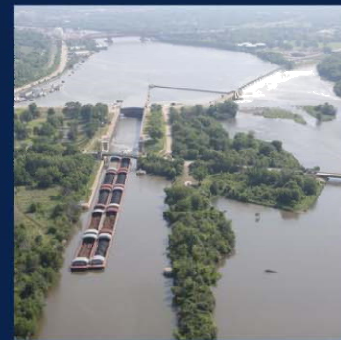
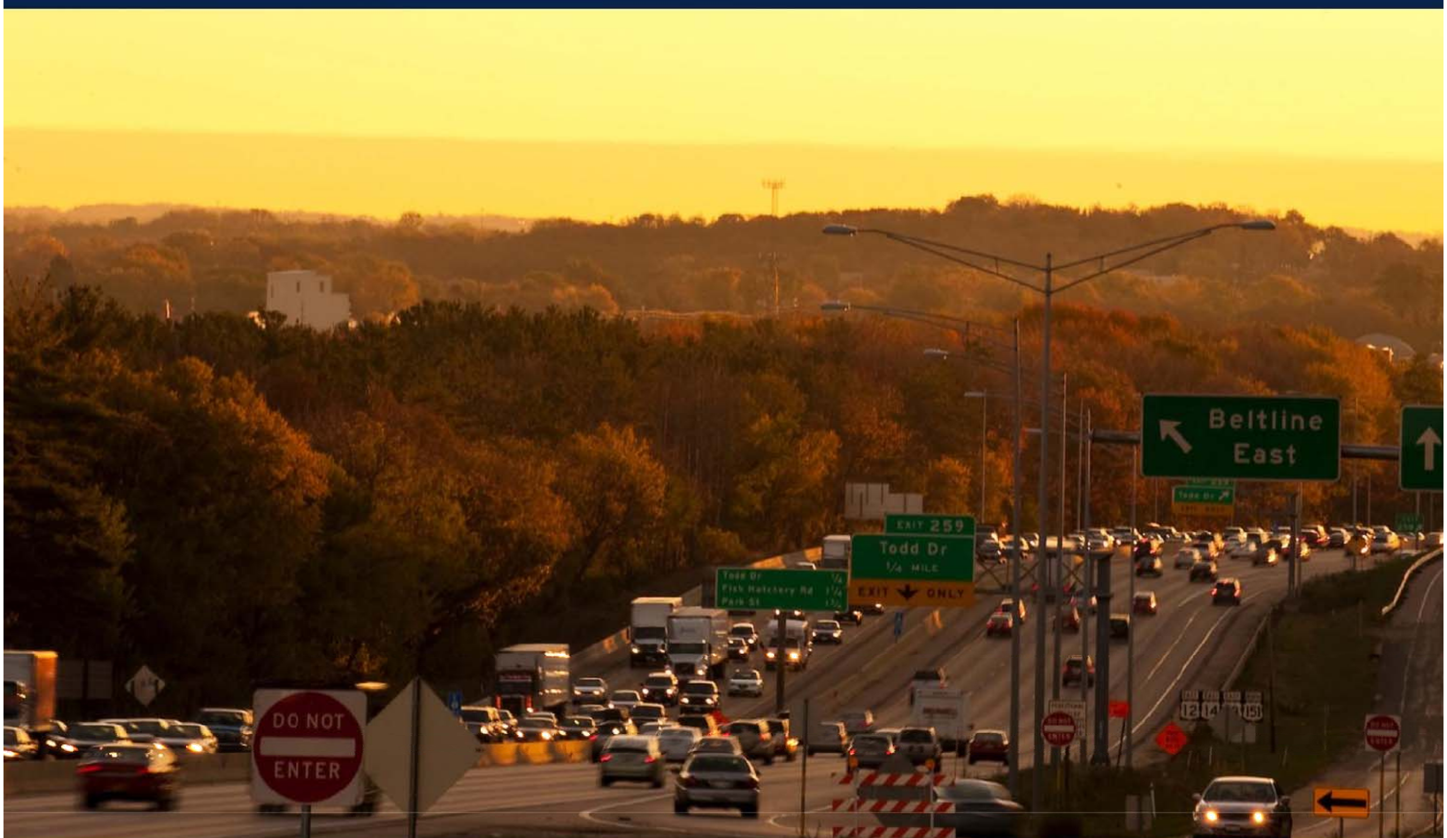




Assessment of Multimodal (Marine and Highway) Bottlenecks in the MAASTO Region 2018-2019

MID-AMERICA
FREIGHT COALITION

Authors

Youngjun Han
University of Wisconsin–Madison

Ernest Perry
Co-Principal Investigator
University of Wisconsin–Madison

Glenn Vohres
University of Wisconsin–Madison

Wissam Kontar
University of Wisconsin–Madison

Soyoung Ahn
Co-Principal Investigator
University of Wisconsin–Madison

About the Mid-America Freight Coalition (MAFC)

The industries and farms of the Mid-America region can compete in the marketplace only if their products can move reliably, safely and at reasonable cost to market.

State Departments of Transportation play an important role in providing the infrastructure that facilitates movement of the growing amount of freight. The Mid-America Freight Coalition was created to support the ten states of the Mid America Association of Transportation Officials (MAASTO) region in their freight planning, freight research needs and in support of multi-state collaboration across the region.

www.midamericafreight.org

TECHNICAL REPORT DOCUMENTATION

<table>
<tr><td>1. Report No. MAFC 19</td><td>2. Government Accession No.</td><td colspan="2">3. Recipient’s Catalog No. CFDA 20.701</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
Assessment of Multimodal (Marine and Highway) Bottlenecks in the MAASTO Region 2018-2019</td><td colspan="2">5. Report Date January 2019</td></tr>
<tr><td colspan="2">6. Performing Organization Code</td></tr>
<tr><td colspan="2">7. Author/s
Youngjun Han, Ernest Perry, Glenn Vohres, Wissam Kontar, and Soyoung Ahn.</td><td colspan="2">8. Performing Organization Report No.
MAFC 19</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
Mid-America Freight Coalition and the MAASTO Working Group
University of Wisconsin–Madison
1415 Engineering Drive, 2205 EH
Madison, WI 53706</td><td colspan="2">10. Work Unit No. (TRAIS)</td></tr>
<tr><td colspan="2">11. Contract or Grant No.
TPF-5(293) PO# 39500 – 0000011028</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Organization Name and Address
Wisconsin Department of Transportation
Division of Transportation Investment Management
PO Box 7913
Madison, WI 53707</td><td colspan="2">13. Type of Report and Period Covered
Final Report 06/01/2018 – 01/31/2019</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code
TPF-5(293) PO# 39500 – 0000011028</td></tr>
<tr><td colspan="4">15. Supplementary Notes</td></tr>
<tr><td colspan="4">This research investigates major freight bottlenecks in the MAASTO region’s multistate and multimodal freight network including both roadways and marine highways. 14 areas near large cities in the MAASTO region are identified as potential regions where freight bottlenecks are located. By constructing a time-space diagram of Travel Time Index for corridors, locations and activation times of freight bottlenecks are identified. Through location research using GIS and satellite images, possible reasons of bottlenecks are also investigated. Delay analyses for multistate corridors are conducted to prioritize the corridors to be improved. For marine corridors, in order to characterize the bottlenecks, the average delay in each lock and dam is considered and bottlenecks are characterized for certain locations.</td></tr>
<tr><td>17. Key Words
freight bottlenecks, MAASTO, multimodal, marine highway, TTI, GIS, delay analysis</td><td colspan="3">18. Distribution Statement
No restrictions. This report is available to the public through the National Transportation Library Digital Repository.</td></tr>
<tr><td>19. Security Classification (of this report)
Unclassified</td><td>20. Security Classification (of this page)
Unclassified</td><td>21. No. of Pages
84</td><td>22. Price
-0-</td></tr>
</table>

Form DOT F 1700.7 (8-72) Reproduction of form and completed page is authorized.

DISCLAIMER

CONTENTS

TABLE OF FIGURES

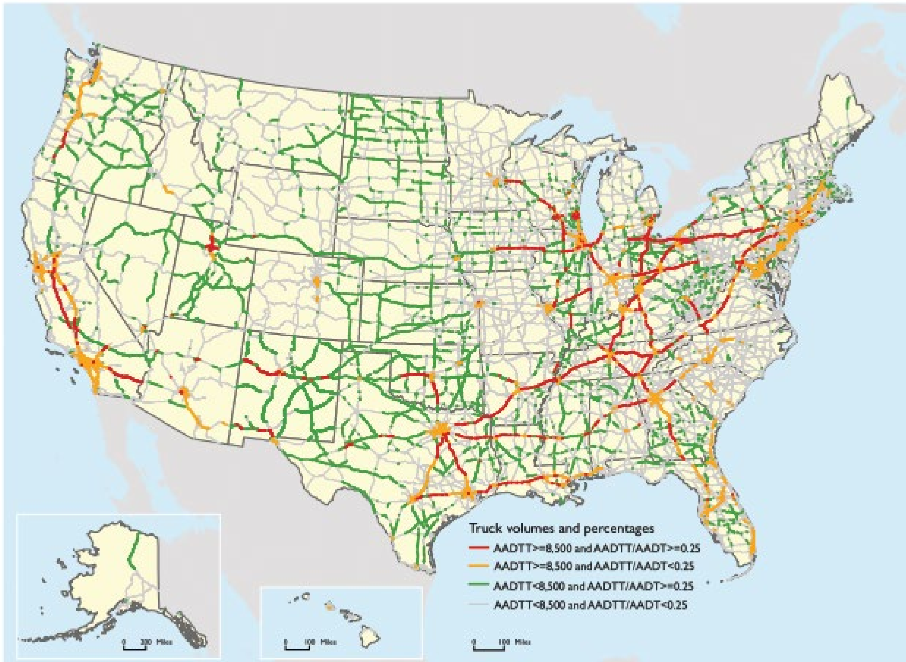
TABLE OF TABLES

1. INTRODUCTION

1.1. Background

Freight transportation has a significant impact on the economy both regionally and nationally, and it is continuously increasing in terms of freight volume and value. The freight transportation system consists of an extensive network of highways, railroads, and waterways, and various strategies have been developed to achieve more reliable and efficient freight traffic operations. However, increasing freight volume is stressing the freight transportation system as demand approaches network capacity. Highway bottlenecks, especially, tend to be a reoccurring problem for trucks. Highway bottlenecks cause significant delay, lost revenue for drivers, and overall economic inefficiencies. In 2016, there were approximately 1.2 billion hours of truck delay on the National Highway System (NHS) due to congestion, causing $74.5 billion in additional operational costs to the trucking industry *(1)*. Other freight modes, such as waterways, also suffer traffic delays near bottlenecks, due to both operational (e.g., high demand) and external (e.g., weather conditions) causes. Thus, the issue of freight bottlenecks on major freight networks is one of the most significant challenges facing the freight transportation system today and the near future.

The MAASTO (Mid America Association of State Transportation Officials) region, which consists of ten states in the Midwestern United States (Illinois, Indiana, Iowa, Kansas, Kentucky, Michigan, Minnesota, Missouri, Ohio, and Wisconsin) encompasses some of the nation's most important freight networks. Figure 1-1 shows the major truck routes on the NHS, for example, and a high volume of Average Annual Daily Truck Traffic (AADTT) is observed in the MAASTO region. Thus, investigating freight bottlenecks in the MAASTO region is important at the national level as well as for the regional freight transportation system.



NOTES: The Freight Analysis Framework (FAF) is based in large part on results from the Commodity Flow Survey (CFS), last administered in 2012. Average annual daily truck traffic (AADTT) includes all freight-hauling and other trucks with six or more tires and includes all motor vehicles.

SOURCE: U.S. Department of Transportation, Bureau of Transportation Statistics and Federal Highway Administration, Freight Analysis Framework, Version 4.3.1, 2016.

Figure 1-1. Major Truck Routes on the National Highway System in 2012 (Adopted from *Freight Facts and Figures (2)*).

1.2. Research Objectives and Scope

This research aims to identify and characterize freight bottlenecks in the MAASTO region's multistate and multimodal freight network, including both highway and marine highway systems. The research scope focuses on National Highway Freight Network (NHFN) as a major freight network, and thus, bottlenecks on local roads are not investigated in detail. This research takes a data-driven approach using time-series data to identify specific times and locations of freight bottlenecks. Detailed location research is also conducted through GIS and satellite imagery to identify the potential causes of bottlenecks.

1.3. Report Organization

This report is organized as follows:

- Section 2 presents a literature review of freight bottlenecks and their impacts. Previous works that have identified and characterized bottlenecks and recent guidelines from the Federal Highway Administration (FHWA) are also reviewed.
- Section 3 shows the methods and results for highway freight bottleneck identification in the MAASTO region. Detailed results for freight bottlenecks are provided with maps.
- Section 4 provides freight bottlenecks at the multistate-corridor level. A delay analysis considering truck volume is conducted to prioritize the corridors in terms of freight delay. Two examples of how to avoid bottlenecks in the time and space domains are also presented.

- Section 5 shows the methods to identify freight bottlenecks and results of applying those methods on marine highways.
- Section 6 shows the possible solutions for mitigating freight bottlenecks based on the current planning strategies developed by state departments of transportation (DOTs).
- Section 7 provides conclusions based on this research.

2. LITERATURE REVIEW

2.1. Characteristics of Freight Bottlenecks

2.1.1 Truck Freight Bottlenecks

The National Performance Management Measures rules define a truck freight bottleneck as “a segment of roadway that cause a significant impact on freight mobility and reliability” (23 CFR Part 490.101). Truck freight bottlenecks are typically caused by congestion, which can be divided into recurrent and non-recurrent congestion.

Firstly, recurrent congestion occurs when traffic demand exceeds a road’s capacity. Most recurrent congestion occurs in sections with certain traffic operation, traffic control, or physical roadway characteristics such as:

- Freeway on and off ramps
- Weaving areas
- Lane drops
- Traffic control devices (e.g. traffic signals)
- Steep grades
- Sharp curves

Research by FHWA presents that the bottlenecks from recurrent congestion are responsible for approximately 40% of congestion events *(3)*. One notable feature of recurrent congestion is consistency in time and location. Thus, many traffic control methods, such as ramp metering, have been developed and applied to mitigate “expected” traffic congestion.

On the other hand, non-recurrent congestion occurs with unexpected traffic events or other factors such as:

- Traffic incidents
- Work zones
- Special events
- Severe weather

The FHWA research shows that non-recurrent congestion makes up approximately 55% of the sources of congestion events, with the various types of events accounting for: traffic incidents (25%), work zones (10%), special events (5%), and severe weather (15%) *(3)*. Since most non-recurrent congestion is un-expected, a fast detection system together with an active provision for real-time traffic information would be effective methods to manage non-recurrent bottlenecks.

2.2.2 Marine Highway Freight Bottlenecks

Marine freight transportation is characterized by the transport of cargo by vessels traversing the marine highways. The Maritime Administration recognizes marine highways as an extension of the surface transportation modes, which can aid in mitigating congestion *(4)*. Currently, marine highway transport carries only 4% of total freight tonnages in the United States *(2)*. Yet, marine highway transportation still suffers from bottlenecks, especially at locks and dams.

Previous research on marine freight bottlenecks identified different factors contributing to congestion-associated delay and non-congestion delay at locks and dams *(5, 6)*.

Congestion-associated delay can be characterized by:

- Seasonal surges in traffic
- Towing events
- Loading\unloading of barges
- Processing of recreational\non-commercial vessels
- Insufficient chamber lengths at locks

Non-congestion delay can be characterized by:

- Operational limitations of locks
- Weather conditions
- Mechanical repairs of locks

Typically, processing of freight vessels at locks and dams takes no more than 30 minutes, but the Lock Performance and Monitoring System (LPMS) shows significant delays experienced at marine highways with some exceeding eight hours at a single lock or dam. Studies have shown that an increase in delayed vessels results in an increase in cost for barges and thus, economic loss *(7)*.

2.2. Previous Studies to Identify Freight Bottlenecks

2.2.1 Truck Freight Bottlenecks

The National Center for Freight and Infrastructure Research and Education (CFIRE) identified major freight bottlenecks in the Mississippi Valley Region, which includes the 10 states of the MAASTO region *(6)*. For highway freight bottleneck identification, CFIRE used data from a Highway Performance Monitoring System (HPMS) for the roadways of the National Highway Planning Network (NHPN). They used *truck unit delay* as a bottleneck indicator based on empirical models *(8)*, which require annual average daily traffic (AADT), capacity, signal density, and signal progression type of a given section as input factors. The results indicate that *interchanges* make up the highest proportion of the freight bottlenecks, followed by *lane drops* and *signalized intersections*. Figure 2-1 shows the bottlenecks by interchange in that research. The research also found that the bottlenecks are usually located within the beltways and central corridors of major metropolitan areas.

