generate several potential points of disruption in this area (between A and C as illustrated in Figure 5.6). Traffic congestion queue on I-94 EB often grows beyond point C.



Figure 5.6 Aerial Map of I-94 and I-35E Interchange in St. Paul, MN.

Insufficient capacity, roadway geometry, and multiple weaving points at this location are the key causes of recurring congestion. The truck mobility (TTR), reliability (TTTR95) and delays are plotted in Figure 5.7. The average TTR at this location is 2.02 with a standard deviation of 0.34. On average, truck travel time on a weekday PM peak period is twice as long as the travel time of a passenger vehicle. The average TTTR95 is 4.15 with a standard deviation of 1.56. The truck travel time reliability measure in Mar. 2015 was significantly higher (9.9) than the TTTR95 in the other months (see Figure 5.7). The TTR in

Mar. 2015 was relatively lower (1.17) than the TTR in the other months. The unreliable truck travel time may be caused by winter weather or roadway incidents in Mar. 2015. The column chart in Figure 5.7 displays the daily average truck delay in the PM peak by month at this location. In 2015 & 2016, the average truck delay in the PM peak at this location ranges from 344 to 843 hours on a weekday.

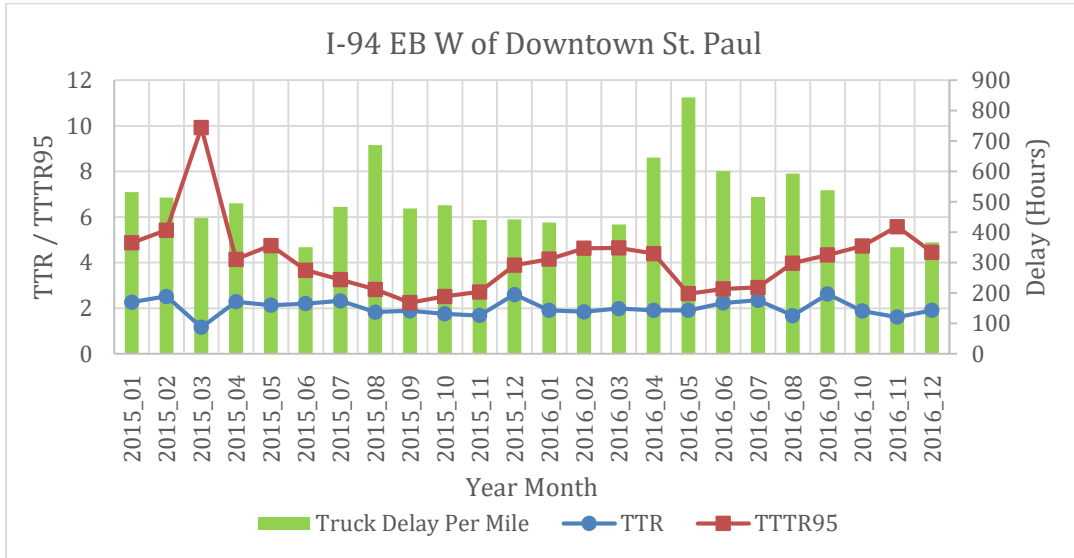


Figure 5.7 Average TTR, TTTR95, and Delay per Mile at I-94 EB & I-35E.

Figure 5.8 is a photo from MnDOT RTMC camera at I-94 and I-35E in St. Paul in the PM peak period. The I-94 EB and I-35E NB interchange is less than 1/2 mile downstream.

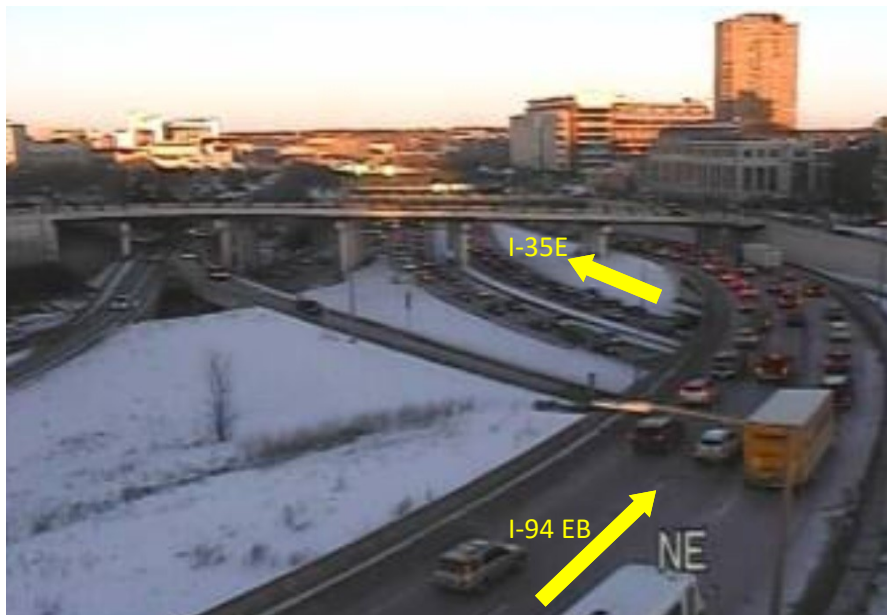


Figure 5.8 Screenshot of MnDOT RTMC Camera at I-94 and I-35E.

5.4 I-494 EB AT MN-100

The location of I-494 EB at MN-100 interchange in Bloomington is illustrated in Figure 5.9. The 2016 HCAADT and AADT for I-494 EB traffic at this location (TMC 118N04131 & TMC 118N04133) were 8,750 and 164,500, respectively. Commercial trucks make up 5.3% of all vehicles traveling through this location. Recurring traffic congestion occurred in peak hours on weekdays. Roadway geometry on I-494 from US-169 to I-35W is pretty straight with posted speed limit of 60 MPH. However, there are many office and retail business on both sides of the highway. There are 6 on/off-ramps and interchanges between I-35W and US-169. Many motorists try to get on/off/through this highway segment during the peak hours. Congestion queue on I-494 EB in the PM peak period often goes beyond point C on a regular weekday

In addition, heavy traffic going from I-494 EB to I-35W SB through a single lane off-ramp (A) often generates delays when I-35W SB is usually busy. Insufficient capacity and density of weaving points in this location are the key causes of traffic delays. The truck mobility (TTR), reliability (TTTR95) and delays are plotted in Figure 5.10. The average TTR at this location is 1.36 with a standard deviation of 0.16. The average TTTR95 is 3.23 with a standard deviation of 0.82. The truck travel time reliability measures in Jan. 2015 was relatively higher (5.9) than the TTTR95 in the other months (see Figure 5.10). The unreliable truck travel time at this location may be related to winter weather. The column chart in Figure 5.10 displays the daily average truck delay in the PM peak by month at this location. In 2015 & 2016, the average truck delay in the PM peak at this location ranges from 314 to 701 hours on a daily basis.

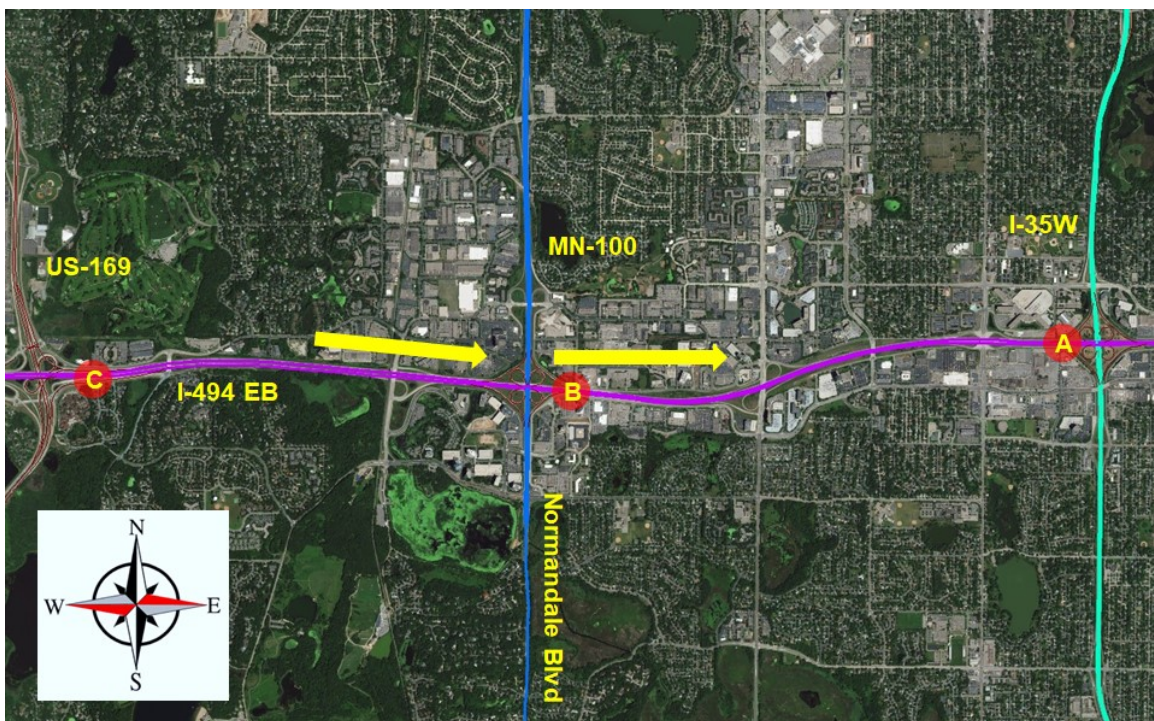


Figure 5.9 Aerial Map of I-494 and MN-100 in Bloomington, MN.

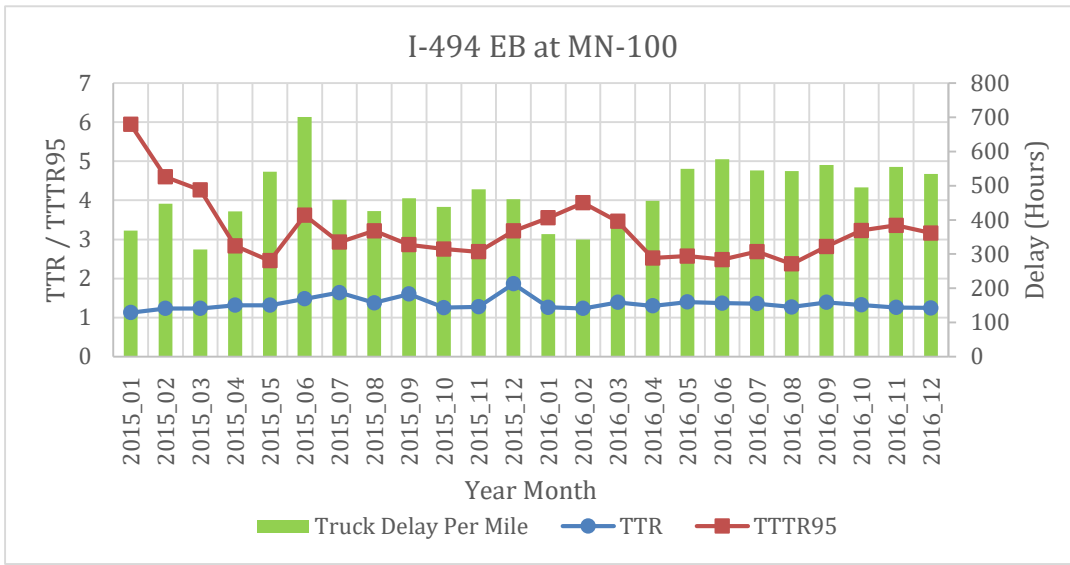


Figure 5.10 Average TTR, TTR95, and Delay per Mile at I-494 EB at MN-100.

Figure 5.11 is a photo from MnDOT RTMC camera at I-494 and MN-100 in Bloomington in the PM peak period on a weekday.



Figure 5.11 Screenshot of MnDOT RTMC Camera at I-494 and MN-100.

5.5 I-694/94 WB WEST OF US-169

The location of I-694 WB west of US-169 interchange in Maple Grove is illustrated in Figure 5.12. The 2016 HCAADT and AADT for I-94 EB traffic at this location (TMC 118P04153) were 10,000 and 118,000, respectively. This location has the highest commercial truck volume as compared to the other sites discussed in this chapter. Commercial trucks make up 8.5% of all vehicles traveling through this location. Recurring traffic congestion occurred in peak hours on a regular basis. Point A (as illustrated in Figure 5.12) is a weaving location for traffic coming from I-494 NB to I-94 toward St. Cloud. Horizontal and vertical curves for traffic leaving I-694 WB to I-494 SB (point D, splitting to I-494 SB and I-94 WB) could affect the traffic flow upstream. Speed limit between point A and C is 65 MPH. In addition, multiple paths of traffic weaving in (from US-169, I-494 NB, and Hemlock Lane) and out (to I-494 SB and Hemlock Lane) generate several potential points of disruption in this area (between A and C as illustrated in Figure 5.12). Traffic congestion queue on I-694/94 WB often grows beyond point C.

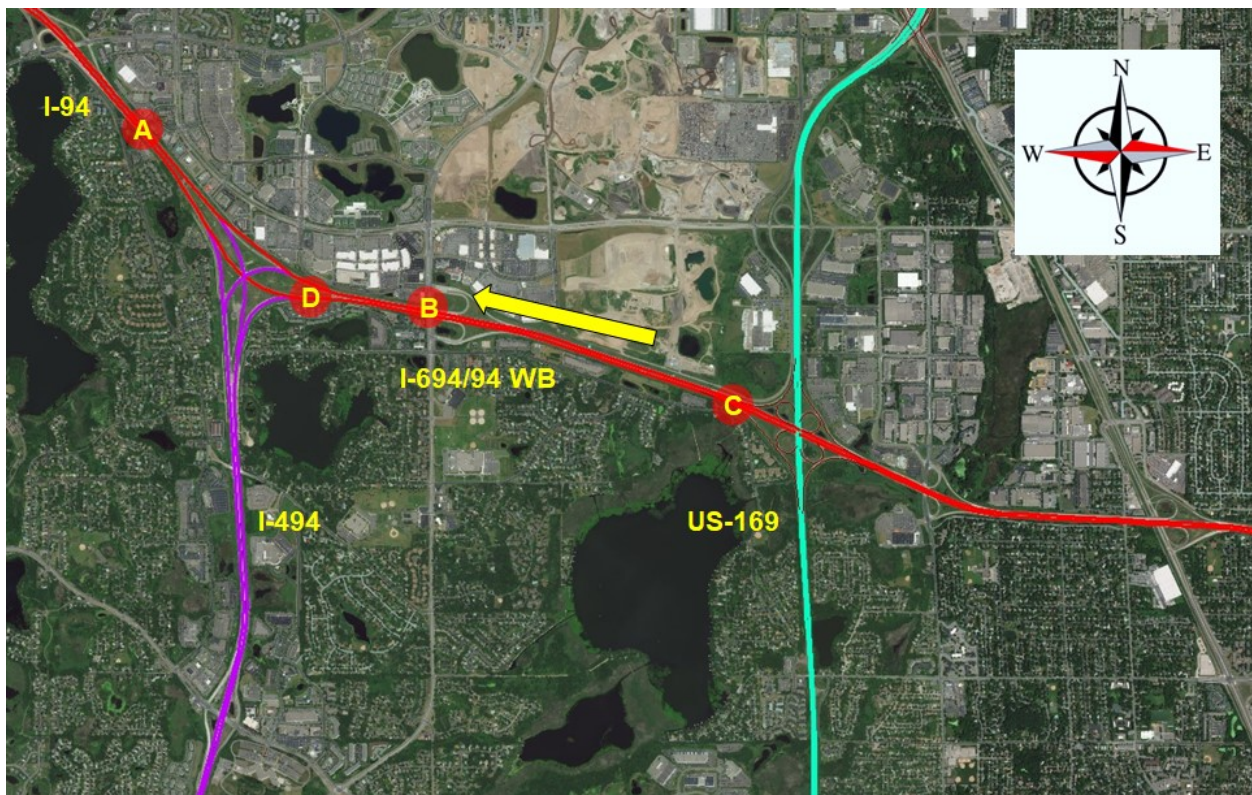


Figure 5.12 Aerial Map of I-694 at US-169 in Maple Grove, MN.