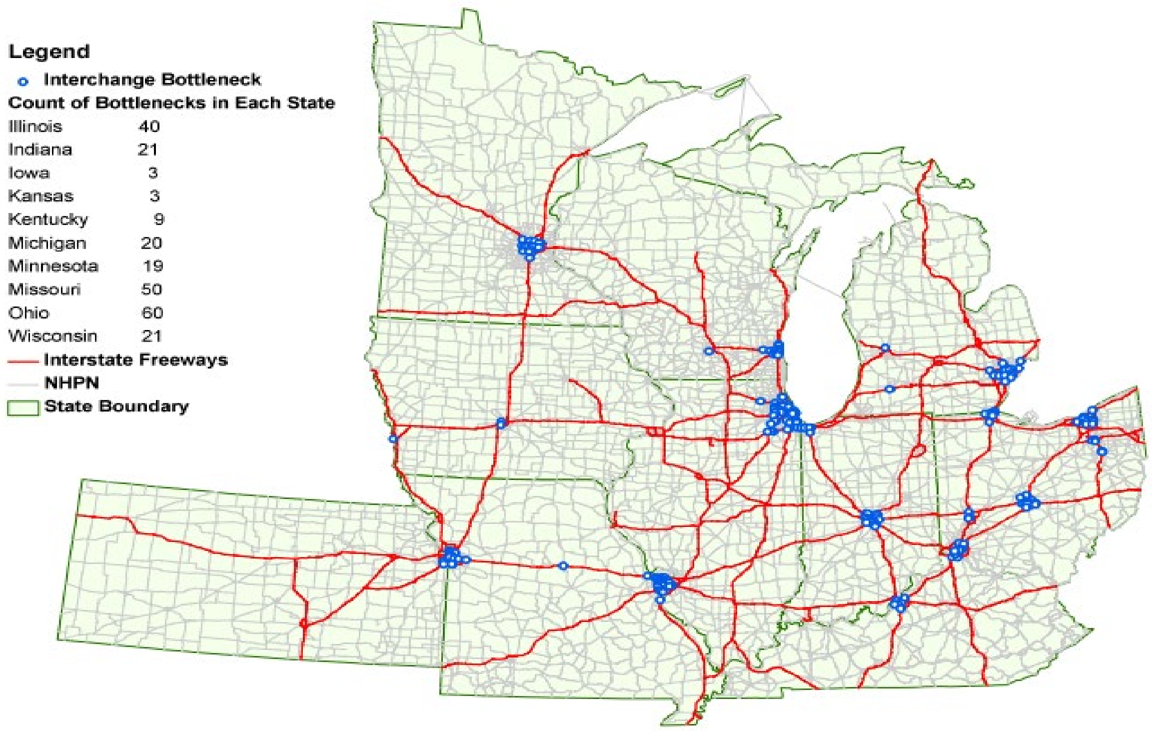


Figure 2-1. Interchange Bottlenecks *(6)*.

Recently, Minnesota DOT (MnDOT) conducted research to estimate truck delays and identify freight bottlenecks *(9)*. Using a National Performance Management Research Data Set (NPMRDS), MnDOT investigated truck travel-time reliability by comparing passenger-vehicle travel time and estimated truck delay during rush hour. The research was conducted on key freight corridors in Minnesota, which were selected from other previous studies *(10)*. This research estimated truck delay and identified major truck bottlenecks where significant truck delays occur. Figure 2-2 shows the example of truck-delay visualization in the afternoon peak in the Minneapolis-St. Paul, Minnesota area.

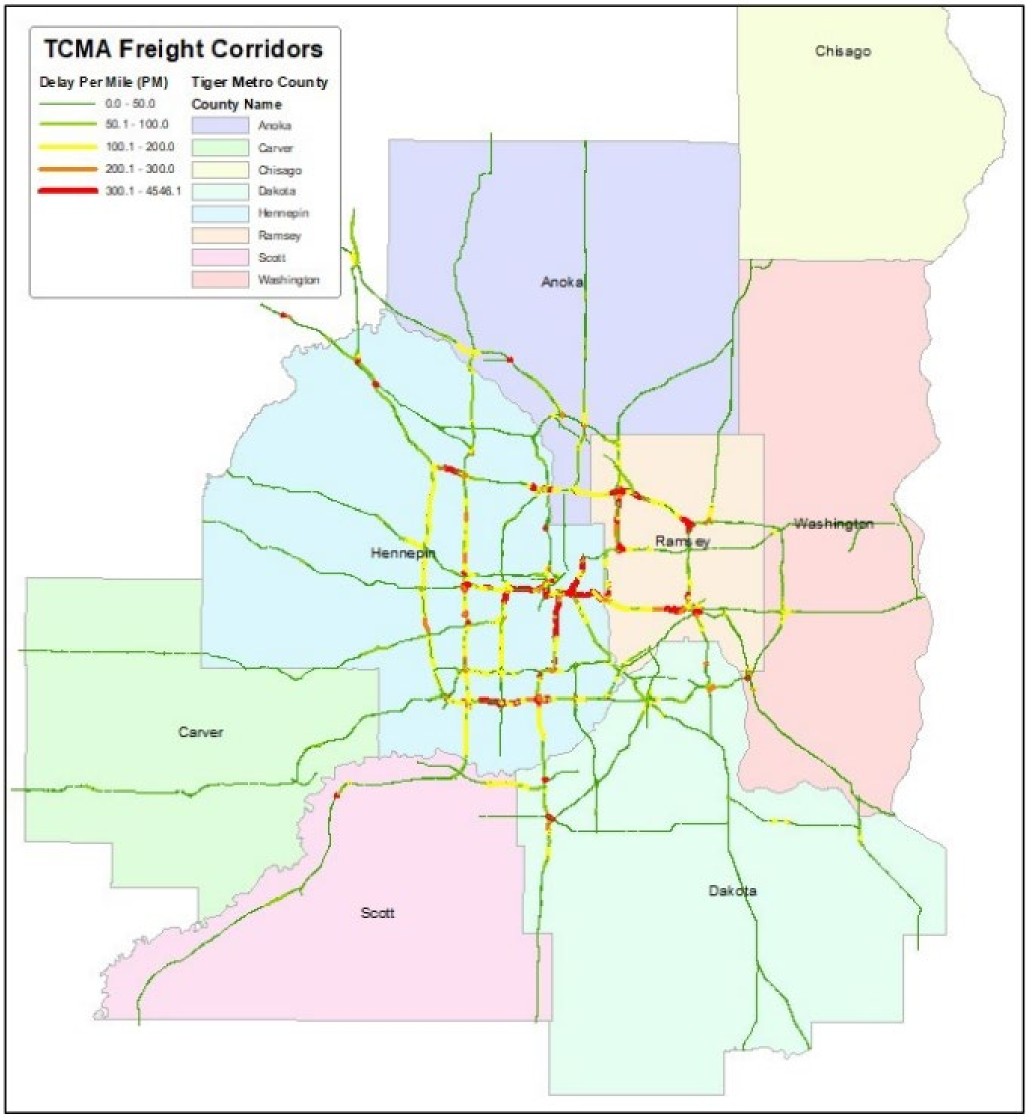


Figure 2-2. Average Truck Delay by Metro County in the Afternoon Peak Traffic Time in the Minneapolis-St. Paul, Minnesota area *(9)*.

Similarly, other state DOTs have conducted various studies to identify major freight bottlenecks in their regions (e.g. *(11, 12)*). Adding to this effort, beginning in October 2018, state DOTs are required to submit *Truck Freight Bottleneck Reports* every four years to FHWA. Nevertheless, there are few efforts to identify freight bottlenecks at the multistate corridor level.

2.2.2. Marine Highway Freight Bottleneck

A previous study by the National Center for Freight and Infrastructure Research and Education identified major bottlenecks in marine highways by assessing delay experienced at locks and dams. The marine freight network analyzed included the Mississippi Valley along with the Great Lakes and the locks and dams associated with the inland waterways of the Mississippi, Missouri, Ohio, and Illinois rivers. The analysis utilized LPMS data on vessel delay at locks and dams to map bottlenecks along the waterways. As for bottlenecks, they were characterized by an experienced average tow delay of greater than one hour. Figure 2-3 shows the mapping of lock delays through the inland waterway system while Table 2-1 gives the bottleneck locations determined by the study.

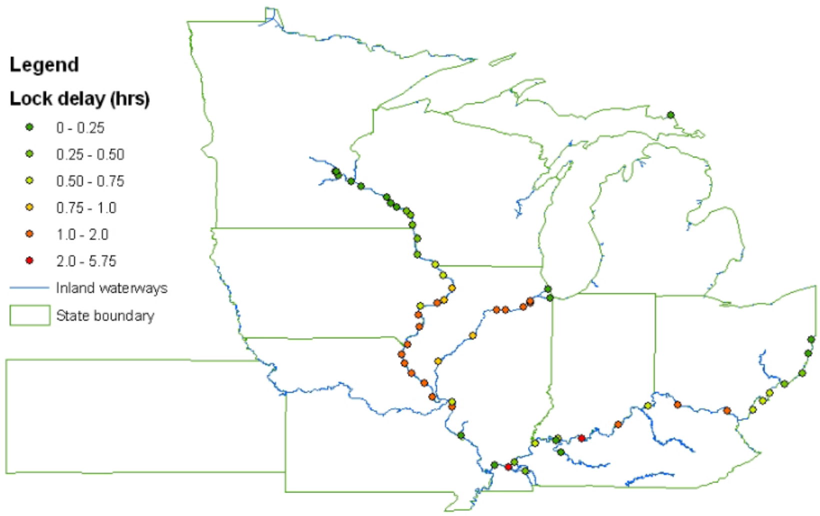


Figure 2-3. Lock Delays throughout the inland waterway system 2006 *(6)*.

Table 2-1. Locks Experiencing Average Delay Greater than One Hour *(6)*.

Delay rank	Waterway	Lock Name	Total # Barges	Average Delay (hours)	Main Chamber Length	Additional Chambers
1	Ohio	Lock 52	91,344	5.68	1200	yes
2	Ohio	Cannelton	55,747	2.31	1200	yes
3	Mississippi	Lock 25	28,037	1.84	600	no
4	Illinois	Marseilles	18,601	1.75	600	no
5	Illinois	Brandon Rd	17,895	1.71	600	no
6	Ohio	Greenup	69,393	1.64	1200	yes
7	Ohio	Captain Anthony Meldahl	55,258	1.58	1200	yes
8	Illinois	Lockport	17,430	1.56	600	no
9	Mississippi	Lock 21	26,457	1.52	600	no
10	Mississippi	Lock 22	26,758	1.5	600	no
11	Mississippi	Lock 27	63,056	1.46	1200	yes
12	Mississippi	Lock 24	28,044	1.38	600	no
13	Mississippi	Lock 15	20,039	1.37	600	yes
14	Illinois	Starved Rock	19,691	1.36	600	no
15	Mississippi	Lock 20	24,788	1.22	600	no
16	Illinois	Dresden Island	19,180	1.22	600	no
17	Ohio	McAlpine	49,569	1.11	1200	yes
18	Mississippi	Lock 17	21,319	1.09	600	no
19	Mississippi	Lock 18	22,530	1.08	600	no
20	Mississippi	Lock 19	23,502	1.07	1200	no

2.3. Summary of the Truck Freight Bottleneck Reporting Guidebook Steps

In July 2018, FHWA provided the *Truck Freight Bottleneck Reporting Guidebook (13)* to support state DOTs with the truck freight bottleneck reporting required by 23 U.S.C. 150(e)(4). This guidebook offers specific guidance with six steps to identify truck freight bottlenecks based on the best practices from previous freight bottleneck analyses. This section provides a summary of each step in the proposed framework in the guidebook. Note that we focus on the congestion-based bottlenecks, though the guidebook also covers bottlenecks by truck restriction.

Step 1: Select Roadway Network for Freight Bottleneck Analysis

The first step is selecting a roadway network to be investigated. The guidebook suggests using pre-existing, freight-related system classifications or combinations of them, such as:

- Interstate System
- National Highway System (NHS)
- NHS Intermodal Connectors
- Primary Highway Freight System (PHFS)
- Critical Rural Freight Corridors (CRFCs)
- Critical Urban Freight Corridors (CUFCs)
- Non-PHFS Interstates
- National Network
- State-defined Highway Truck Freight Network

Another suggested method for selecting roadways is based on truck-volume thresholds, which could be the total number of trucks and/or the percentage of truck traffic. Alternatively, proximity to important freight facilities could be used as the selection criteria. The possible major facilities include:

- Intermodal facilities
- Major freight generators
- Border crossings and ports of entry
- Energy sector corridors

Step 2: Gather Data for Bottleneck Identification and Analysis

For identifying recurrent congestion bottlenecks, the guidebook recommends a data-driven approach with an objective basis for selecting freight bottlenecks. Note, however, that the results from data analysis should be supplemented with input from stakeholders to confirm the bottlenecks identified based on data analysis, and to incorporate other (qualitative) factors that are not represented by data. Data needed for such an analysis include:

- Vehicle travel-time data through NPMRDS: Speed and travel time information for all road segments on the NHS based on the Traffic Message Channel (TMC) network with five-minute intervals for passenger vehicles, freight trucks, and combined traffic.
- Truck-volume counts through state DOTs: Traffic volume information collected by permanent and temporary roadway detectors, video, and other methods in hourly, daily, or annual terms.

- Paired travel-time and truck-volume data: The two data sets need to be joined to perform bottleneck analysis with geographic information systems (GIS) tools.
- Data and outcome from a region's Congestion Management Process (CMP).

The non-recurrent congestion bottlenecks can be identified using the above data. However, additional screening processes are needed, with data relevant to potential causes of non-recurrent bottlenecks, to better understand potential solutions. Key types of data to review include:

- Vehicle crashes and other incidents
- Construction activities
- Bad weather
- Special events

Step 3: Screen for Truck Freight Bottlenecks

To identify freight bottlenecks, performance measures for road sections should be decided. The suggested measures in the *Truck Freight Bottleneck Reporting Guidebook* are presented in Table 2-2. Once the measures are selected, certain thresholds should be set and compared with calculated results for actual road performance using data in Step 2. To identify non-recurrent congestion, additional efforts such as interviews with local traffic operations staff would be required.

Table 2-2. Recommended Performance Measures for Screening Bottlenecks

Measure	Description
Total Delay per Segment	Vehicle-hours per segment
Total Delay per Mile per Segment	Delay per segment, normalized by segment length vehicle-hours
Hours of Delay per Truck	Vehicle-hours of delay normalized by number of trucks
Frequency of Congestion per Segment	How often time intervals of speed data are congested
Total Hours When Congestion is Present	Sum of time intervals meeting a congestion threshold
Travel Time Index	Ratio of the actual travel time to the uncongested travel time
Planning Time Index	The ratio of the 95th percentile travel time to the 50th percentile travel time (reliability measure) or reference travel time (similar to the national TTTR measure)
Planning Time Index 80^{th}	The ratio of the 80^{th} percentile travel time to the 50^{th} percentile travel time (reliability measure) or reference travel time
Commuter Stress Index	Same as Travel Time Index except for the peak direction rather than both directions

Step 4: Validation of the Truck Freight Bottleneck List

Considering false positives and false negatives from data analysis results, validation of the bottleneck list in Step 3 would be required. The proposed method for validation is:

- Compare with complementary data
- Seek expert validation of locations
- Research unanticipated bottlenecks

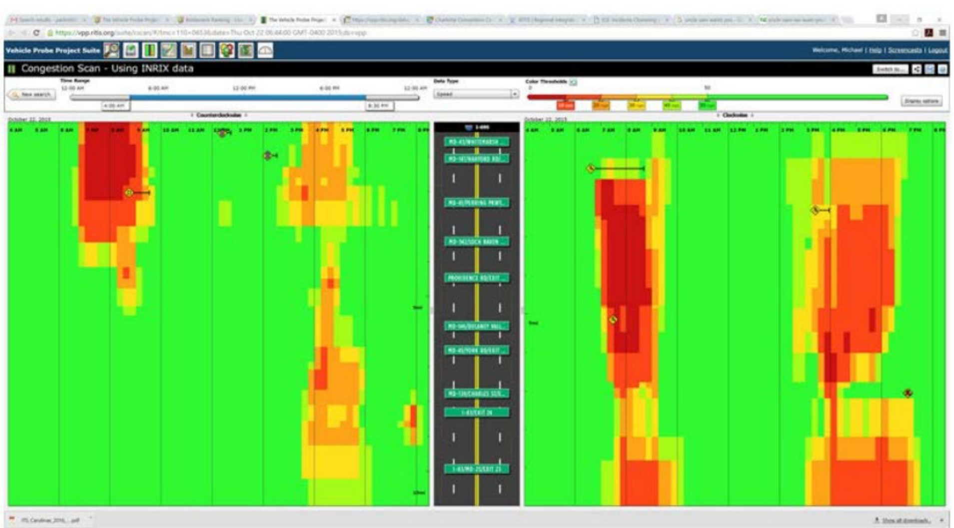
There would be several reasons to adjust the bottleneck list such as low data quality, competing goals with other agency, stakeholders' preferences, and lack of solutions.

Step 5: Evaluate Truck Freight Bottleneck Causes

Understanding bottleneck causes is essential to developing possible solutions, though it can be quite challenging due to the complexity of factors that causes the bottleneck. This guidebook suggests several techniques such as:

- Data visualizations of bottlenecks
- Indicator analysis
- Location research

Figure 2-4 shows an example of data visualization which helps depict patterns of recurring congestion. After identifying the congestion type, analysts can investigate the location in detail to find the potential causes of bottlenecks.



Source: National Performance Management Research Data Set (NPMRDS)

Figure 2-4. Visualization of Bottlenecks (adopted from the *Truck Freight Bottleneck Reporting Guidebook (13)*)

Step 6: Prioritize Truck Freight Bottlenecks

The *Truck Freight Bottleneck Reporting Guidebook* recommends prioritizing the bottleneck list, although it is not required for reporting. The bottlenecks can be ranked based on the total delay or by comparing expected impact with and without improvement projects. This step aims to utilize limited resources for more efficient freight planning efforts.