Insufficient capacity and multiple weaving points at this location are the key causes of recurring congestion. The truck mobility (TTR), reliability (TTTR95) and delays are plotted in Figure 5.13. The average TTR at this location is 1.35 with a standard deviation of 0.26. On average, truck travel time on a weekday PM peak period is 35% longer than the travel time of a passenger vehicle.

The average TTTR95 is 4.09 with a standard deviation of 1.44. The truck travel time reliability measures from May to Sep. 2016 were significantly lower (1.8) than the TTTR95 in the other months (see Figure

5.13). The research team found that I-494 was partially closed for rehabilitation between I-394 and the I-94/I-494/I-694 interchange from mid-April 2016 through November 2016. In fact, the I-694 WB to I-494 SB ramp (point D in Figure 5.12) was closed for a period of time. Upstream traffic on I-694/94 WB was affected by the construction during the period. The reliable truck travel time may be caused by the downstream construction from mid Apr. to Nov. 2016.

The column chart in Figure 5.13 displays the daily average truck delay in the PM peak by month at this location. In 2015 & 2016, the average truck delay in the PM peak at this location ranges from 149 to 580 hours on a weekday. Truck congestion increased to almost twice as much the delay before the construction. However, the truck travel time reliability measure (TTTR95) decreased (more reliable) when the traffic became reliably slow during the I-494 rehabilitation period.

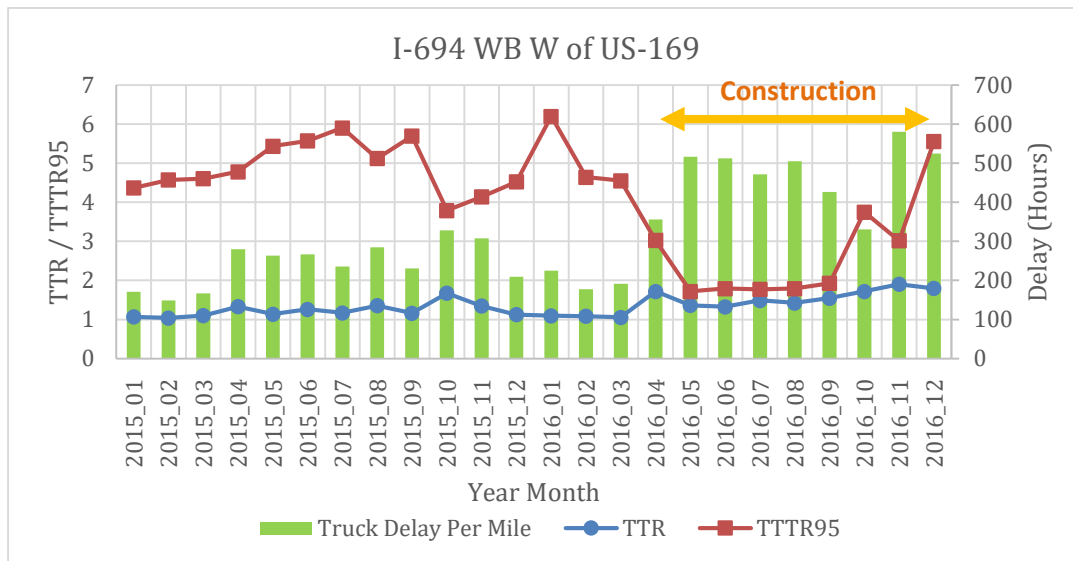


Figure 5.13 Average TTR, TTTR95, and Delay per Mile at I-694 WB W of US-169.

5.6 I-394 EB WEST OF I-94

The location of I-394 EB west of I-94 interchange in Minneapolis is illustrated in Figure 5.14. The 2016 HCAADT and AADT for I-94 EB traffic at this location (TMC 118P04354) were 3,400 and 134,000, respectively. This location has the lowest commercial truck volume as compared to the other locations discussed in this chapter. Commercial trucks make up only 2.5% of all vehicles traveling through this location. Recurring traffic congestion occurred in peak hours on a regular basis. Point A (as illustrated in Figure 5.14) is a merging location for traffic coming from I-394 EB (general & HOV lanes) to I-94 EB toward St. Paul. Horizontal and vertical curves between A and B on a single lane off-ramp really restrict the traffic flow upstream. Speed limit at off-ramp (between point A and B) is 30 MPH. In addition, multiple paths of traffic weaving in (from MN-100 and Penn Ave.) and out (to I-94 WB and Downtown Minneapolis) generate several potential points of disruption in this area (between B and D as illustrated in Figure 5.14). Traffic congestion queue on I-394 EB often grows beyond point D in the PM peak hours.



Figure 5.14 Aerial Map of I-394 and I-94 in Minneapolis, MN.

Insufficient capacity and roadway geometry near this location are the key causes of recurring congestion. The truck mobility (TTR), reliability (TTTR95) and delays are plotted in Figure 5.15. The average TTR at this location is 1.34 with a standard deviation of 0.25. On average, truck travel time during a weekday PM peak period is 34% longer than the travel time of a passenger vehicle. The average TTTR95 is 7.6 with a standard deviation of 2.2. Truck travel time in this area is very unreliable with large variations throughout the 24-month study period. The unreliable truck travel time may be caused by the dynamic nature of congested traffic and driver behaviors. Many impatient drivers like to cut in the single lane off-ramp at the beginning of I-94 EB & WB off-ramp split (location B in Figure 5.14). The column chart in Figure 5.15 displays the daily average truck delay in the PM peak by month at this location. In 2015 & 2016, the average truck delay in the PM peak at this location ranges from 137 to 566 hours on a weekday. Figure 5.16 is a photo from MnDOT RTMC camera at I-394 and Penn Ave in Minneapolis during PM peak period on a weekday.

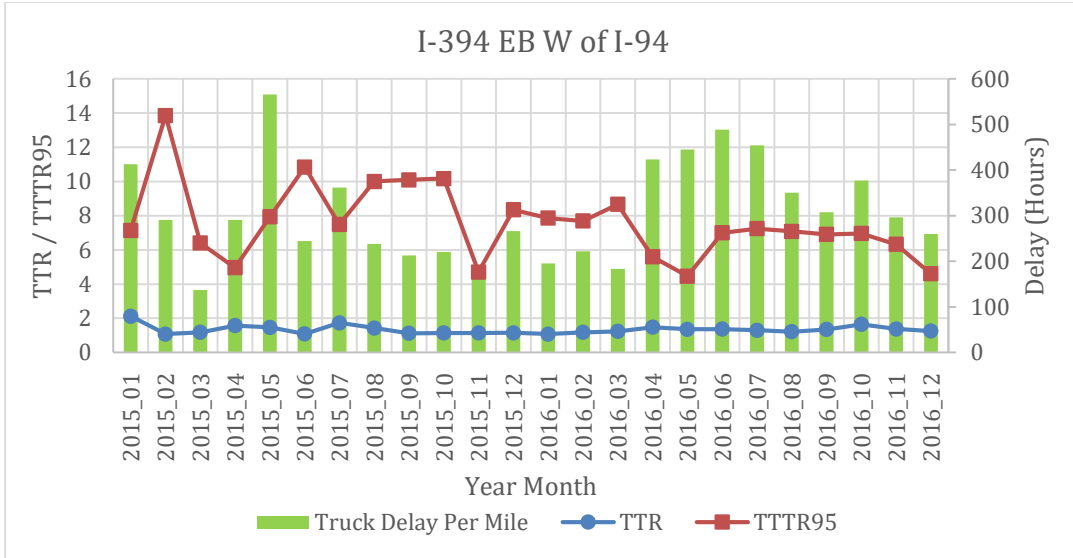


Figure 5.15 Average TTR, TTTR95, and Delay per Mile at I-394 EB W of I-94.



Figure 5.16 Screenshot of MnDOT RTMC Camera at I-394 and Penn Ave.

CHAPTER 6: SUMMARY AND DISCUSSION

Freight transportation provides a significant contribution to our nation's economy. A reliable and accessible freight network enables business in Twin Cities to be competitive in the Upper Midwest region. Many urban roadways are facing challenges with traffic volumes being over capacity during peak periods. As a result, time and money are lost due to traffic congestion. Operational and design constraints such as interchange, steep grade, signalized intersection, work zone, merging, lane drop and others, could contribute additional delays for commercial vehicles.

The research team worked with MnDOT staff and TAP members to prioritize a list of key truck corridors in the Twin Cities Metro Area (TCMA). Monthly NPMRDS data were processed to measure travel time reliability and estimate truck delay at the corridor level and then to identify system impediments during peak hours. Performance measures, including truck mobility ratio, travel time reliability, and delay, were defined and computed using the National Performance Management Research Data Set (NPMRDS).

The research team processed 24 months of NPMRDS data to generate truck performance measures on key freight corridors in the TCMA. Truck mobility analysis was conducted (Chapter 4.1) by comparing the truck travel time with the passenger vehicle travel in the same TMC segment. In addition, 3 reliability measures (RI95, TTTR80, and TTTR95) were analyzed to evaluate the truck travel time reliability at the corridor level (Chapter 4.2). Furthermore, truck delay was computed by using truck volume data and truck bottleneck was identified by using the processed performance measures (Chapter 4.3).

6.1 PERFORMANCE MEASURES AT THE CORRIDOR LEVEL

Figure 6.1 displays the signalized intersections on key freight corridors in the TCMA. On average, roadways with signalized or un-signalized intersections have a higher percentage of truck-to-car travel time ratio (TTR). On average, trucks travel an average of 10% more slowly than cars on freeways. As listed in Table 4.1, trucks on US and interstate highways have about a 10% longer travel time than cars. On state highways, the TTR reaches 1.2 and 1.4 in the AM and PM peak periods, respectively. Trucks travel significantly slower than cars on county roads. The TTR on county roads is around 1.5 during mid-day and spikes to 1.7 and 1.9 in the AM and PM peak periods, respectively. The increase of TTR on county roads may largely be due to the number of intersections in a TMC segment and delays at signalized intersections.

For example, the average truck travel time on 34% of county road 30 is over 50% longer than the average passenger vehicle travel time in the PM peak. In the PM peak hours, the average truck travel time on 6.8% of the I-94 roadway in the TCMA is over 50% longer than the average passenger vehicle travel time. Similarly, the average truck travel time on 6.6% of I-394 roadway is over 50% longer than the average passenger vehicle travel time.

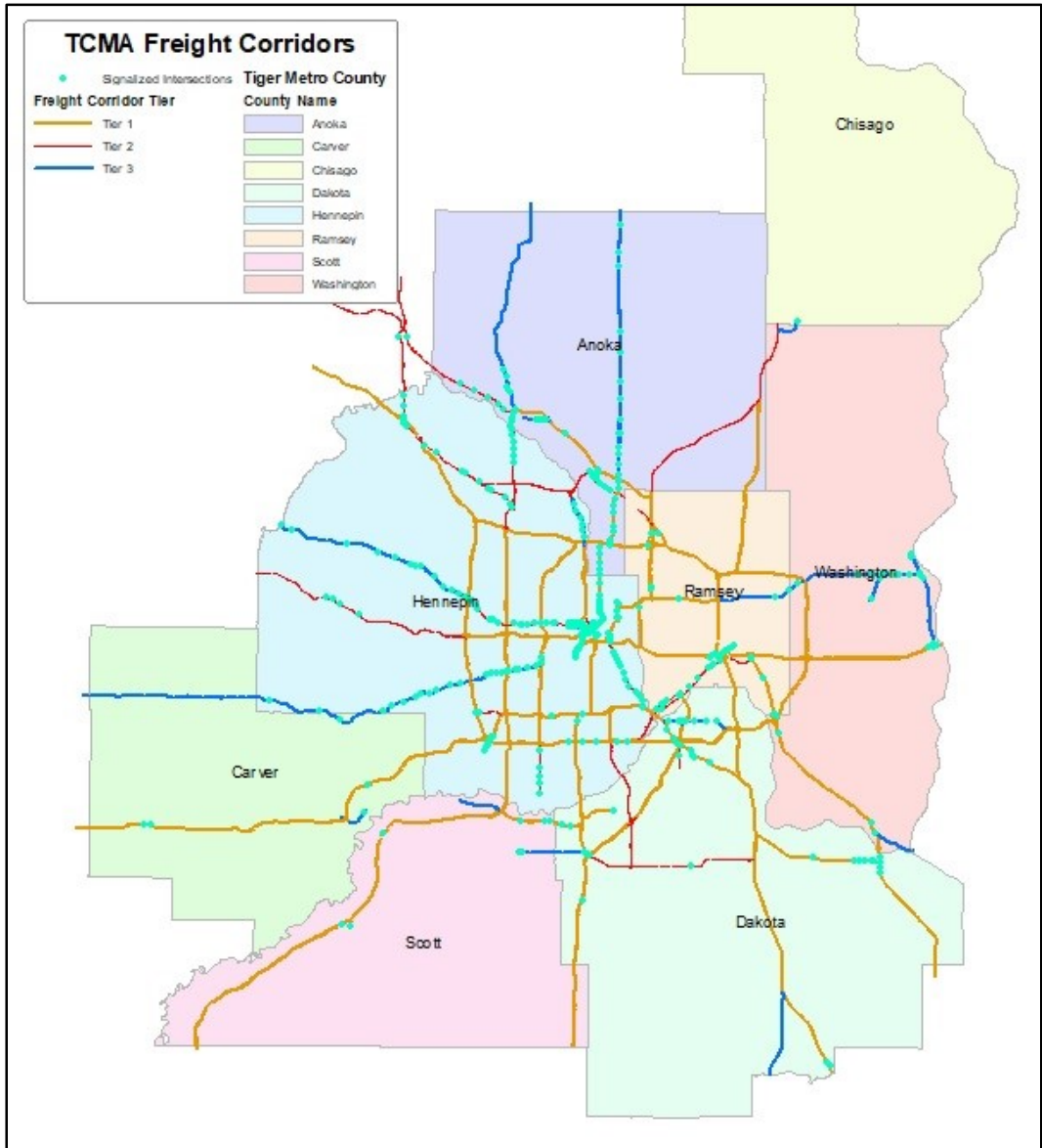


Figure 6.1 Signalized Intersections on Key Freight Corridors in the TCMA.

Three reliability measures (RI95, TTTR80, and TTTR95) were processed and analyzed to evaluate the truck travel time reliability. All measures indicate that the truck travel time in the PM peak period is less reliable than the travel time in the AM peak period. Similar to the TTR measure, roadways with signalized or un-signalized intersections are generally less reliable than freeways. At the corridor level, the TTTR95 measure is much higher than the RI95 measure. The variability of TTTR95 is also higher than the RI95 measure. This is mostly caused by the long-tail distribution of truck travel time from the NPMRDS data.

For example, the 95th percentile truck travel time on 80% of CR-42 is over twice as long as the average truck travel time in the PM peak. In the PM peak hours, the 95th percentile truck travel time on 75.5% of MN-65 roadway in the TCMA is over twice as long as the average truck travel time. Similarly, the 95th

percentile truck travel time on 52.7% of I-394 roadway is over twice as long as the average truck vehicle travel time.