3. HIGHWAY BOTTLENECK IDENTIFICATION IN THE MAASTO REGION

This section describes the process adopted in the present study to identify highway bottlenecks in the MAASTO region. In section 3.1, the roadway network and data for the analysis are defined. In section 3.2, the methodologies developed to identify bottlenecks are described in detail. The results of freight bottleneck identification are provided in section 3.3.

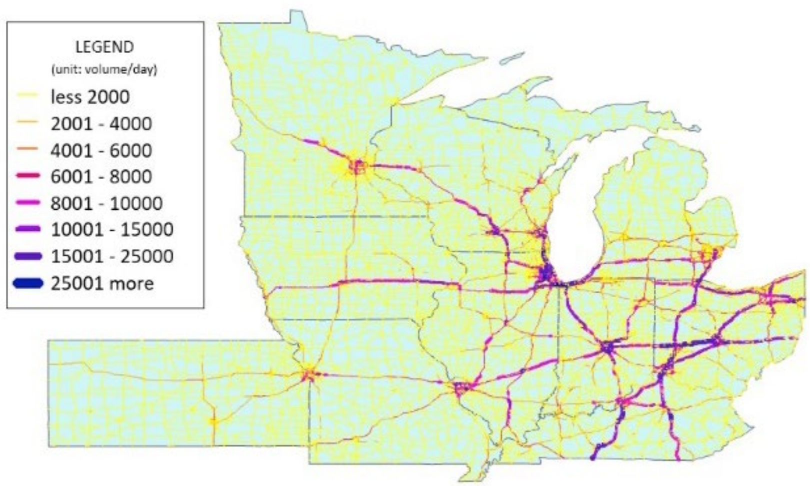
3.1. Network and Data

3.1.1 Network: NHFN

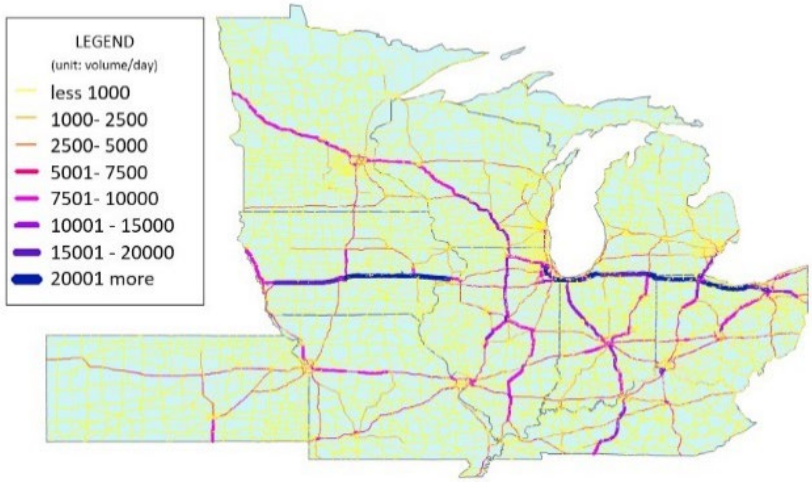
As presented in the *Truck Freight Bottleneck Reporting Guidebook (13)*, the first step to identify freight bottlenecks is deciding a network to be analyzed. The previous work by the Mid-America Freight Coalition (MAFC), *Identification and Characterization of the MAASTO Region's Multimodal Freight Network (14)*, investigated physical (e.g., road length) and operational (e.g., truck volume) features of corridors in the MAASTO region to define the major freight network. The results of that work show that the National Highway Freight Network (NHFN) is a network that carries the majority of truck volumes, especially long-distance truck volumes. Figure 3-1(a) shows the NHFN in the MAASTO region, and Figure 3-1(b) and Figure 3-1(c) present distributions of all truck volume (AADTT) and long-distance truck volume in corridors in the MAASTO region, respectively. Clearly, the NHFN and truck-volume distribution are similar, which verifies that NHFN represents the major freight network in the MAASTO region. Thus, in this research, we define the NHFN as a freight network to be investigated for freight bottleneck identification.


MINNESOTA
WISCONSIN
MICHIGAN
IOWA
ILLINOIS
INDIANA
OHIO
KANSAS
MISSOURI
KENTUCKY
Minneapolis
Madison
Milwaukee
Chicago
Detroit
Cleveland
Des Moines
Indianapolis
Columbus
Springfield
Kansas City
St. Louis
Cincinnati
Louisville

(a)


LEGEND
(unit: volume/day)
less 2000
2001 - 4000
4001 - 6000
6001 - 8000
8001 - 10000
10001 - 15000
15001 - 25000
25001 more

(b)



(c)

Figure 3-1. (a) NHFN in MAASTO region; (b) Distribution of AADTT (All Trucks); (c) Distribution of AADTT (Long-distance Trucks) (adopted from *Identification and Characterization of the MAASTO Region's Multimodal Freight Network (14)*)

3.1.2. Data: NPMRDS

Since 2013, FHWA has provided the National Performance Management Research Data Set (NPMRDS) that includes archived traffic data covering the area of the NHS *(15)*. This data set includes speeds and travel times at 5-minute intervals for three types of vehicles (passenger vehicles, trucks, and both). The NPMRDS is especially appropriate for large-scale analysis since it covers major networks, nationwide, providing time-series data for several years. Thus investigating NPMRDS enables the visualization of the dynamics of freight congestion in the time-space domain as well as the identification of bottleneck locations. Currently there are two versions of NPMRDS with different providers covering different time periods; *Version 1* is from *HERE (*a mapping and location data company) and covers October 2011–January 2017, and *Version 2* is from *INRIX (*a transport company) and covers dates beginning January 2017 to present (as of January 2019). These two versions are not connected since the road segments for each version are different. Thus, in this research, we use the truck speed data set of Version 1 (January 2014–January 2017) since Version 2 only had one year of data at the commencement of this research.

Table 3-1 shows an example of raw data from NPMRDS. The data is provided based on TMC, which uniquely identifies each road segment. A TMC generally spans a stretch of road from one exit or entrance ramp to the next, and the length varies from less than a mile to several miles. From the speed data of each timestamp, we derive an hourly average speed for each TMC segment along the NHFN. Note that, in this report, hourly time interval is marked by the beginning timestamp (e.g., AM07 = 7:00–7:59 AM).

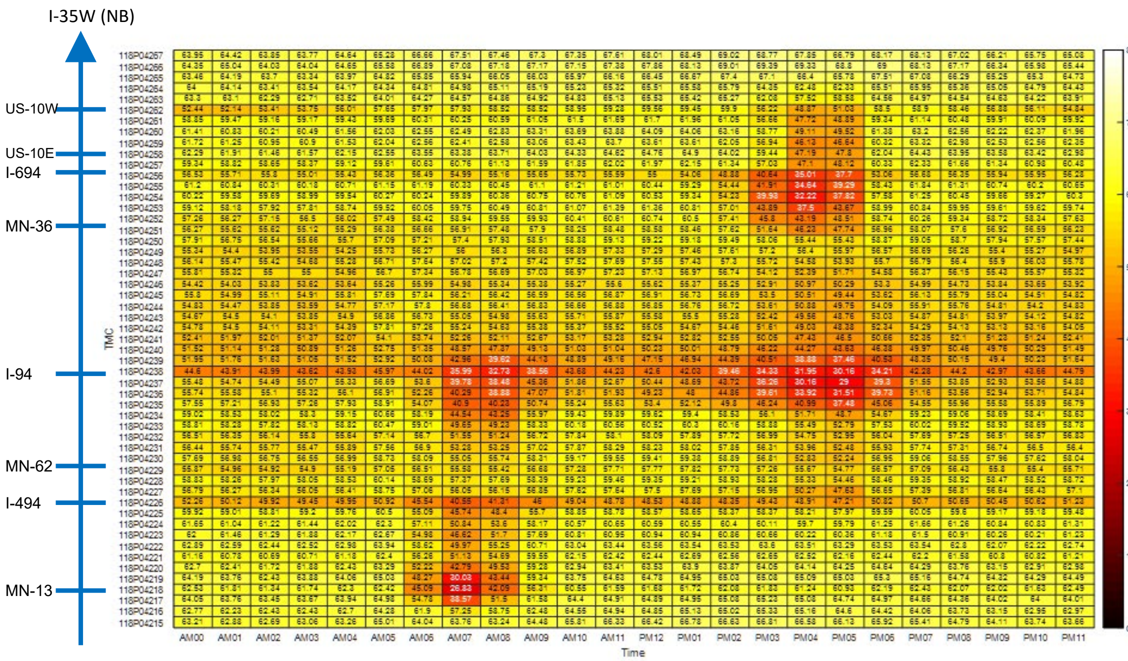
Table 3-1. Example of NPMRDS Data (Eastbound I-94 in Wisconsin)

TMC ID	Timestamp	Speed (mph)	Average Speed (mph)	Reference Speed (mph)	Travel Time (seconds)
107N04675	5/4/2015 17:20	65	67	71	37.22
107N04675	5/4/2015 17:25	63	67	71	38.4
107N04675	5/4/2015 17:30	58	67	71	41.71
107N04675	5/4/2015 17:35	61	67	71	39.66

3.2. Measures and Criterion for Freight Bottlenecks

As presented in Section 2.3 (Step 3), there are several measures for screening bottlenecks. Considering the property of NPMRDS, however, volume-related measures, such as total delay per segment (unit: vehicle-hour), are not available since NPMRDS does not provide flow rate or truck volume for each timestamp. Note that NPMRDS provides AADT and AADTT for each TMC, but it is challenging to estimate a delay using these since flow rate or flow rate distribution for each timestamp is not available.

Another option is to use speed data, such as the *frequency of congestion per segment* or *total hours when congestion is presented* as suggested in Table 2-2. For the large-scale analysis, however, using speed value could be inappropriate since the definition of low speed in congestion can vary by location. Figure 3-2(a), a time-space diagram of speed for I-35W (northbound) in Minnesota's Twin Cities shows an example of false selection of bottlenecks using speed data. From the diagram, the interchange between I-35W and I-94, TMC segment of 118P04238, can be a bottleneck of this corridor since the speed is low and the congestion propagates upstream. However, even early morning (e.g., AM03), the speed is still lower than other sections, and thus the bottleneck would be considered to be activated all day. The location research, however, reveals that there is a sharp curve near the road segment, which suggests a low reference speed (i.e., low free-flow speed or speed limit). The Street View from Google Maps near this section is presented in Figure 3-2(b) and shows a low advisory speed limit. Since it would be challenging to perform location research for all road segments, using just speed data would be inefficient.



(a)

(b)

Figure 3-2. (a) Example of Time-Space Diagram of Speed (Northbound I-35W in Twin Cities, MN); (b) Sharp Curve Warning Sign with Advisory Speed Limit *(16)*.

On the other hand, travel time index (TTI) is a measure that presents road segments where the travel time is higher than the free-flow state as:

$$Travel\ Time\ Index = \frac{Actual\ Travel\ Time}{Uncongested\ Travel\ Time}$$

Figure 3-3 shows the time-space diagram of TTI for the same corridors from Figure 3-2. Note that the *uncongested travel time* is estimated using reference speed of each TMC. Clearly, this diagram also presents the bottleneck near the interchange between I-35W and I-94, but it shows that the bottleneck activates only in the morning and evening rush hours. Thus, using TTI could be a more effective way to identify the bottleneck activation time as well as its location. Thus, in this research, we mainly use TTI as a measure to identify freight bottlenecks and consult speed data for complementary purposes.

Note that selecting a single TTI threshold for all locations is still challenging since TTI is still a relative value. By trying several threshold values, we found that 1.4 is a reasonable value to reveal the most major freight bottlenecks without creating an over-selection issue. However, we also provide all time-space diagrams of speed and TTI in the Appendix to provide readers with the flexibility of changing measures and criteria.

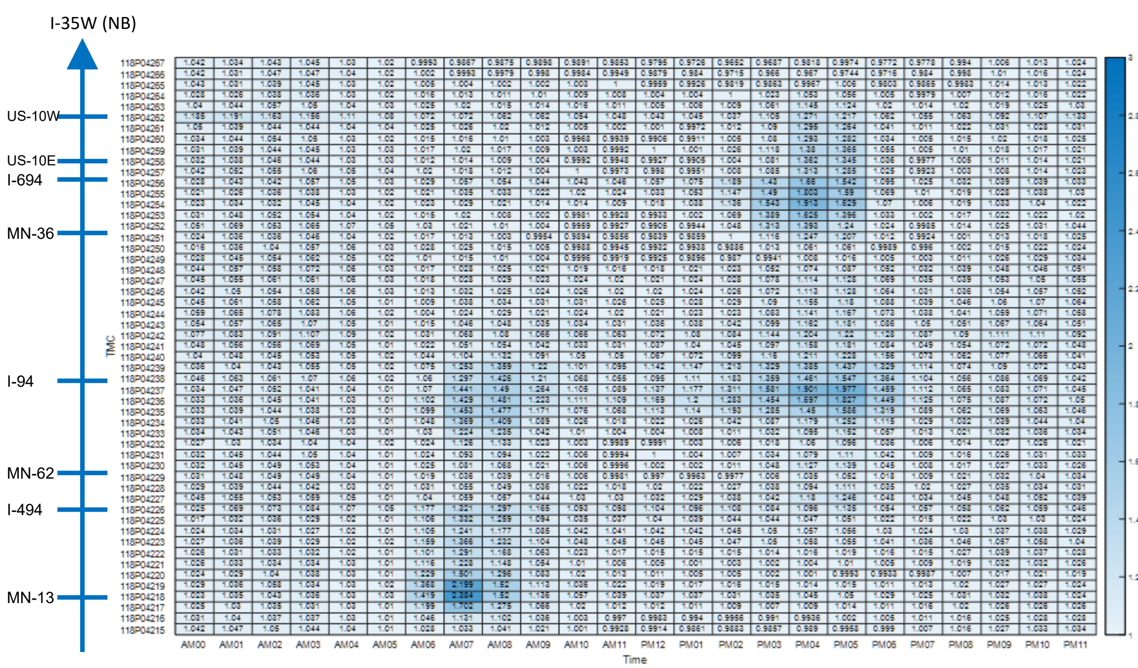


Figure 3-3. Example of a Time-Space Diagram of TTI (Northbound I-35W in Minnesota's Twin Cities)

3.3. Identification of Freight Bottlenecks

To get a sense of locations of freight bottlenecks across the MAASTO region, we first derived TTIs for each segment for each time (e.g., AM00–PM11) and then quantified the maximum TTI value for each road segment among 24 time windows using a GIS map as presented in Figure 3-4. This figure presents that the segments near large cities usually have relatively high maximum TTI values, whereas the maximum TTI in rural areas is near 1.0. The result suggests that most major freight bottlenecks reside near large cities. Based on the result, we set 14 major areas that include major freight bottlenecks, as presented in Figure 3-4.

In the next step, each area is divided at the corridor level, taking road directions into consideration, to identify more precise bottleneck locations and their activation times. To this end, time-space diagrams of TTI (complemented with speed data) for all corridors are constructed, as illustrated in Figure 3-3. From the diagrams, bottleneck locations, duration, and total queue length are measured. Specifically, the bottleneck locations are identified by searching a TMC that separates a congested traffic state upstream and a free-flow state downstream. The bottleneck activation times are also determined from the time-space diagram for the time windows where TT exceeds the threshold set at 1.4 in this study. After identifying the location and activation time of a bottleneck, the bottleneck cause is investigated through location research with satellite and GIS maps. In this research, we categorize the bottleneck type as *interchange*, *merge*, or *multiple* (several interchanges and/or ramps) since the investigated network is mostly along the Interstate system in NHFN. In addition, the queue length is estimated from TMC segments of which TTI exceeds the threshold during congestion. For example, in Figure 3-3, bottleneck activation is observed near the interchange between I-35W and I-94 during AM07–AM08. The maximum number of TMCs is observed at AM08 as 118P04234–118P04238, and then, the maximum queue length is the estimated sum of these TMC lengths. Readers are referred to the Appendix for the time-space diagrams depicting bottleneck activations and dynamic queue propagations for all corridors. In the following subsections, the analysis results for each area are provided.