Table 6.1 lists the top-5 corridors with significant truck delays in the studied area. I-35W, I-94, US-169, I-494, and MN-55 have an average total truck delay over 3,000 hours in the AM peak period. And I-94, I-35W, I-494, US-169, I-694, and MN-55 have an average total truck delay of over 3,000 hours in the PM peak period. Overall, the truck delay in the PM peak is more significant than the delay in the AM peak.

Table 6.1 Top 5 Truck Delay at the Corridor Level

AM Peak		PM Peak	
Corridor	Delay (hours)	Corridor	Delay (hours)
I-35W	5,464	I-94	7,519
I-94	4,659	I-35W	6,804
US-169	4,532	I-494	6,741
I-494	3,719	US-169	6,117
MN-55	3,589	I-694	3,693

In the AM Peak, interchanges at I-694 & US-169, I-394 & US-169, I-35W & I-494, I-394 & I-94, I-35E & I-94, I-35E & I-694, and US-52 & I-94 were congested. In addition, roadway segments at I-35W NB between MN-13 and CR-42 had an average truck delay of over 300 hours per mile.

In the PM peak, the major truck congestions occurred at the I-394 & US-169, I-494 & MN-100, I-35W & I-494, I-394 & I-94, I-35W & I-94, I-35W & I-694, I-35E & I-694, I-94 & I-35E, and US-52 & I-94 interchanges. In addition, segments at I-94 WB between US-169 and I-494, I-394 EB between MN-100 & I-94, I-35W NB S of Downtown Minneapolis, I-35W SB N of I-94, I-94 WB between MN-280 and I-394, I-35W NB between MN-36 and I-694, I-94 EB W of Downtown St. Paul, and I-494 EB between US-169 and I-35W, had significant truck delay in the PM peak hours.

A list of TMC segments (non-interchange locations) with recurring truck congestion in the PM peak hours are listed in Table 4.3. Among those 6 locations, TMC 118P04198 and TMC 118P04199 segments (I-94 WB at I-35W in Minneapolis) have the highest truck delay per mile in the PM peak on an average weekday. Average truck delay in the PM peak in this segment is 570 hours per mile, or 775 hours in total. TMC 118P04237 (I-35W NB south of Downtown Minneapolis) has the second highest truck delay in the PM peak on an average weekday. Average truck delay in the PM peak in this segment is 523 hours per mile. TMC 118N04188 (I-94 EB west of Downtown St. Paul) has the third highest truck delay in the PM peak on a regular weekday. Average truck delay in the PM peak in this segment is 495 hours per mile, or 366 hours in total. Insufficient capacity, increasing demand, roadway geometry, and density of weaving points are the key causes of traffic congestion among the 6 truck bottlenecks.

Our list of truck congestion locations is based on the computed truck delays. Our delay-based approach is different from the bottleneck ranking methodology used by the American Transportation Research Institute (ATRI). The recent top-100 truck bottlenecks report [26], published by ATRI in January 2018,

listed 5 truck bottlenecks in the TCMA (Table 6.2). The ATRI's truck bottlenecks are ranked by congestion values based on calculation of truck speed below free flow speed and volume [27].

Table 6.2 ATRI's Top Truck Bottlenecks in TCMA

ATRI's Top Truck Bottlenecks in MN [26]			
Congestion Ranking (2017)	Location Description	Average Speed (MPH)	Peak Average Speed (MPH)
42	I-94 at US 52	42.9	35.2
55	I-35W at I-494	47.2	38.2
56	I-35W at I-94	38.4	28.8
61	I-35E at I-94	43.5	35.7
88	I-35W at I-694	48.0	39.0

6.2 FUTURE RESEARCH

The NCHRP report 08-98 [28, 29], published in 2017, provides guidelines for identifying, classifying, evaluating, and mitigating truck bottlenecks. Figure 6.2 illustrates a block diagram of truck bottleneck analysis. This project focused on the data analysis to identify truck bottlenecks as described in block #1 to #3 in Figure 6.2. A follow-up project (focusing on block #4 to #6 in Figure 6.2) will leverage our current effort to investigate potential causes of truck bottlenecks and develop mitigation strategies on major truck highway corridors in the TCMA. Results from this project will be used to, (1) develop a systematic reporting tool to rank truck bottlenecks on freeways, (2) investigate the potential causes of the congestion, and (3) develop mitigation strategies.

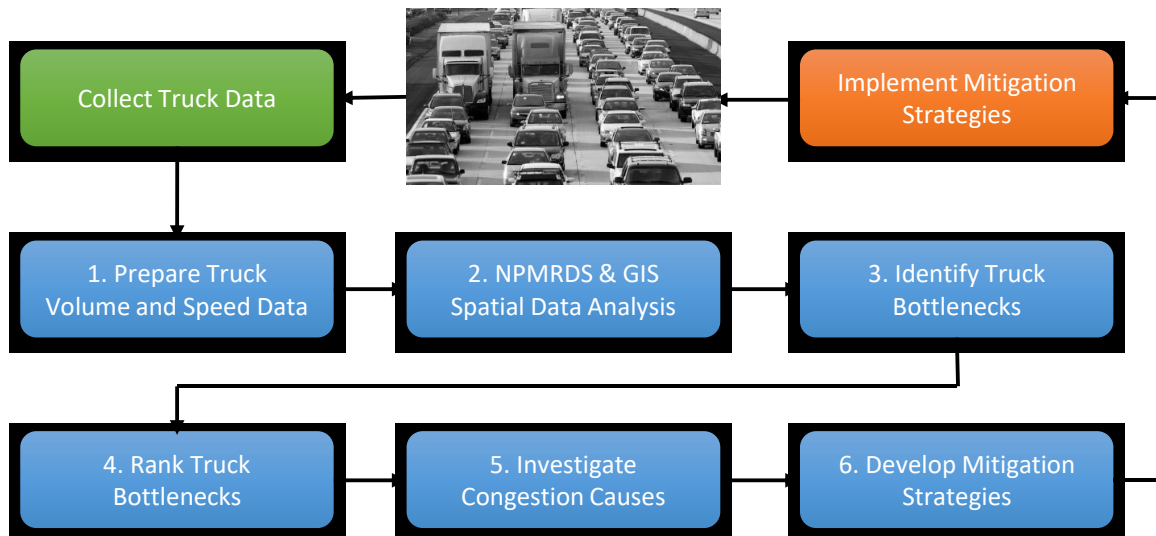


Figure 6.2 Flowchart of Truck Bottleneck Analysis.

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APPENDIX A

COMPARISON OF RELIABILITY MEASURES

A.1 Comparison of Reliability at TMC Level

Comparison of RI95, TTTR80 and TTTR95 at TMC level is presented here. Figure A.1 and A.2 display the monthly reliability measures of a TMC segment on MN-55 WB east of I-494 (in Plymouth, MN) during AM and PM peak hours. This 0.8 mile TMC segment contains signalized intersections.

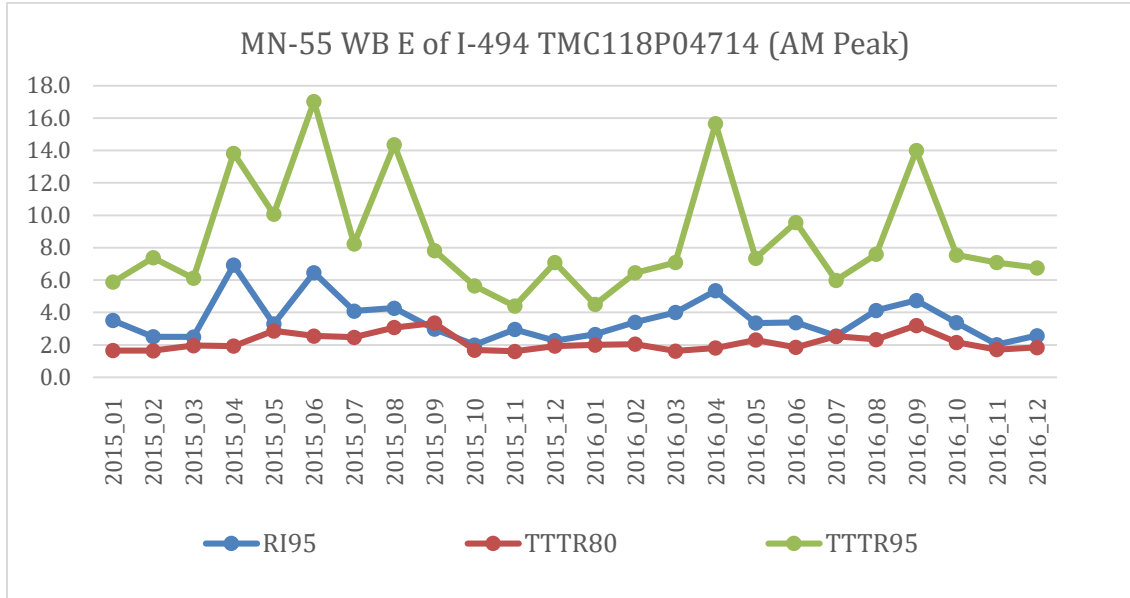


Figure A.1 Monthly Reliability Measures at TMC 118P04714 in the AM Peak

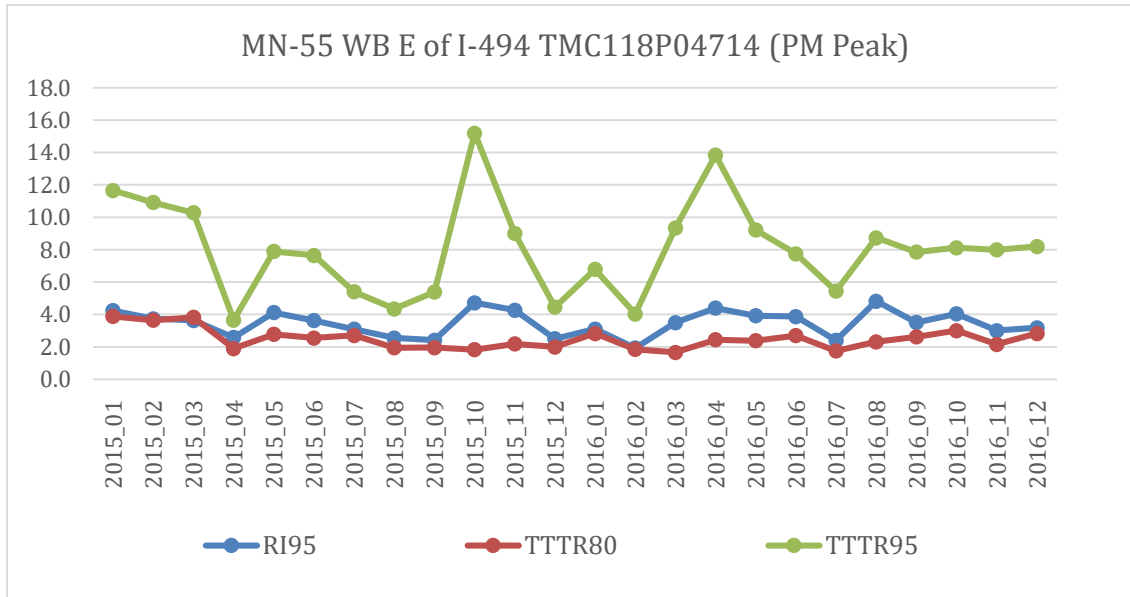


Figure A.2 Monthly Reliability Measures at TMC 118P04714 in the PM Peak

Figure A.3 and A.4 display the monthly reliability measures of a highway TMC segment on I-35 NB south of County Road 97 (Forest Lake, MN) during AM and PM peak hours. The variation of reliability measures on highway TMC is small than roadway segment with intersections.

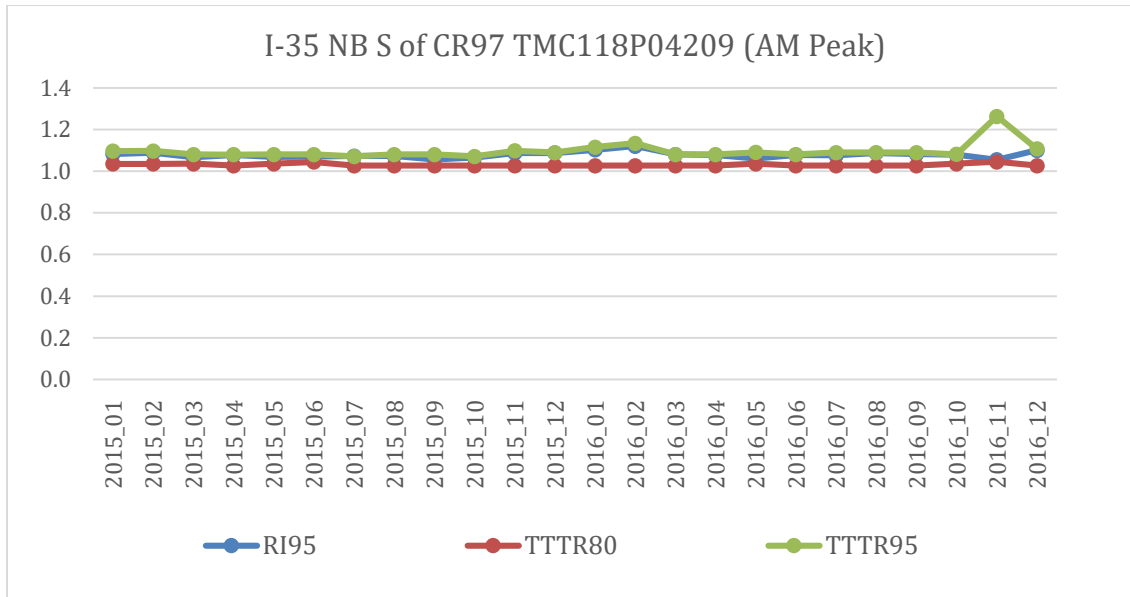


Figure A.3 Monthly Reliability Measures at TMC 118P04209 in the AM Peak

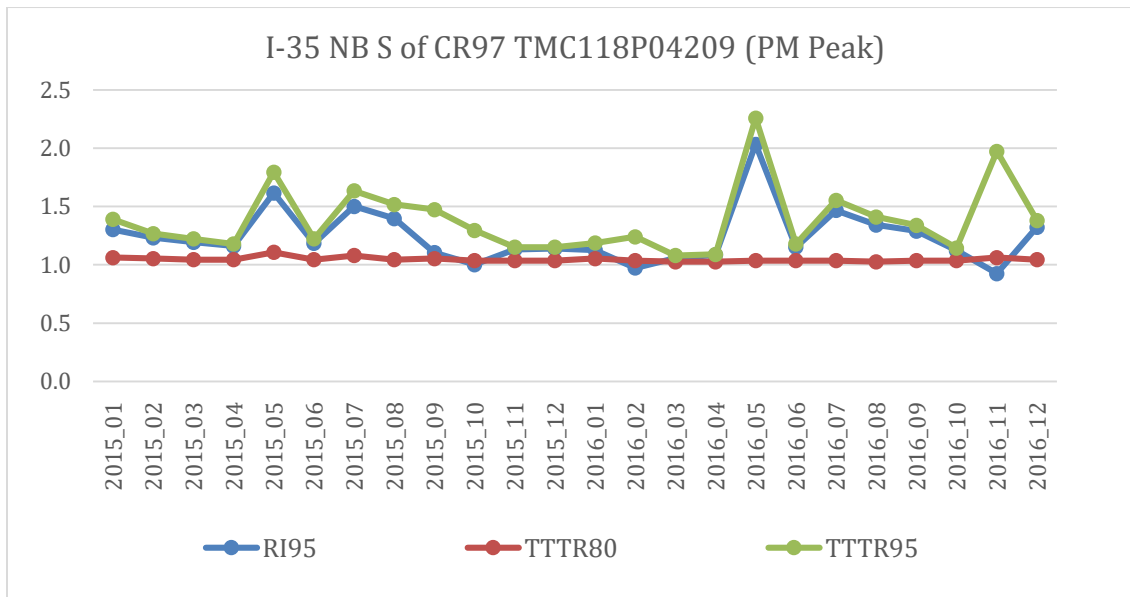


Figure A.4 Monthly Reliability Measures at TMC 118P04209 in the PM Peak

A.2 Comparison of Reliability at the Corridor Level

Comparison of RI95, TTTR80 and TTTR95 at the corridor level is presented here. Figure A.5 and A.6 display the monthly reliability measures of MN-7 in EB direction during AM and PM peak hours. Overall, the TTTR95 has higher variability than the other 2 measures.