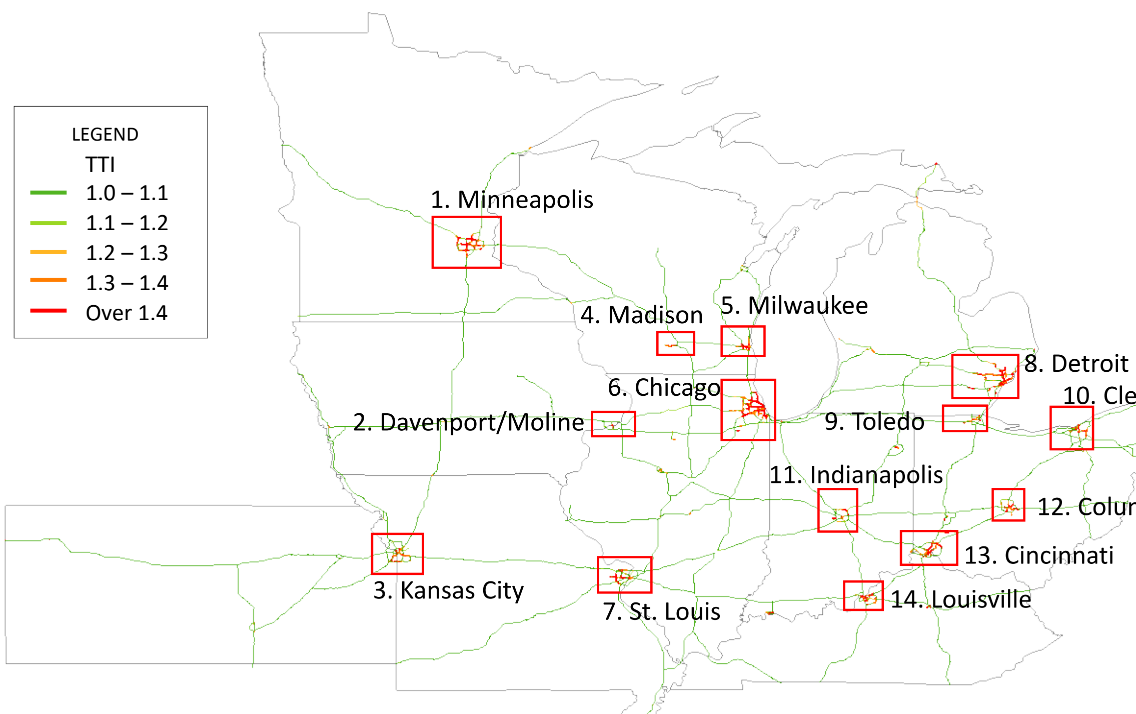


Figure 3-4. GIS Map with Maximum TTI and Major Areas Including Freight Bottlenecks

3.3.1 Area 1: Twin Cities (MN)

Area 1 is the Twin Cities (Minneapolis-St. Paul) area in Minnesota. There are six major freight corridors in this area characterized as:

- Mainly running east and west: I-94, I-394
- Mainly running north and south: I-35W, I-35E
- Beltways: I-494, I-694

The sketch of corridors and bottlenecks in the Twin Cities is presented in Figure 3-5. Note that, in section 3.3.1-3.3.14, the major freight corridors are highlighted with different colors in figures. The type, activation time, and the maximum queue length for each bottleneck are also presented in Table 3-2.

The results show that bottlenecks are typically located near major interchanges and ramps on urban corridors located in the areas inside beltways. The bottlenecks are typically activated during morning (AM06–AM08) and/or evening (PM03–PM06) rush hours. But, the bottlenecks near the downtown area are activated earlier than typical evening rush hours (bottlenecks 1-14, 1-18, 1-22, 1-36, and 1-42). Related to the bottleneck severity, there are four bottlenecks where the maximum queue length exceeds five miles. Two bottlenecks are located on I-35W (southbound) near the interchange with I-694 and I-94 in the morning rush hour (bottlenecks 1-11 and 1-12). The congestion at the interchange between I-35W (southbound) and I-94 extends over 14 miles with a congested speed of less than 20 mph. The congestion on I-494 (eastbound) near the interchange with I-35W and on I-494 (westbound) near the on-ramp from MN-55 are affected by adjacent interchanges and ramps that result in extensive queue propagation (bottlenecks 1-22 and 1-26).

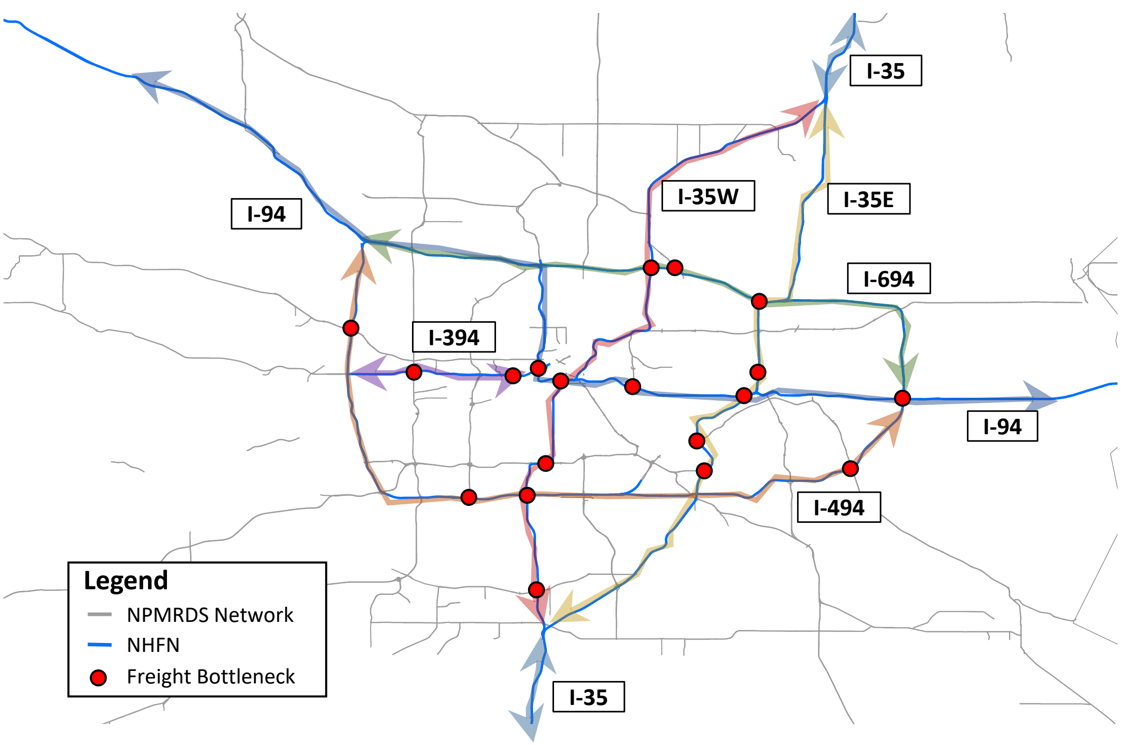


Figure 3-5. Corridors and Locations of Freight Bottlenecks in Area 1 (Twin Cities)

Table 3-2. Freight Bottlenecks in Area 1 (Twin Cities)

No.	Corridor	Direction	Location	Type	Time	Max Queue (mile)
1-1	I-35E	North	@MN-62	Merge	AM7	1.19
1-2	I-35E	North	@I-94	Interchange	PM3–5	1.07
1-3	I-35E	North	@I-694	Interchange	PM4–5	0.81
1-4	I-35E	North	@MN-62	Merge	PM5	1.24
1-5	I-35E	South	@Cayuga St.	Merge	AM7	2.35
1-6	I-35E	South	@MN-62, MN-5	Merge	PM4–5	2.69
1-7	I-35W	North	@MN-13	Merge	AM6–8	3.42
1-8	I-35W	North	@I-94	Interchange	AM7–8	3.34
1-9	I-35W	North	@I-694	Interchange	PM3–5	3.20
1-10	I-35W	North	@I-94	Interchange	PM3–6	3.55
1-11	I-35W	South	@I-694	Interchange	AM6–7	5.24
1-12	I-35W	South	@I-94	Interchange	AM7–8	14.60
1-13	I-35W	South	@MN-62	Merge	AM8	1.40
1-14	I-35W	South	@I-94	Interchange	PM1–6	4.02
1-15	I-35W	South	@MN-13	Merge	PM4–5	1.15
1-16	I-394	East	@Louisiana Ave	Merge	AM7	1.52
1-17	I-394	East	@Penn Ave	Merge	AM7–8	0.91
1-18	I-394	East	@Penn Ave	Merge	PM1–6	3.95
1-19	I-394	West	@I-94	Interchange	PM5	1.02
1-20	I-494	East	@MN-55	Merge	AM7	4.30
1-21	I-494	East	@MN-100	Merge	AM7–8	1.24
1-22	I-494	East	@I-35W, MN-100	Multiple	PM12–6	5.30
1-23	I-494	East	@I-94	Interchange	PM5	0.51
1-24	I-494	West	@US-10	Interchange	AM7	0.73
1-25	I-494	West	@I-35W	Interchange	AM7–8	3.70
1-26	I-494	West	@MN-55, I-394	Multiple	PM3–5	7.18
1-27	I-494	West	@I-35W	Interchange	PM4–5	4.18
1-28	I-694	East	@US-10	Interchange	AM7	0.42
1-29	I-694	East	@US-10	Interchange	PM3–5	3.62
1-30	I-694	East	@I-94	Interchange	PM3–5	0.72
1-31	I-694	West	@I-35E	Interchange	AM7	1.53
1-32	I-694	West	@I-35E	Interchange	PM3–5	2.73

1-33	I-694	West	@I-94	Interchange	PM4–5	1.77
1-34	I-694	West	@I-94	Interchange	PM5	2.77
1-35	I-94	East	@I-394	Interchange	AM7–8	2.41
1-36	I-94	East	@I-394	Interchange	PM2–5	3.43
1-37	I-94	East	@I-35E	Interchange	PM3–5	3.14
1-38	I-94	East	@MN-280	Merge	PM5	0.25
1-39	I-94	West	@I-35E	Interchange	AM7	3.39
1-40	I-94	West	@MN-280	Merge	AM7	0.88
1-41	I-94	West	@I-35W	Interchange	AM7–8	1.43
1-42	I-94	West	@I-394, I-35W	Multiple	PM2–6	4.19
1-43	I-94	West	@I-494	Interchange	PM4–5	1.77

3.3.2 Area 2: Davenport/Moline (IA, IL)

Area 2 is Davenport/Moline in Iowa and Illinois. There are four major freight corridors in this area characterized as:

- Mainly running east and west: I-80, I-88
- Mainly running north and south: I-74
- Beltways: I-280

The sketch of corridors and bottlenecks in Davenport/Moline are presented in Figure 3-6. The type, activation time, and maximum queue length for each bottleneck are presented in Table 3-3. The results show that two mild bottlenecks are located on I-74 near the Mississippi River. The bottlenecks are activated in the morning (AM07–AM08) and/or evening (PM04–PM05) rush hours. The maximum queue lengths in Table 3-3 are relatively small with the criterion of TTI >1.4. However, the time-space diagram shows that the queues propagate for nearly a mile with travel speeds of 30–40 mph.

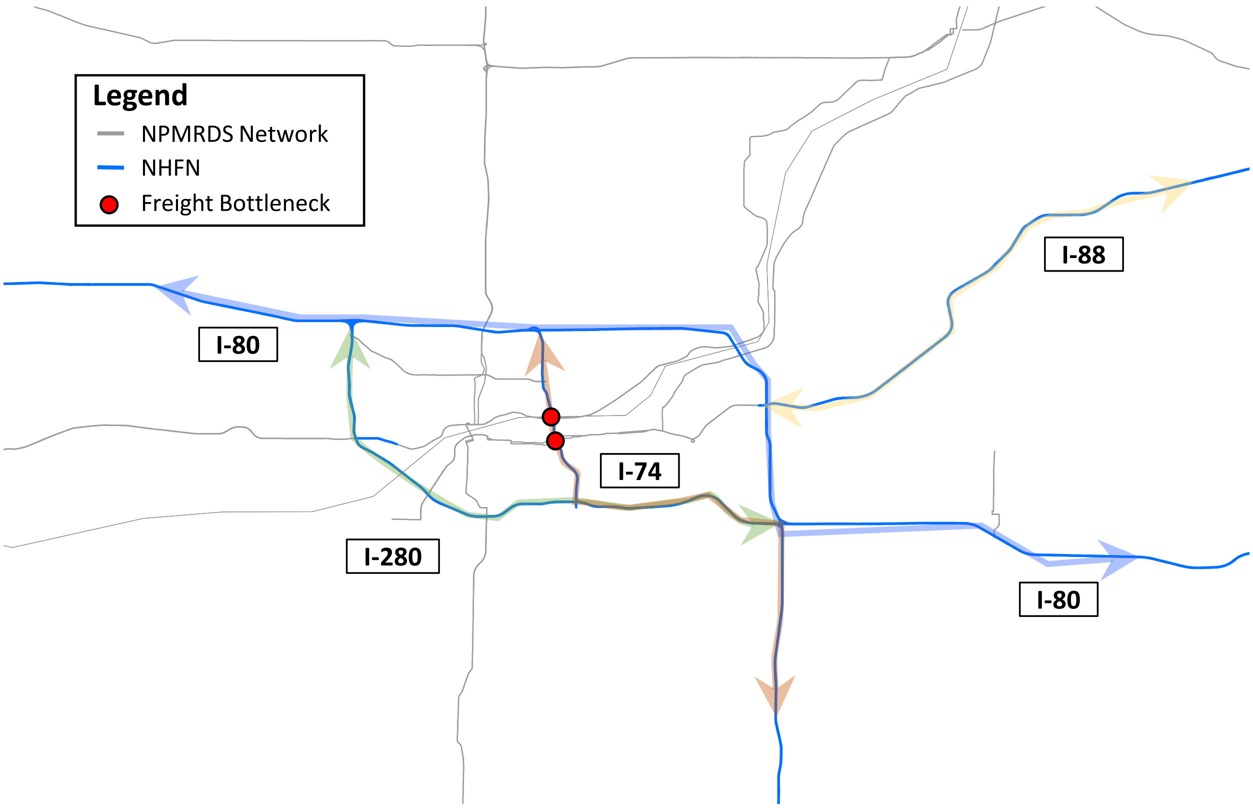


Figure 3-6. Corridors and Locations of Freight Bottlenecks in Area 2 (Davenport/Moline)

Table 3-3. Freight Bottlenecks in Area 2 (Davenport/Moline)

No.	Corridor	Direction	Location	Type	Time	Max Queue (mile)
2-1	I-74	East	@US-67	Merge	AM7–8	0.16
2-2	I-74	East	@US-67	Merge	PM4–5	0.33
2-3	I-74	West	@River Dr.	Merge	PM4–5	0.16

3.3.3 Area 3: Kansas City (KS, MO)

Area 3 is Kansas City in Kansas and Missouri. There are six major freight corridors in this area characterized as:

- Mainly run east and west: I-70
- Mainly run north and south: I-29, I-35
- Beltways: I-435, I-470, I-635

The sketch of corridors and bottlenecks in Kansas City are presented in Figure 3-7. The type, activation time, and the maximum queue length for each bottleneck are presented in Table 3-4.

The results show that most bottlenecks are located near the major interchanges and ramps on I-29, I-35, and I-435. The bottlenecks are typically activated during morning (AM07–AM08) and/or evening (PM04–PM05) rush hours. Related to the bottleneck severity, there are two bottlenecks where the maximum queue length exceeds four miles. One is on I-35 (southbound) by several interchanges and ramps from Shawnee Mission Pkwy to South 7th Street (bottleneck 3-8). Another one is on I-435 (counterclockwise) near interchange with I-470 (bottleneck 3-11).

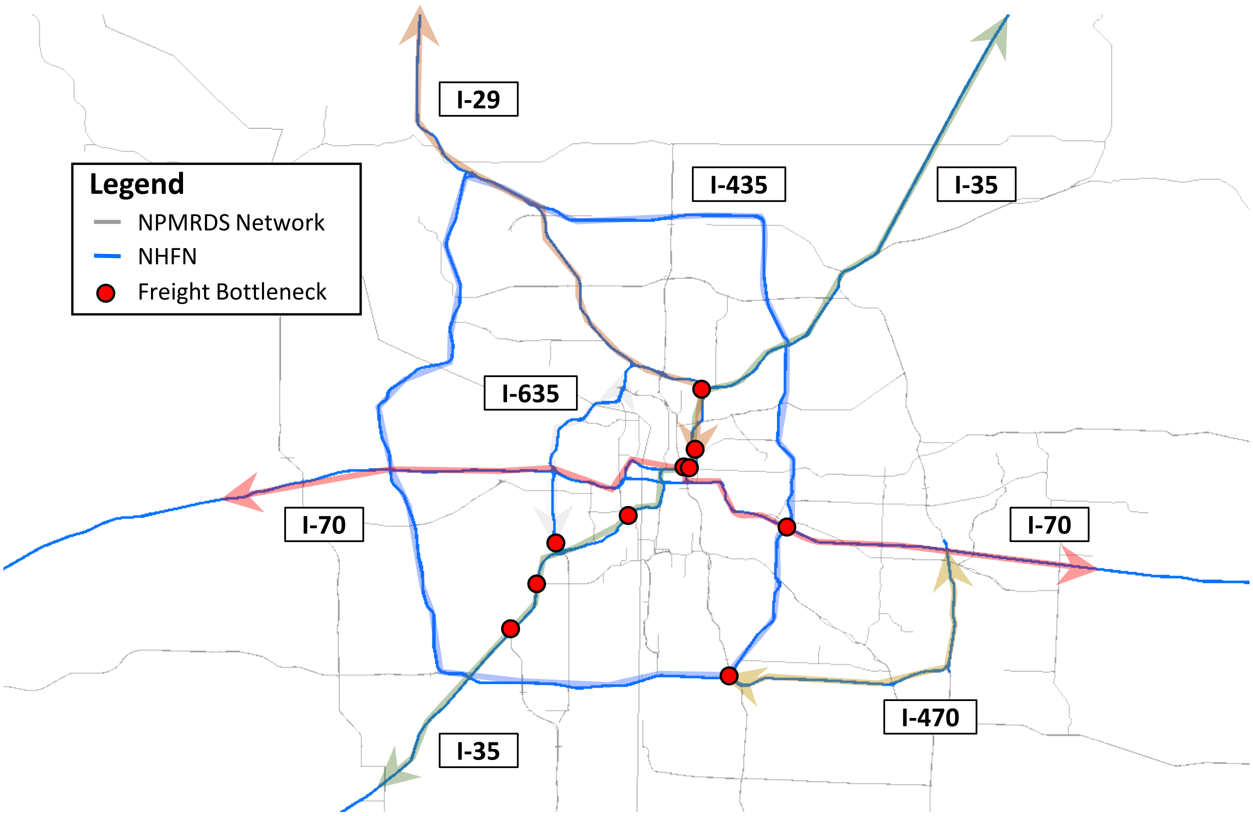


Figure 3-7. Corridors and Location of Freight Bottlenecks in Area 3 (Kansas City)

Table 3-4. Freight Bottlenecks in Area 3 (Kansas City)

No.	Corridor	Direction	Location	Type	Time	Max Queue (mile)
3-1	I-29	North	@Front St	Interchange	PM4–5	0.85
3-2	I-29	South	@I-35	Multiple	AM7	0.18
3-3	I-35	North	@Switzer Bypass	Interchange	AM7–8	1.69
3-4	I-35	North	@Switzer Bypass	Interchange	PM4–5	1.69
3-5	I-35	North	@I-29	Multiple	PM4–5	1.28
3-6	I-35	North	@I-70	Multiple	PM4–5	0.80
3-7	I-35	South	@Shawnee Mission Pkwy	Multiple	AM07	1.00
3-8	I-35	South	@Shawnee Mission Pkwy–S 7th St	Multiple	PM4–5	4.90

3-9	I-435	Clockwise	@I-470	Multiple	AM7	1.66
3-10	I-435	Clockwise	@I-470	Multiple	PM5	1.20
3-11	I-435	Counter-clockwise	@I-470	Multiple	PM4–5	6.88
3-12	I-635	South	@I-35	Multiple	AM7	0.21
3-13	I-70	East	@I-435	Multiple	PM4–5	3.44
3-14	I-70	East	@I-35	Multiple	PM4–5	3.95

3.3.4 Area 4: Madison (WI)

Area 4 is Madison in Wisconsin. There are three major freight corridors in this area characterized as:

- Mainly running east and west: I-94
- Mainly running north and south: I-90
- Beltways: US-12/US-18

The sketch of corridors and bottlenecks in Madison are presented in Figure 3-8. The type, activation time, and the maximum queue length for each bottleneck are presented in Table 3-5.