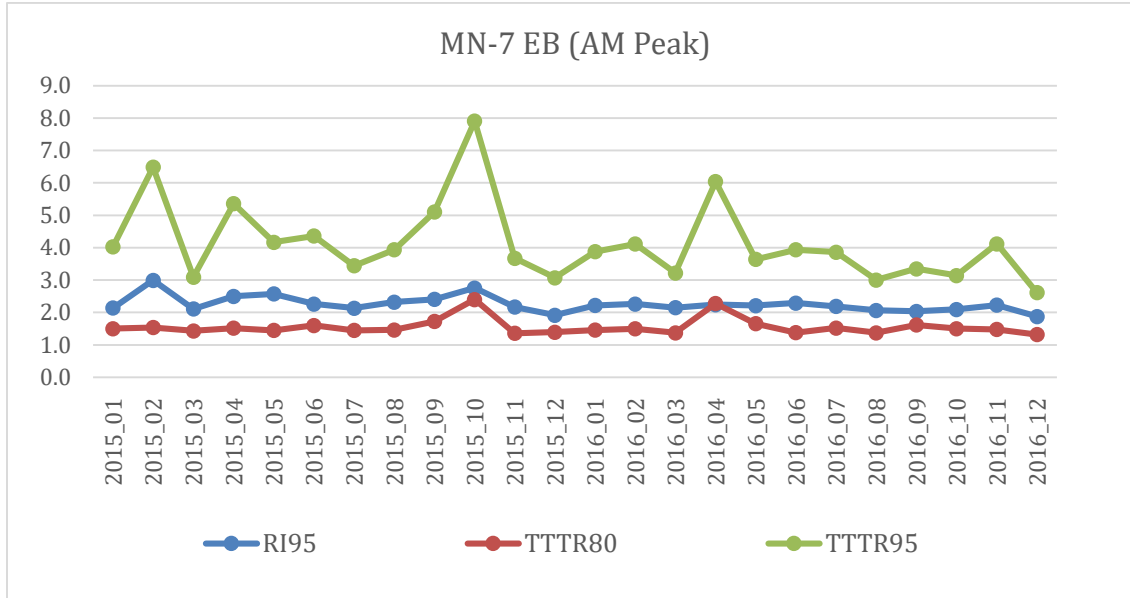


Figure A.5 Monthly Reliability Measures of MN-7 EB in the AM Peak

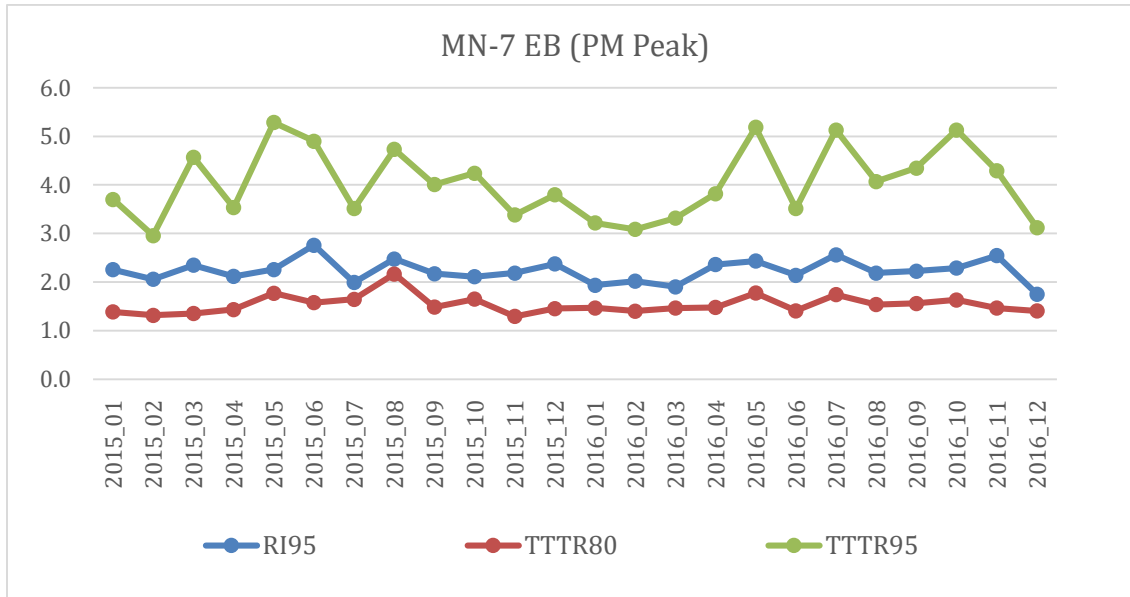


Figure A.6 Monthly Reliability Measures of MN-7 EB in the PM Peak

Figure A.7 and A.8 display the monthly reliability measures of I-94 in EB direction during AM and PM peak hours. In general, the variation of reliability measures on highways is smaller than that on arterial corridors.