The results show that most bottlenecks are located on the beltway near the interchanges with I-90, US-14, and local ramps. The bottlenecks are activated during morning (AM07) and/or evening (PM04–PM05) rush hours. The queue lengths from bottlenecks range from one to nearly three miles, resulting from the combined impact of several interchanges and ramps.

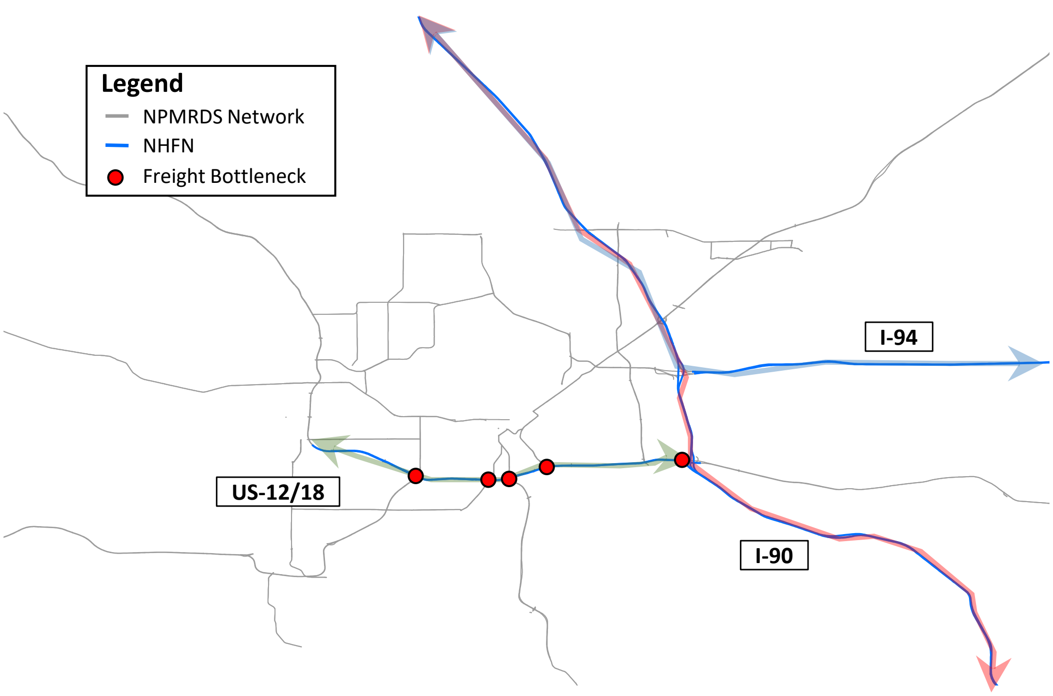


Figure 3-8. Corridors and Locations of Freight Bottlenecks in Area 4 (Madison)

Table 3-5. Freight Bottlenecks in Area 4 (Madison)

No.	Corridor	Direction	Location	Type	Time	Max Queue (mile)
4-1	US-12	East	@US-18	Merge	PM4–5	1.11
4-2	US-18	East	@US-14, John Nolen Dr.	Multiple	PM4–5	2.75
4-3	US-18	West	@I-90	Interchange	AM7	0.82
4-4	US-18	West	@US-14, Fish Hatchery Rd.	Multiple	AM7	2.34
4-4	US-18	West	@Fish Hatchery Rd.	Merge	PM5	1.55

3.3.5 Area 5: Milwaukee (WI)

Area 5 is Milwaukee in Wisconsin. There are four major freight corridors in this area characterized as:

- Mainly running east and west: I-94, I-794
- Mainly running north and south: I-41, I-43

The sketch of corridors and bottlenecks in Milwaukee are presented in Figure 3-9. The type, activation time, and the maximum queue length for each bottleneck are presented in Table 3-6.

The results show that most bottlenecks are located near the major interchanges and ramps on I-41, I-43, and I-94. The bottlenecks are typically activated during morning (AM06–AM08) and/or evening (PM03–PM05) rush hours. The interchange between I-41 and I-94 causes severe bottlenecks with queue lengths of several miles (bottlenecks 5-3, 5-8, 5-11, 5-14, and 5-15).

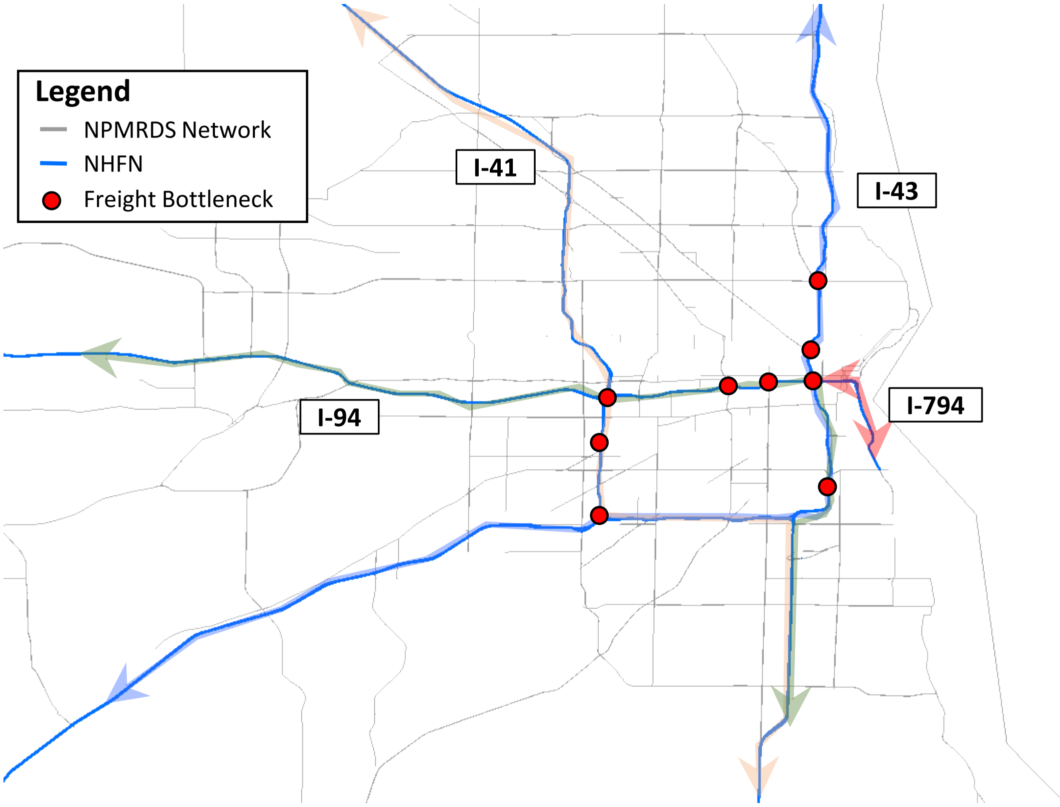


Figure 3-9. Corridors and Locations of Freight Bottleneck in Area 5 (Milwaukee)

Table 3-6. Freight Bottlenecks in Area 5 (Milwaukee)

No.	Corridor	Direction	Location	Type	Time	Max Queue (mile)
5-1	I-41	North	@Lincoln Ave, National Ave, Oklahoma Ave	Merge	AM6–8	3.48
5-2	I-41	North	@I-43	Interchange	AM7	0.64
5-3	I-41	South	@I-94	Interchange	PM3–5	4.79
5-4	I-43	North	@Holt Ave	Merge	AM7	2.07
5-5	I-43	North	@7th ST, WI-145	Merge	PM4–5	1.84
5-6	I-43	South	@WI-190	Merge	AM7–8	0.16
5-7	I-43	South	@I-94	Interchange	PM3–5	6.3
5-8	I-94	East	@I-41	Interchange	AM7	2.63
5-9	I-94	East	@St.Paul Ave, WI-175	Merge	AM7–8	3.79
5-10	I-94	East	@I-43	Interchange	PM3–5	2.51
5-11	I-94	East	@I-41	Interchange	PM4–5	2.63

5-12	I-94	East	@St.Paul Ave, WI-175	Merge	PM5	1.12
5-13	I-94	West	@Holt Ave	Merge	AM7	2.71
5-14	I-94	West	@I-41	Interchange	AM7	3.17
5-15	I-94	West	@I-41	Interchange	PM3–5	3.64

3.3.6 Area 6: Chicago (IL)

Area 6 is Chicago in Illinois. There are nine major freight corridors in this area characterized as:

- Mainly running east and west: I-55, I-80, I-88, I-90, I-94, I-290
- Mainly running north and south: I-57, I-294, I-355

The sketch of corridors and bottlenecks in Chicago are presented in Figure 3-10. The type, activation time, and the maximum queue length for each bottleneck are presented in Table 3-7.

The results show that I-55, I-90, I-94, and I-290 near downtown (to the east of I-294) have congestion at most times except the very early morning with a combined impact from interchanges and ramps for bottleneck activation. The impacts from interchanges and ramps are cumulative and evolve into severe bottlenecks with several miles of queue length (some exceeding 15 miles). The major interchanges on I-355 with other highways also cause bottlenecks (bottlenecks 6-6, 6-14, 6-15, 6-16, 6-25) in the morning (AM07–AM08) and/or evening (PM04–PM05) rush hours. South of downtown, the interchange between I-94 and I-90 also causes a bottleneck in the afternoon (bottlenecks 6-30 and 6-38).

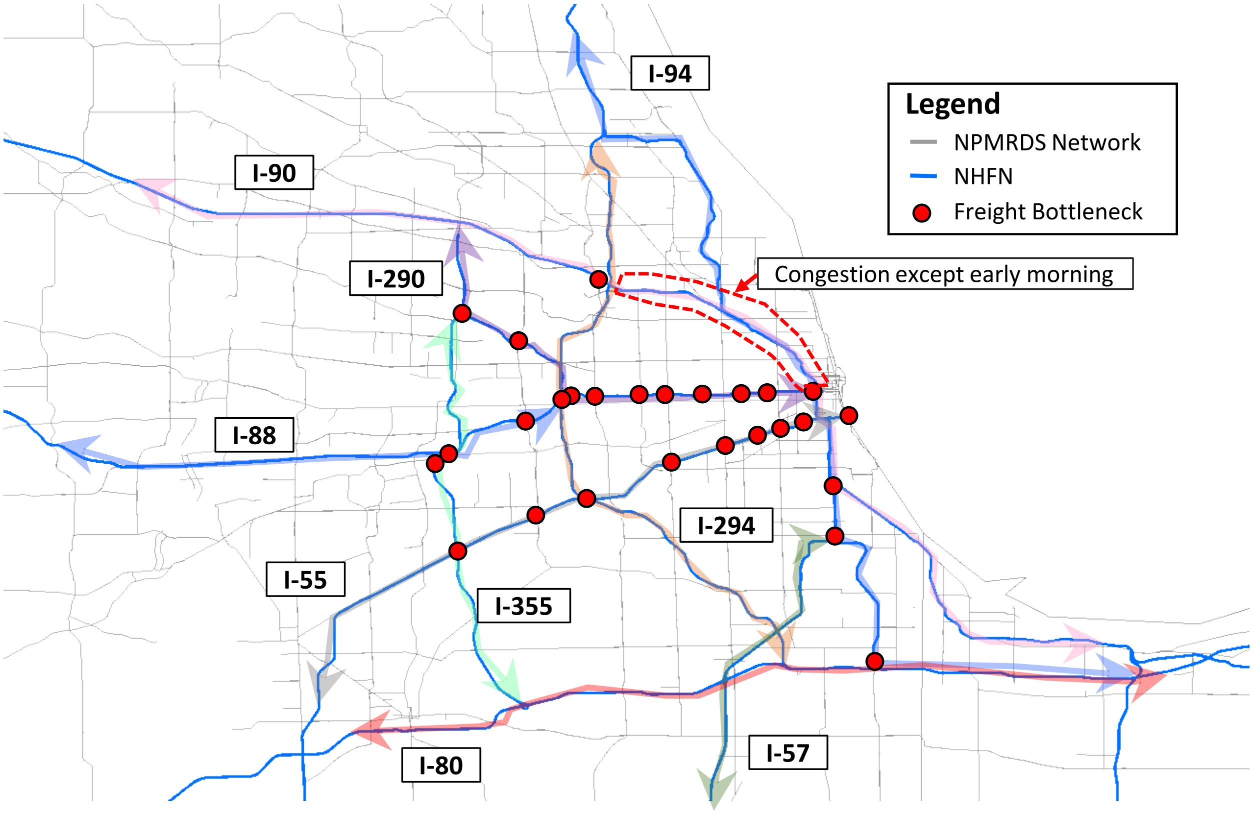


Figure 3-10. Corridors and Locations of Freight Bottlenecks in Area 6 (Chicago)

Table 3-7. Freight Bottlenecks in Area 6 (Chicago)

No.	Corridor	Direction	Location	Type	Time	Max Queue (mile)
6-1	I-290	East	@I-90	Interchange	AM10–PM11	3.00
6-2	I-290	East	@IL-43, IL-171, US-45	Multiple	AM10–PM6	5.42
6-3	I-290	East	@I-90 - I-88	Multiple	AM6–9	15.84
6-4	I-290	East	@I-294	Interchange	AM7–9	1.72
6-5	I-290	East	@I-294	Interchange	PM1–6	2.96
6-6	I-290	East	@I-355	Interchange	PM4–5	3.43
6-7	I-290	West	@US-45, IL-171, IL-43	Multiple	AM6–8	6.68
6-8	I-290	West	@IL-171, IL-43, Flournoy St., Harrison St., Congress Pkwy	Multiple	PM12–7	9.95
6-9	I-290	West	@IL-83	Interchange	PM5	1.61
6-10	I-294	North	@I-55	Interchange	AM7–8	5.71
6-11	I-294	North	@I-88	Interchange	AM7–8	2.93

6-12	I-294	South	@I-88	Interchange	PM3–6	7.59
6-13	I-294	South	@I-55	Interchange	PM3–6	6.21
6-14	I-355	North	@US-34	Interchange	AM7	4.01
6-15	I-355	North	@I-290	Interchange	AM7–8	0.93
6-16	I-355	South	@I-88	Interchange	PM4–5	5.20
6-17	I-55	North	@US-41	Interchange	AM6–10	1.16
6-18	I-55	North	@Kedzie Ave, IL-50m Harlem Ave	Multiple	AM6–9	6.34
6-19	I-55	North	@US-41	Interchange	PM1–6	1.16
6-20	I-55	North	@Harlem Ave	Merge	PM3–6	5.31
6-21	I-55	North	@IL-83	Interchange	PM4–5	5.45
6-22	I-55	South	@Kedzie Ave	Merge	AM6–7	1.23
6-23	I-55	South	@Kedzie Ave, I-90	Multiple	PM12–6	6.53
6-24	I-55	South	@IL-83	Interchange	PM2–5	5.85
6-25	I-55	South	@I-355	Interchange	PM4–5	1.54
6-26	I-57	North	@I-94	Interchange	AM6–7	3.36
6-27	I-57	South	@I-94	Interchange	PM4–5	0.96
6-28	I-88	West	@IL-83	Interchange	PM5	1.84
6-29	I-90	East	@I-290, Ohio St, IL-64, Kimball Ave, I-94, IL-171, I-190, I-294	Multiple	AM6-PM10	16.78
6-30	I-90	East	@I-94	Interchange	PM2–6	3.74
6-31	I-90	West	@Bryn Mawr Ave, I-94, IL64, Ohio St.	Multiple	AM11–PM7	11.57
6-32	I-90	West	@I-290, I-55	Interchange	AM6–8	5.22
6-33	I-90	West	@Bryn Mawr Ave, I-94	Multiple	AM6–9	8.11
6-34	I-90	West	@I-290	Interchange	AM9–PM7	1.90
6-35	I-90	West	@Devon Ave	Merge	PM4–5	1.01
6-36	I-94	East	@I-55, I-290, Ohio St., IL-64, Kimball Ave, I-90, Lake Ave, US-41	Multiple	AM10–PM10	23.52
6-37	I-94	East	@I-290, Ohio St., IL-64, Kimball Ave, I-90	Multiple	AM6–9	11.31
6-38	I-94	East	@130th St., US-20, I-57, I-90	Multiple	PM2–6	13.71
6-39	I-94	West	@I-290, I-55	Interchange	AM6–10	5.22
6-40	I-94	West	@Skoki Blvd, IL-58, Touhy Ave, US-14, I-90	Multiple	AM6–8	14.12
6-41	I-94	West	@I-90, I-57, US-20	Multiple	AM6–8	7.16

6-42	I-94	West	@IL-64, Ohio St, I-290, I-55	Multiple	PM12–7	5.35
6-43	I-94	West	@I-90	Interchange	PM1–6	4.72
6-44	I-94	West	@I-90	Interchange	PM1–6	5.64

3.3.7 Area 7: St. Louis (IL, MO)

Area 7 is St. Louis in Illinois and Missouri. There are seven major freight corridors in this area characterized as:

- Mainly running east and west: I-44, I-64, I-70
- Mainly running north and south: I-55, I-170
- Beltways: I-255, I-270

The sketch of corridors with bottlenecks and a list of bottlenecks with type, activation time and maximum queue length are presented in Figure 3-11 and Table 3-8, respectively.