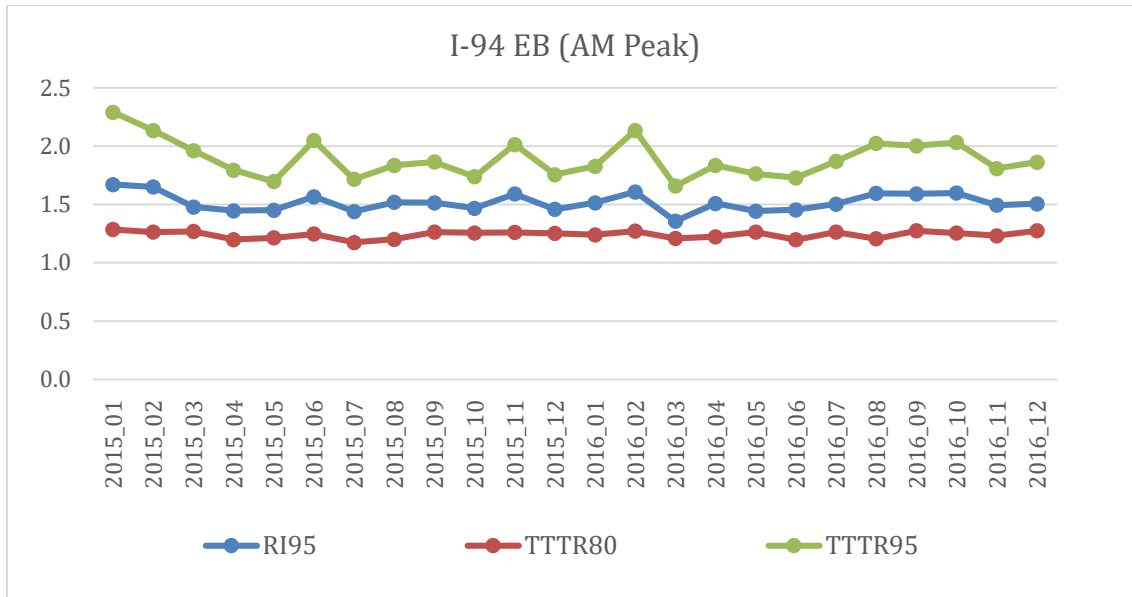


Figure A.7 Monthly Reliability Measures of I-94 EB in the AM Peak

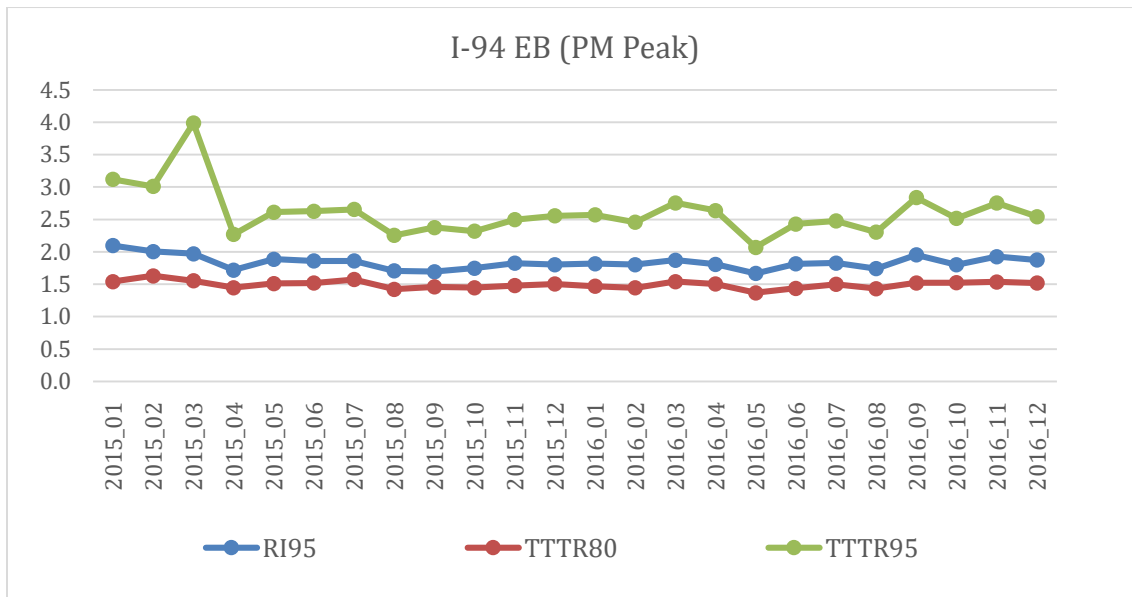


Figure A.8 Monthly Reliability Measures of I-94 EB in the PM Peak

APPENDIX B

HOURLY TRUCK VOLUME DISTRIBUTION

A comparison of hourly truck volume distribution from probe vehicle and Weigh-In-Motion (WIM) counts is displayed in Figure B.1. The probe truck volume distributions (both red and green curves) on weekdays follow closely with the actual hourly truck volume distribution derived from the WIM data.

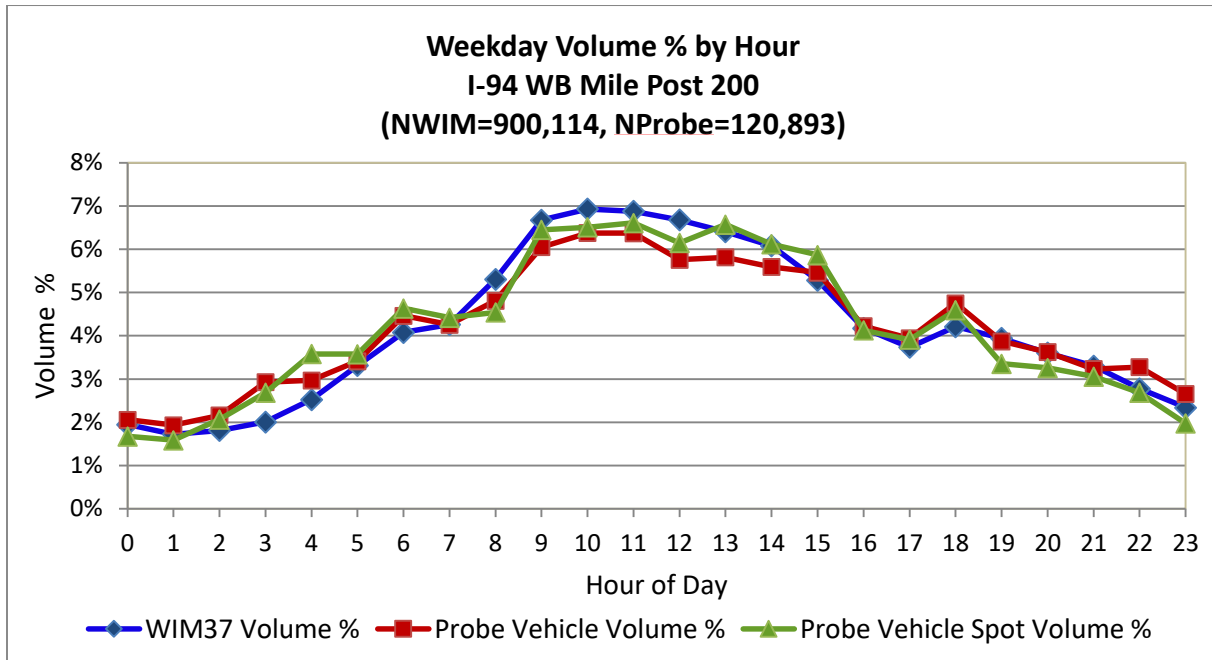


Figure B.1 Hourly Truck Volume Distribution of a TMC segment

The network-wide hourly volume distribution is displayed in Figure B.2. The blue curve represents the truck volume distribution on weekdays and the red curve represents the distribution on weekends.

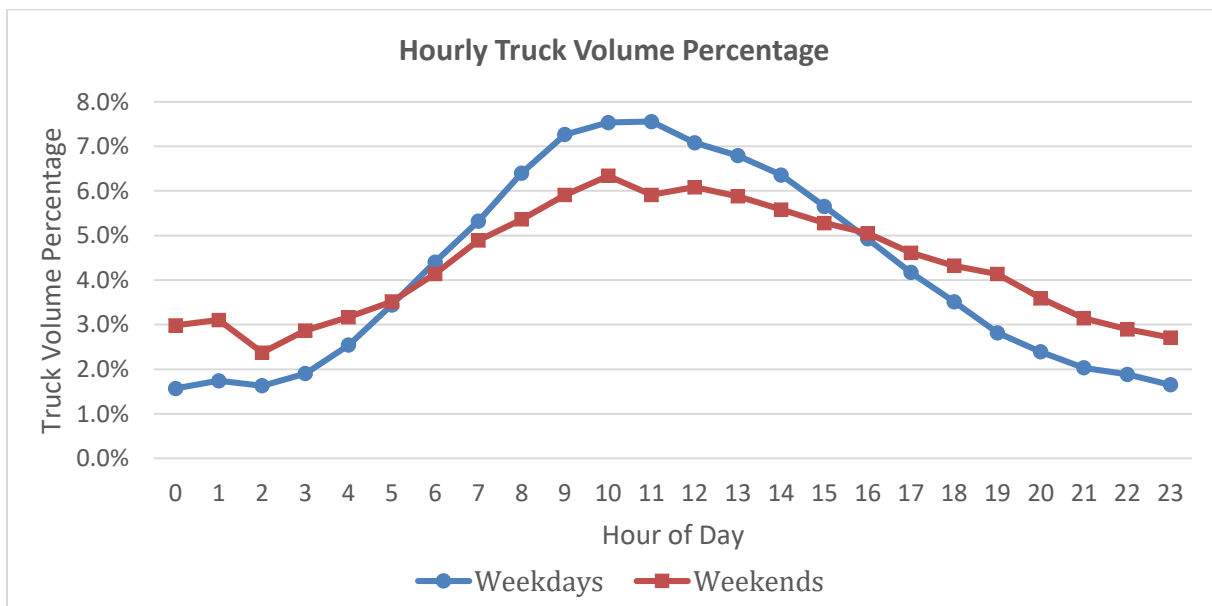


Figure B.2 Network-Wide Hourly Truck Volume Distribution