The most bottlenecks are located on I-64 with interchanges and ramps with other highways (bottlenecks 7-2, 7-3, 7-4, 7-6, 7-7, 7-9, 7-10, 7-11, 7-12, 7-13, and 7-14). The bottlenecks activate during morning (AM07–AM08) and/or evening (PM03–PM06) rush hours. On I-270 (clockwise), the interchanges with I-64 and I-44 cause severe bottlenecks in the morning rush hour with eight miles of queue length (bottleneck 7-4). On I-270 (counterclockwise), on the other hand, the interchanges with I-64 and I-44 cause a bottleneck in the evening with 7.9 miles of queue length (bottleneck 7-6).

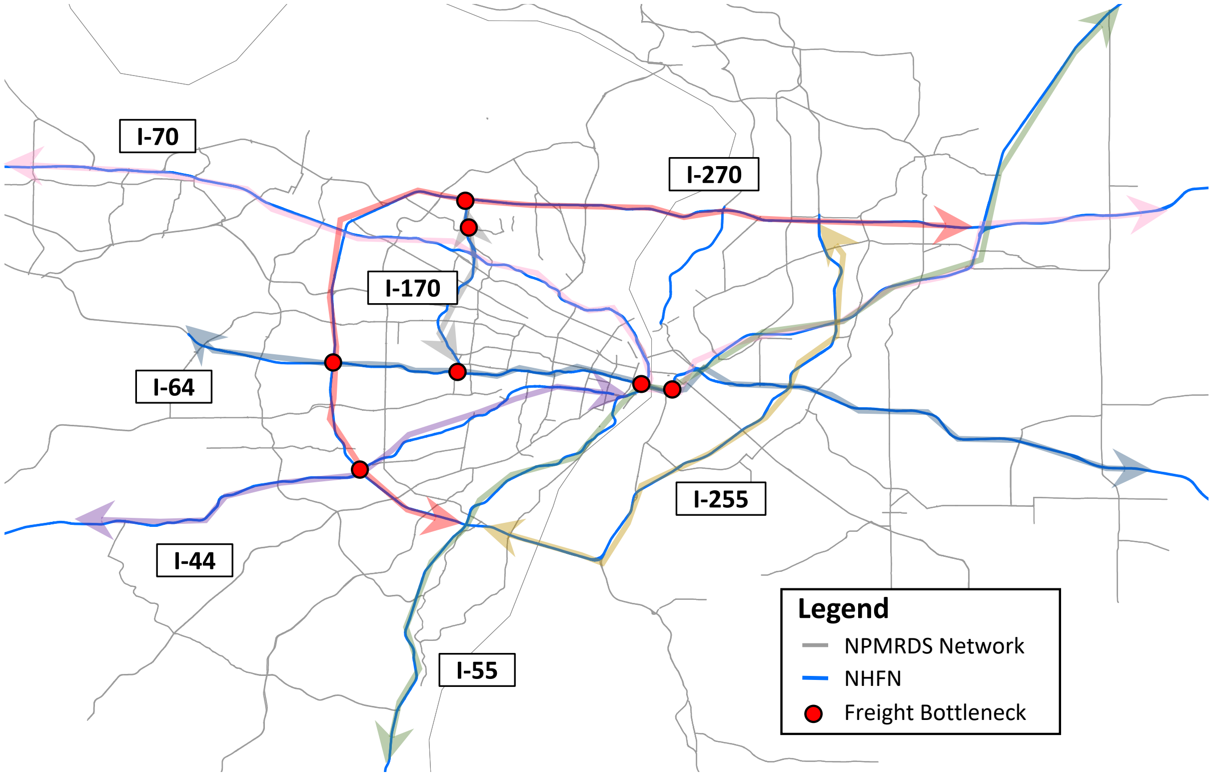


Figure 3-11. Corridors and Locations of Freight Bottlenecks in Area 7 (St. Louis)

Table 3-8. Freight Bottlenecks in Area 7 (St. Louis)

No.	Corridor	Direction	Location	Type	Time	Max Queue (mile)
7-1	I-I70	North	@Airport Rd	Interchange	PM4–5	1.32
7-2	I-I70	South	@I-64	Multiple	AM7–8	0.80
7-3	I-I70	South	@I-64	Multiple	PM4–6	3.20
7-4	I-270	Clockwise	@I-64	Multiple	AM7	8.00
7-5	I-270	Clockwise	@I-170	Multiple	PM4–5	3.05
7-6	I-270	Counterclockwise	@I-64	Multiple	PM4–5	7.90
7-7	I-55	North	@I-64	Multiple	PM3–5	0.90
7-8	I-55	South	@I-70	Multiple	AM7	1.18
7-9	I-64	East	@I-170	Multiple	AM7–8	1.69
7-10	I-64	East	@I-170	Multiple	PM4–5	1.69
7-11	I-64	East	@I-55 & I-70	Multiple	PM 4–5	2.20
7-12	I-64	West	@Hampton Avenue	Multiple	AM7	2.50

7-13	I-64	West	@Hampton Avenue	Multiple	PM4–5	4.32
7-14	I-64	West	@I-55 & I-70	Multiple	AM7	1.58
7-15	I-70	East	@I-55 & I-64	Multiple	PM4–5	1.80

3.3.8 Area 8: Detroit (MI)

Area 8 is Detroit in Michigan. There are five major freight corridors in this area characterized as:

- Mainly running east and west: I-94, I-96, I-696
- Mainly running north and south: I-75, I-275

The sketch of corridors with bottlenecks and a list of bottlenecks with type, activation time and maximum queue length are presented in Figure 3-12 and Table 3-9, respectively.

The most bottlenecks are located near the downtown area at the interchange of highways (bottlenecks 8-4, 8-5, 8-8, 8-9, 8-10, 8-11, 8-13, 8-14, 8-15, 8-16, 8-19, and 8-21). The bottlenecks are activated during morning (AM07–AM08) and/or evening (PM03–PM06) rush hours. I-75 (southbound) with I-696 and I-94 (bottleneck 8-13) and I-94 (westbound) at the upstream of the interchange with I-75 (bottleneck 8-19) have severe congestion in the morning rush hour. On the other hand, the interchange between I-696 and I-96 causes severe congestion in the evening rush hour (bottleneck 8-7).

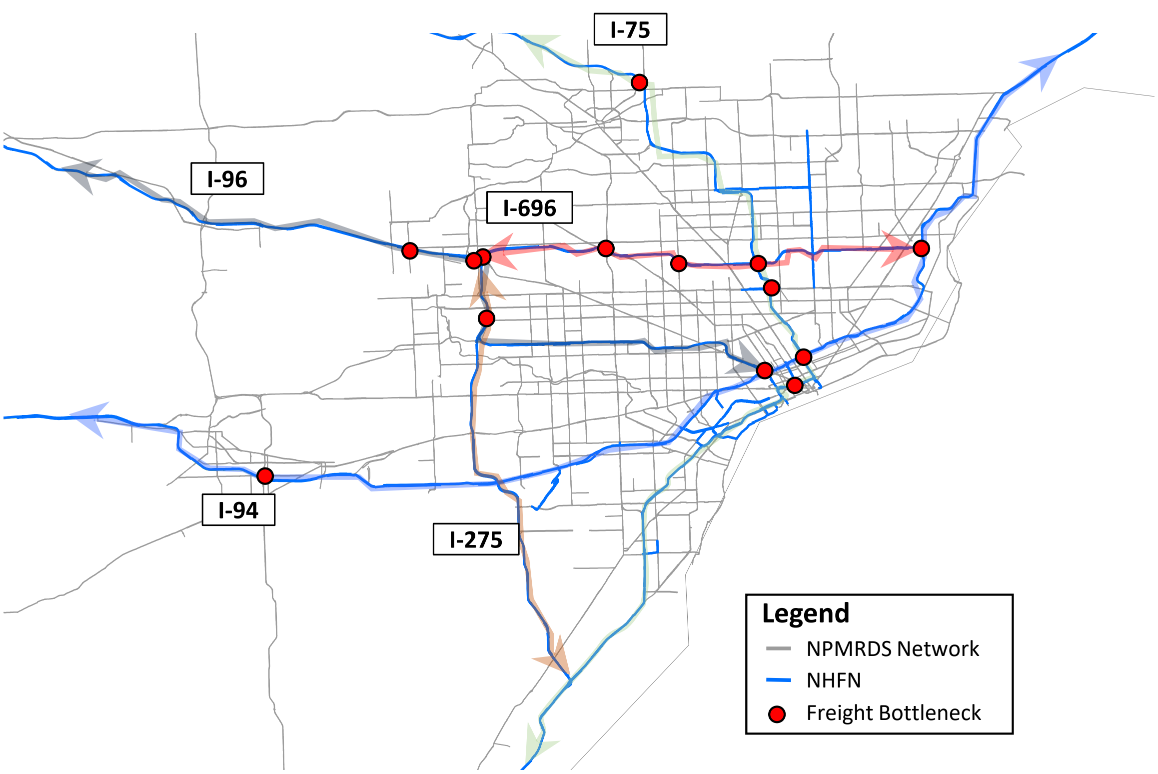


Figure 3-12. Corridors and Locations of Freight Bottlenecks in Area 8 (Detroit)

Table 3-9. Freight Bottlenecks in Area 8 (Detroit)

No.	Corridor	Direction	Location	Type	Time	Max Queue (mile)
8-1	I-275	South	@Six Mile Rd.	Merge	PM5	2.24
8-2	I-696	East	@US-24	Interchange	PM4–5	2.11
8-3	I-696	East	@I-94	Interchange	PM4–5	0.65
8-4	I-696	East	@I-75	Interchange	PM5	0.70
8-5	I-696	West	@I-75	Interchange	AM7–8	1.50
8-6	I-696	West	@Greenfield Rd.	Merge	AM8	5.48
8-7	I-696	West	@I-96	Interchange	PM4–5	8.37
8-8	I-75	North	@MI-10	Interchange	AM7–8	0.80
8-9	I-75	North	@I-696	Interchange	AM8	0.91
8-10	I-75	North	@I-696	Interchange	PM3–6	6.19
8-11	I-75	North	@I-94	Interchange	PM5	0.80
8-12	I-75	North	@MI-24	Interchange	PM6	3.40
8-13	I-75	South	@I-94, MI-102, I-696	Multiple	AM7–8	11.56
8-14	I-75	South	@I-696	Interchange	PM4–5	4.02
8-15	I-94	East	@I-96	Interchange	AM7–8	3.96
8-16	I-94	East	@I-75, I-96	Multiple	PM3–5	7.20
8-17	I-94	East	@US-23	Interchange	PM4–5	1.52
8-18	I-94	East	@I-696	Interchange	PM4–5	2.02
8-19	I-94	West	@I-75, local road	Multiple	AM7–8	8.30
8-20	I-94	West	@US-23	Interchange	AM7–8	1.77
8-21	I-94	West	@I-96	Interchange	PM3–5	1.76
8-22	I-96	East	@Beck Rd.	Merge	AM7–8	5.57
8-23	I-96	East	@I-275	Interchange	PM5	2.24
8-24	I-96	West	@I-696	Interchange	PM4–5	1.47

3.3.9 Area 9: Toledo (OH)

Area 9 is Toledo in Ohio. There are four major freight corridors in this area characterized as:

- Mainly running east and west: I-80/90
- Mainly running north and south: I-75, I-280

- Beltway: I-475

The sketch of corridors with bottlenecks and a list of bottlenecks with type, activation time and maximum queue length are presented in Figure 3-13 and Table 3-10, respectively.

There is one bottleneck according to the criterion of TTI > 1.4, on I-75 (northbound) at the ramp from Washington Street. It is activated in the evening (PM04–PM05) with queue length of less than a mile.

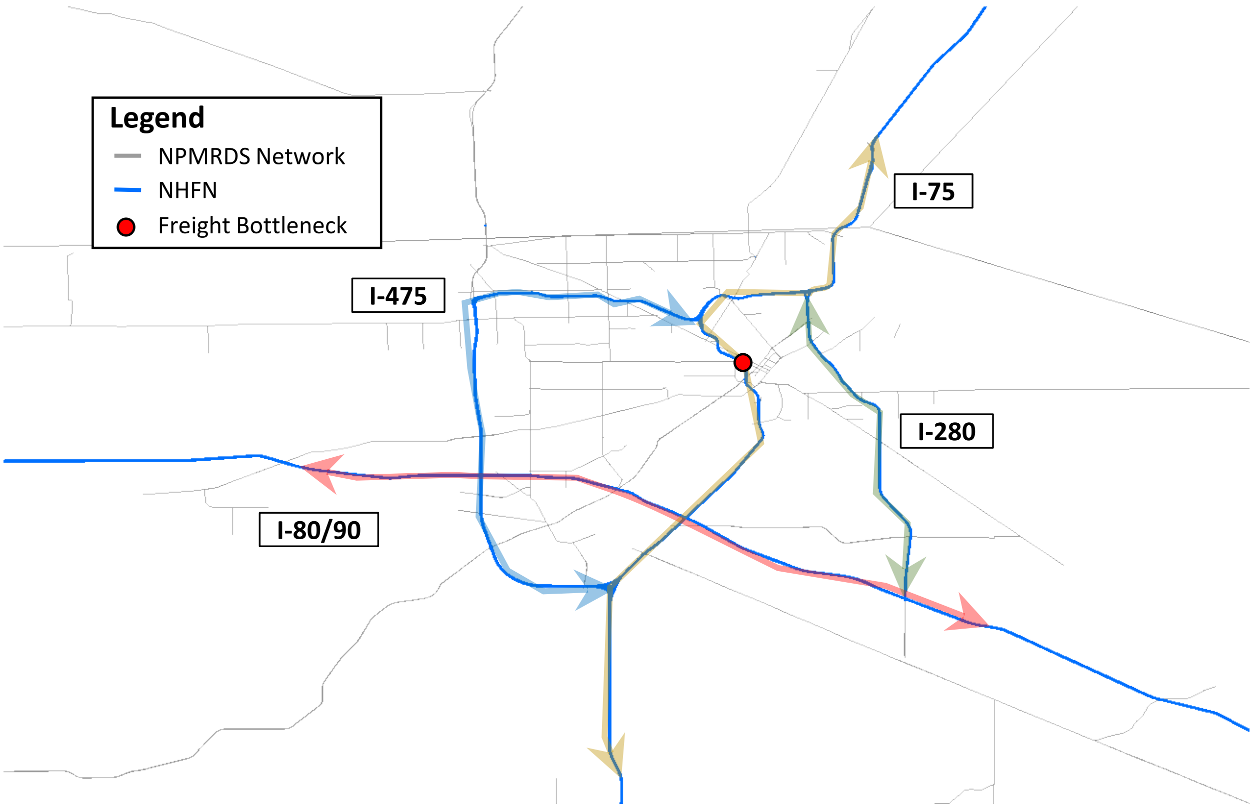


Figure 3-13. Corridors and Locations of Freight Bottlenecks in Area 9 (Toledo)

Table 3-10. Freight Bottlenecks in Area 9 (Toledo)

No.	Corridor	Direction	Location	Type	Time	Max Queue (mile)
9-1	I-75	North	@Washington St.	Merge	PM4–5	0.92

3.3.10 Area 10: Cleveland (OH)

Area 10 is Cleveland in Ohio. There are six major freight corridors in this area characterized as:

- Mainly running east and west: I-80, I-90, I-480

- Mainly running north and south: I-71, I-77, I-271

The sketch of corridors with bottlenecks and a list of bottlenecks with type, activation time, and maximum queue length are presented in Figure 3-14 and Table 3-11, respectively.

The bottlenecks are located near the downtown area at the interchange between highways (bottlenecks 10-10, 10-11, 10-12, 10-13, and 10-14). Other bottlenecks are usually on the I-480 near the interchange with I-271 (bottlenecks 10-5 and 10-7), I-77 (bottlenecks 10-3 and 10-9), and OH-14 (bottlenecks 10-4 and 10-8). The bottlenecks are mostly activated during the morning (AM07–AM08) and/or evening (PM04–PM05) rush hours. The congestions near the downtown area propagate several miles, and the bottleneck between I-271 and I-480 also causes a long-propagated queue (bottlenecks 10-1 and 10-2).

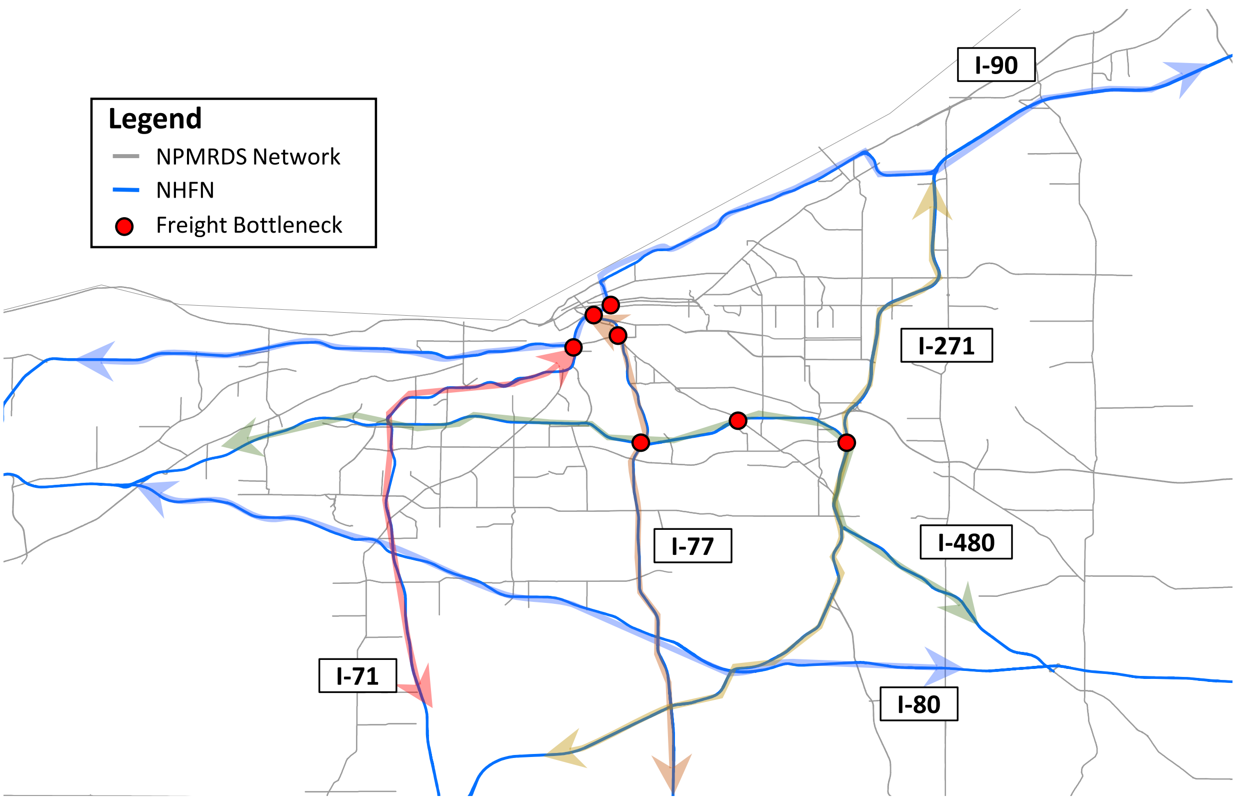


Figure 3-14. Corridors and Locations of Freight Bottlenecks in Area 10 (Cleveland)

Table 3-11. Freight Bottlenecks in Area 10 (Cleveland)

No.	Corridor	Direction	Location	Type	Time	Max Queue (mile)
10-1	I-271	North	@I-480	Interchange	AM7–8	4.19
10-2	I-271	South	@I-480	Interchange	PM4–5	3.60
10-3	I-480	East	@I-77	Interchange	AM7	1.66
10-4	I-480	East	@OH-14	Merge	AM7–8	3.17

10-5	I-480	East	@I-271	Interchange	PM4–5	0.16
10-6	I-480	East	@OH-14	Merge	PM5	1.94
10-7	I-480	West	@I-271	Interchange	AM7–8	1.90
10-8	I-480	West	@OH-14	Merge	PM4–5	1.70
10-9	I-480	West	@I-77	Interchange	PM5	1.47
10-10	I-71	North	@I-90	Interchange	AM6–9	2.56
10-11	I-77	North	@I-90	Interchange	AM7	0.24
10-12	I-77	North	@I-490	Interchange	AM7–8	5.00
10-13	I-90	East	@I-71	Interchange	AM7–8	4.73
10-14	I-90	West	@I-77, US-20	Multiple	PM3–5	3.12

3.3.11 Area 11: Indianapolis (IN)

Area 11 is Indianapolis in Indiana. There are six major freight corridors in this area characterized as:

- Mainly running east and west: I-70, I-74, I-865
- Mainly running north and south: I-65, I-69
- Beltway: I-465

The sketch of corridors with bottlenecks and a list of bottlenecks with type, activation time, and maximum queue length are presented in Figure 3-15 and Table 3-12, respectively.

There are two bottlenecks, with criterion TTI > 1.4, in this area. One is on I-465 (clockwise) at the interchange with I-69, and another is on I-65 (southbound) at the interchange with I-65. Both bottlenecks are activated in the evening rush hour (PM04–PM05) with 4.4 and 1.7 miles of maximum queue length, respectively.

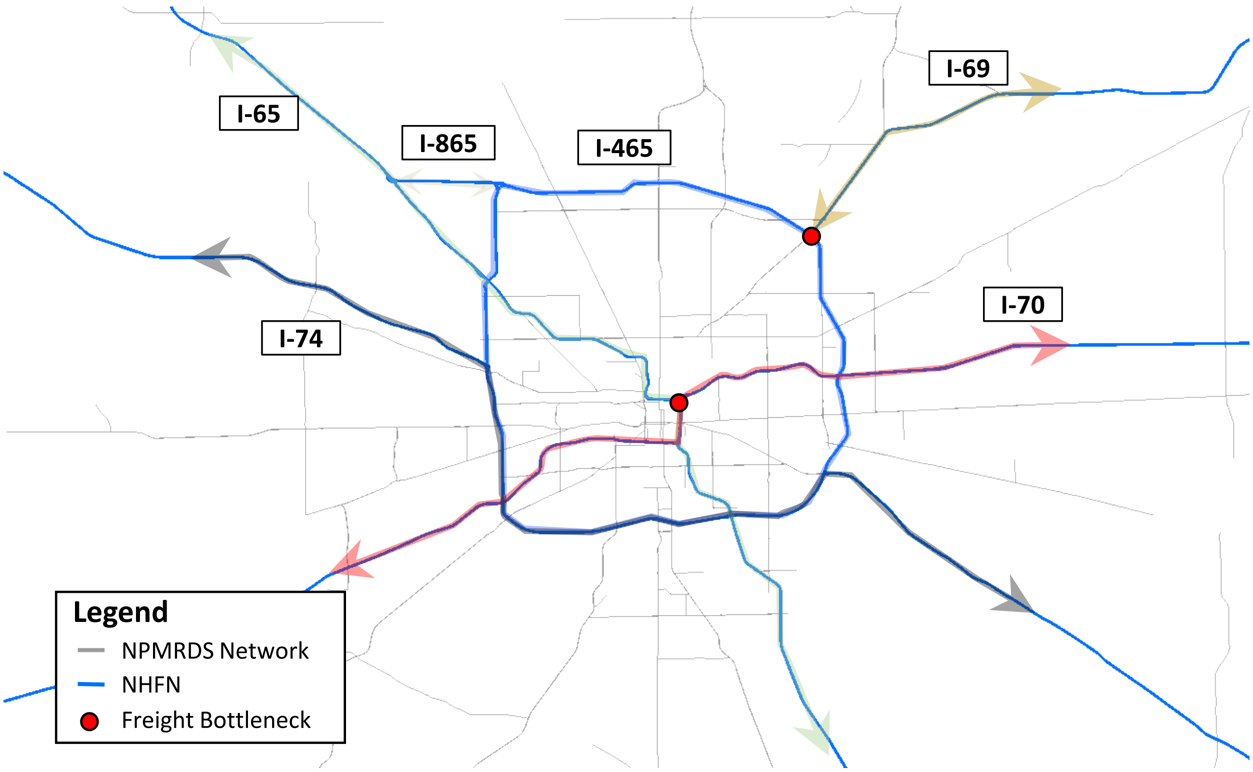


Figure 3-15. Corridors and Locations of Freight Bottleneck in Area 11 (Indianapolis)

Table 3-12. Freight Bottlenecks in Area 11 (Indianapolis)

No.	Corridor	Direction	Location	Type	Time	Max Queue (mile)
11-1	I-465	Clockwise	@I-69	Interchange	PM4–5	4.42
11-2	I-65	South	@I-70	Interchange	PM4–5	1.68

3.3.12 Area 12: Columbus (OH)

Area 12 is Columbus in Ohio. There are four major freight corridors in this area characterized as:

- Mainly running east and west: I-70, I-670
- Mainly running north and south: I-71
- Beltway: I-270

The sketch of corridors with bottlenecks and a list of bottlenecks with type, activation time, and maximum queue length are presented in Figure 3-16 and Table 3-13, respectively.

The bottlenecks are mostly located in the downtown area on the I-70 and I-670, near the interchange with major highways (bottlenecks 12-2, 12-4, 12-5, 12-6, 12-7, 12-11, 12-12, 12-13, 12-14, and 12-16). The interchange between I-70 and I-270 (west side) also causes a bottleneck with several miles of queue length. The bottlenecks are mostly activated during the morning (AM07–AM08) and/or evening (PM04–PM05) rush hours.

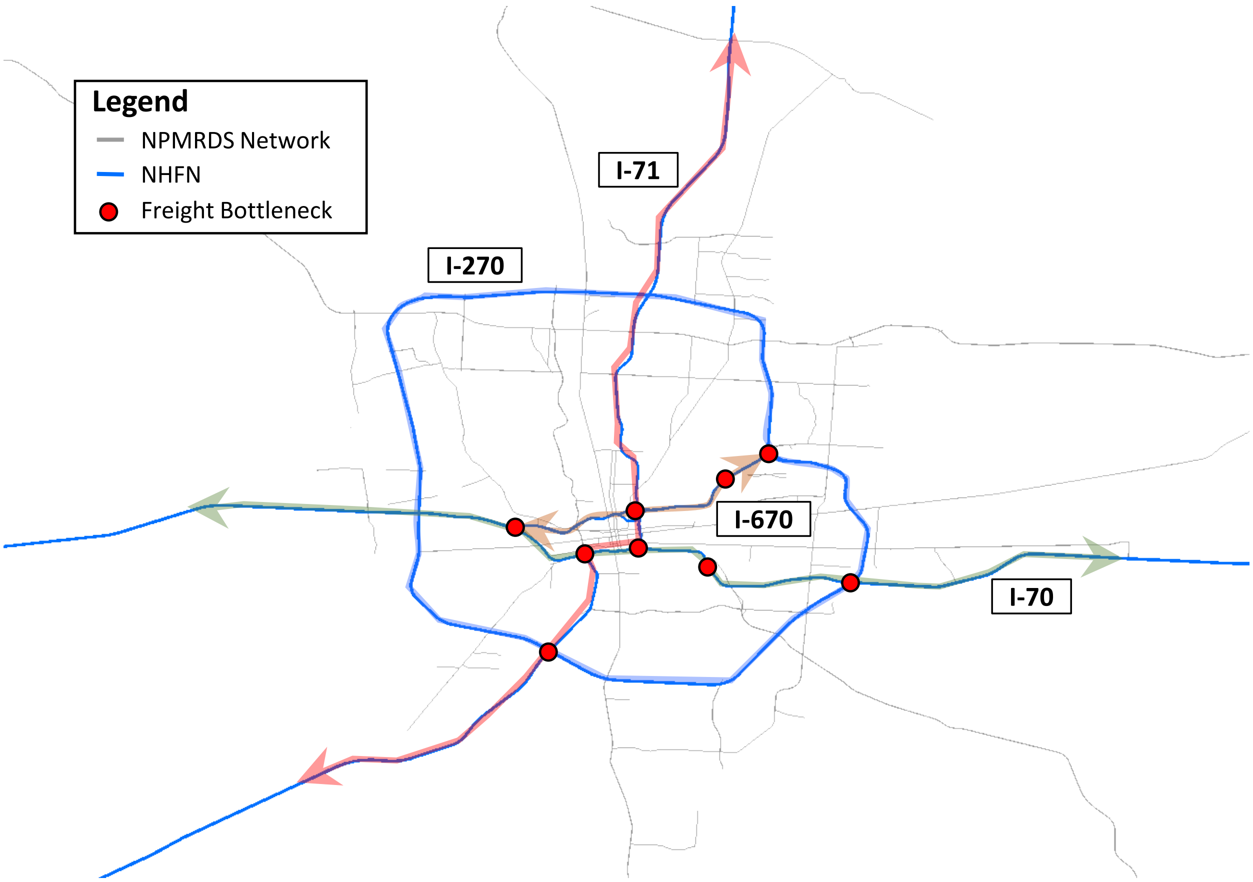


Figure 3-16. Corridors and Locations of Freight Bottlenecks in Area 12 (Columbus)

Table 3-13. Freight Bottlenecks in Area 12 (Columbus)

No.	Corridor	Direction	Location	Type	Time	Max Queue (mile)
12-1	I-270	Clockwise	@I-670	Interchange	AM7	0.03
12-2	I-670	East	@I-270, I-71	Multiple	PM4–5	5.04
12-3	I-670	West	@I-270	Interchange	AM7	0.04
12-4	I-670	West	@I-71	Interchange	AM7–8	0.25
12-5	I-670	West	@I-70	Interchange	PM4–5	2.29
12-6	I-670	West	@I-71	Interchange	PM4–5	0.25
12-7	I-70	East	@I-71	Interchange	PM4	1.21
12-8	I-70	East	@I-270	Interchange	PM4–5	5.56

12-9	I-70	West	@I-270	Interchange	AM7	1.21
12-10	I-70	West	@US-33	Merge	AM7	0.55
12-11	I-70	West	@I-71	Interchange	PM4–5	1.68
12-12	I-71	North	@I-70	Interchange	PM4	1.21
12-13	I-71	North	@I-670	Interchange	PM4–5	2.35
12-14	I-71	South	@I-670	Interchange	PM3–5	0.84
12-15	I-71	South	@I-270	Interchange	PM4–5	2.01
12-16	I-71	South	@I-70, I-70	Multiple	PM4–5	0.87

3.3.13 Area 13: Cincinnati (OH)

Area 13 is Cincinnati in Ohio. There are five major freight corridors in this area characterized as:

- Mainly running east and west: I-74
- Mainly running north and south: I-71, I-75, I-471
- Beltway: I-275

The sketch of corridors with bottlenecks and a list of bottlenecks with type, activation time, and maximum queue length are presented in Figure 3-17 and Table 3-14, respectively.

The bottlenecks are mostly located in the downtown area on the I-71, I-75, and I-471 near the interchange with highways. I-75 and I-71 also have bottlenecks at the interchange with other highways on the east side. The bottlenecks are mostly activated during morning (AM07–AM08) and/or evening (PM04–PM05) rush hours. In the morning rush hour, northbound I-71 and I-75 near the Ohio River have long queue lengths of over five miles (bottlenecks 13-5 and 13-12).

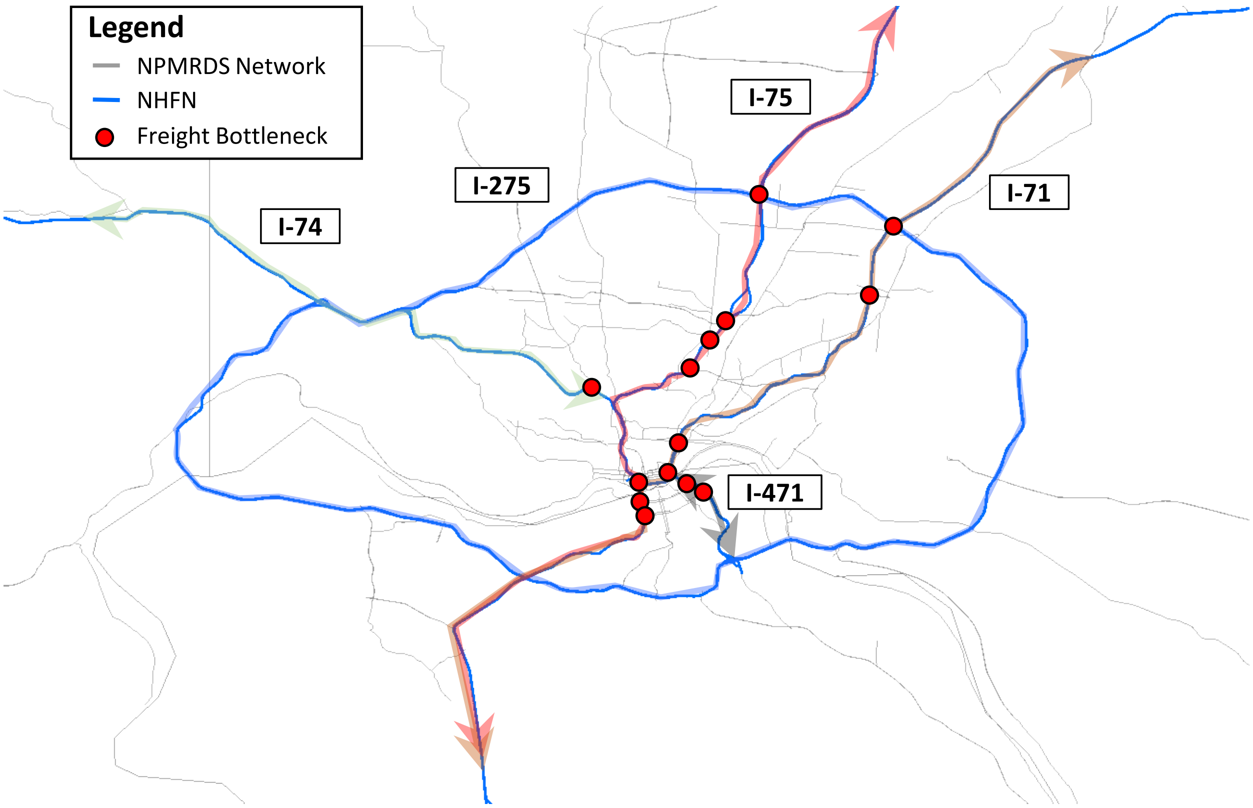


Figure 3-17. Corridors and Locations of Freight Bottlenecks in Area 13 (Cincinnati)

Table 3-14. Freight Bottlenecks in Area 13 (Cincinnati)

No.	Corridor	Direction	Location	Type	Time	Max Queue (mile)
13-1	I-275	Clockwise	@I-71	Interchange	PM5	3.96
13-2	I-275	Counter-clockwise	@I-71	Interchange	PM5	4.02
13-3	I-471	North	@KY-8, KY-1120	Multiple	AM7	2.64
13-4	I-471	South	@KY-8, I-71	Multiple	PM4–5	0.20
13-5	I-71	North	@KY-8, US-25	Multiple	AM7–8	5.86
13-6	I-71	North	@McMillan St.	Merge	PM4–5	4.88
13-7	I-71	South	@OH-126	Merge	AM7	1.61
13-8	I-71	South	@I-75, I-471	Multiple	PM3–6	3.01
13-9	I-71	South	@KY-8	Merge	PM4–5	1.49
13-10	I-71	South	@OH-126	Merge	PM5	1.61
13-11	I-74	East	@US-27	Interchange	AM7	1.30

13-12	I-75	North	@KY-8, US-25	Multiple	AM7–8	5.86
13-13	I-75	North	@I-275	Interchange	PM4–5	2.10
13-14	I-75	North	@Paddock Rd., OH-562	Multiple	PM4–5	4.96
13-15	I-75	South	@I-275	Interchange	AM7	2.60
13-16	I-75	South	@OH-126	Interchange	AM7–8	2.58
13-17	I-75	South	@I-71	Interchange	PM3–6	2.04
13-18	I-75	South	@OH-126	Interchange	PM3–6	3.78
13-19	I-75	South	@KY-8	Merge	PM4–5	1.49

3.3.14 Area 14: Louisville (KY, IN)

Area 14 is Louisville in Kentucky and Indiana. There are five major freight corridors in this area characterized as:

- Mainly running east and west: I-64, I-71
- Mainly running north and south: I-65
- Beltways: I-264, I-265

The sketch of corridors with bottlenecks and a list of bottlenecks with type, activation time, and maximum queue length are presented in Figure 3-18 and Table 3-15, respectively.

The bottlenecks are mostly located in the downtown area on the I-64, I-65, and I-71 near the interchange with major highways and ramps from local roads. The beltways also have bottlenecks at the interchange with I-64, I-65 and I-71. The bottlenecks are mostly activated during morning (AM07–AM08) and/or evening (PM04–PM05) rush hour. In the evening rush hour, some bottlenecks in the downtown area cause long queues of 3–4 miles (bottlenecks 14-2, 14-11 and 14-12), and the interchange between I-71(northbound) and I-265 also causes a 4.1-mile queue (bottleneck 14-16).

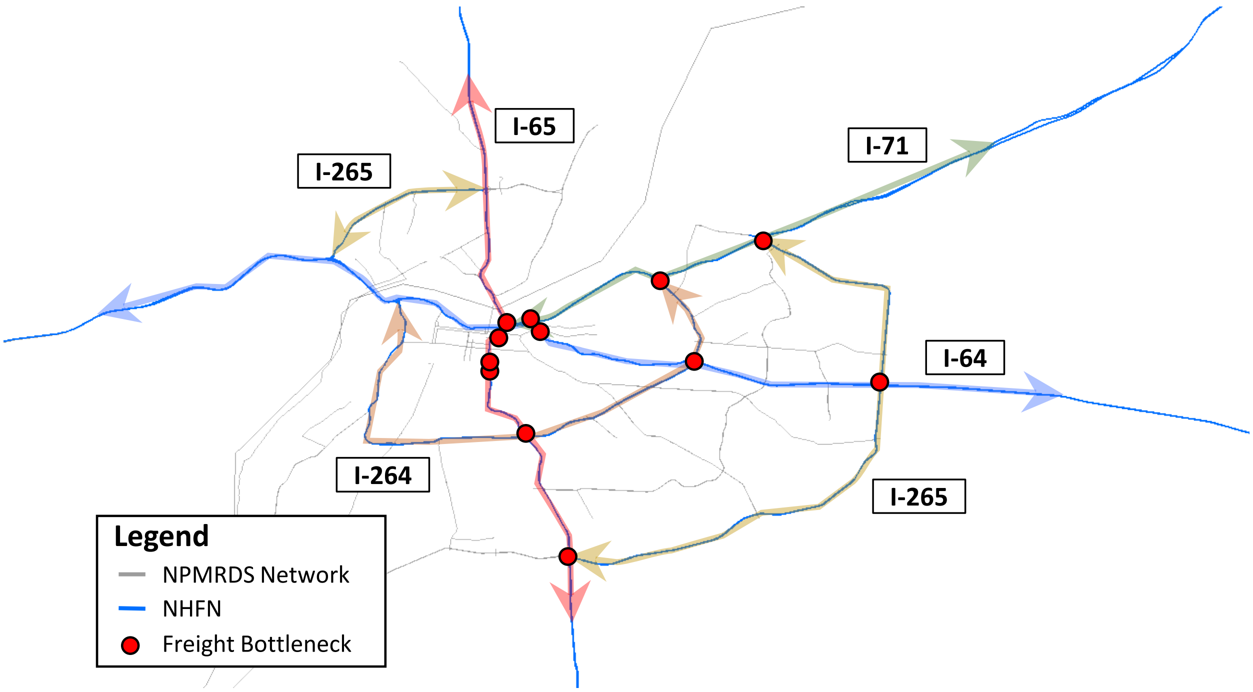


Figure 3-18. Corridors and Locations of Freight Bottlenecks in Area 14 (Louisville)

Table 3-15. Freight Bottlenecks in Area 14 (Louisville)

No.	Corridor	Direction	Location	Type	Time	Max Queue (mile)
14-1	I-264	East	@I-71	Interchange	PM5	1.54
14-2	I-264	West	@I-65	Interchange	PM4–5	3.69
14-3	I-264	West	@I-64	Interchange	PM5	1.27
14-4	I-265	East	@I-71	Interchange	AM7	0.55
14-5	I-265	East	@I-65	Interchange	PM4–5	1.36
14-6	I-265	West	@I-64	Interchange	PM5	1.40
14-7	I-64	East	@I-65	Interchange	PM4–5	1.50
14-8	I-64	East	@I-265	Interchange	PM5	1.73
14-9	I-64	East	@Mellwood Ave	Merge	PM5	0.30
14-10	I-64	West	@I-71	Interchange	AM8	0.80
14-11	I-64	West	@I-71	Interchange	PM3–6	4.39
14-12	I-65	North	@I-64	Interchange	PM3–5	3.45
14-13	I-65	South	@I-64	Interchange	AM7–8	1.99
14-14	I-65	South	@KY-61, Oak St.	Multiple	PM4–5	1.58
14-15	I-65	South	@I-64	Interchange	PM4–5	1.09

14-16	I-71	North	@I-265	Interchange	PM5	4.10
14-17	I-71	South	@I-64	Interchange	AM8	1.92
14-18	I-71	South	@I-64, I-65	Multiple	PM4–5	2.70

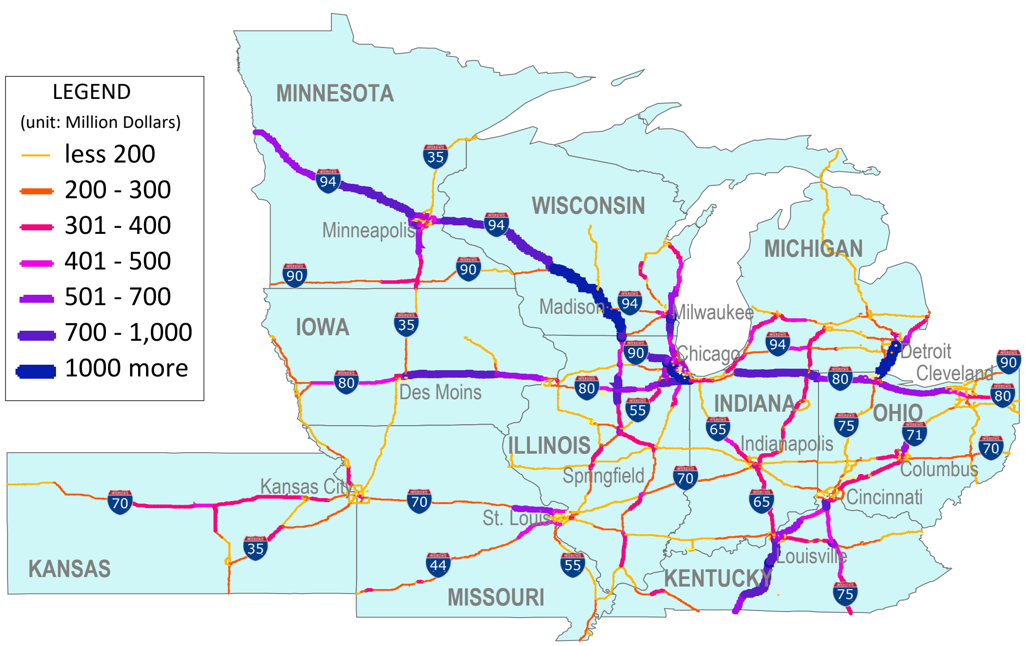
4. ANALYSIS OF MULTISTATE CORRIDORS

4.1. Major Multistate Freight Corridors in MAASTO region

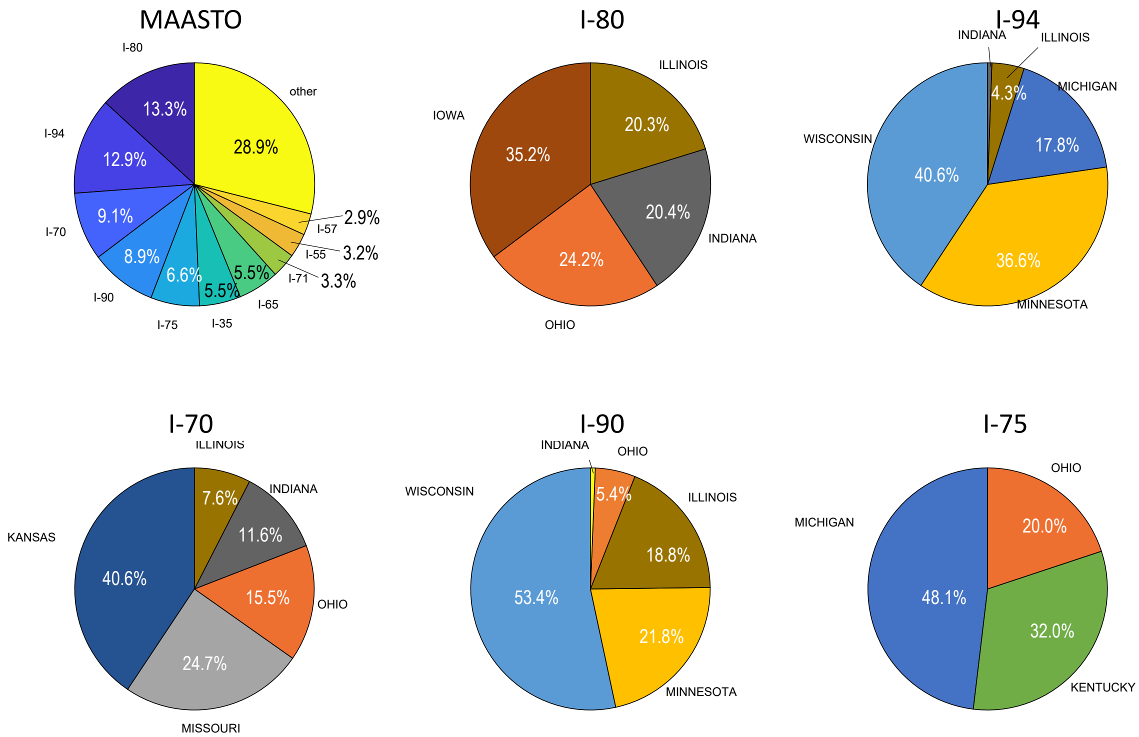
The previous work by MAFC, *Identification and Characterization of the MAASTO Region's Multimodal Freight Network (14)*, identified the major multistate freight corridors in the MAASTO region. Using Freight Analysis Framework (FAF) data, the value of each corridor in the NHFN is determined via the value of freight on the corridors and truck volumes. Figure 4-1(a) shows the GIS map for distribution of corridor value by road section, and Figure 4-1(b) presents the top 10 value corridors (pie chart in the upper-left corner of the figure) with the proportions for each state for the top five value corridors. The bottlenecks in each area described in Section 3 are aggregated into major value corridors. The results show that the corridors below have bottlenecks across multiple states. The detailed list of bottlenecks on multistate corridors are presented in the Appendix.

- I-35, I-55, I-64, I-65, I-70, I-71, I-74, I-75, I-90, and I-94

Interestingly, I-80 is the most valuable corridor in the MAASTO region in terms of economic corridor value as presented in Figure 4-1(b), but it does not have major bottlenecks that meet the criterion of TTI > 1.4.



(a)



(b)

Figure 4-1. (a) Distribution of Road Section Value in the MAASTO Region; (b) The Top Ten Value Corridors in the MAASTO Region with Proportion of States for the Top Five Value Corridors (Adopted from *Identification and Characterization of the MAASTO Region's Multimodal Freight Network (14)*)

4.2. Delay Analysis for Multistate Corridors

This section proposes a method to analyze delays for multistate corridors considering bottleneck activation that cause traffic delay and truck volume to describe relative priorities to be improved.

We assume that a corridor delay is an aggregated result of the road sections' delays. We also assume that a corridor with a larger total delay (across all trucks) should have priority for improvement. With these assumptions, we conduct a delay analysis for multistate corridors in the MAASTO region.

Firstly, using data from NPMRDS, we estimate the delay for each TMC for a given time as:

$$d_{i,c}^{t} = l_{i,c}\left(\frac{1}{v_{i,c}^{r}} - \frac{1}{v_{i,c}^{a}}\right)$$

where, $d_{i,c}^{t}$ is the delay for TMC i ($i = 1 \dots I_c$) of corridor c at time t, I_c is the number of TMCs in corridor c, $l_{i,c}$ is the length of TMC i of corridor c, $v_{i,c}^{r}$ is the reference speed of TMC i of corridor c, and $v_{i,c}^{a}$ is the actual speed of TMC i of corridor c. Then, with the first assumption, the corridor delay is the sum of delays across TMCs. However, this does not reflect the truck-volume impact. Thus, considering the second assumption, we weigh by truck volume, AADTT, to calculate the delay for each TMC as:

$$d_c^t = \frac{\sum_{i=1}^{I_c}\left(AADTT_{i,c} \times d_{i,c}^t\right)}{\sum_{i=1}^{I_c} AADTT_{i,c}}$$

where, $AADTT_{i,c}$ is AADTT for TMC i of corridor c. Then, d_c^t presents AADTT weighted average delay for corridor c per TMC at time t. Note that we calculate the AADTT weighted average delay instead of total delay (in truck-hours) because hourly truck volume data is not available for most locations. Though d_c^t shows a general delay of a corridor, comparing d_c^t for multiple corridors would be unreasonable since the length of TMCs varies by corridor. Thus, we divide d_c^t with the average length of TMC for each corridor to derive AADTT weighted average delay per unit length as:

$$d_{unit,c}^t = d_c^t / l_{TMC,c}$$

where, $l_{TMC,c}$ is an average length of TMC for corridor c. And, finally, using corridor length, l_c, we can derive the AADTT weighted average delay for a corridor as:

$$D_c^t = d_{unit,c} \times l_c$$

where, D_c^t is the AADTT weighted average delay for corridor c at time t. Note that D_c^t presents delay when one truck travels the entire corridor. When it travels only a partial section of corridor, we can change l_c to the length of the travel section to estimate the delay for the travel.

Figure 4-2 shows the $d_{unit,c}^t$ and D_c^t for multistate corridors in the MAASTO region for different times: (a) and (b) for the morning peak (AM06–AM08); (c) and (d) for the evening peak (PM04–PM06); and (e) and (f) for combined morning and evening peaks. For $d_{unit,c}^t$, I-55 has the largest delay for all three cases, and I-65, I-64, I-35 and I-90 follow among the top five corridors of delay. On the other hand, for the corridor delay, I-94 has the largest delay with I-90 and I-75 following in all three cases. Interestingly, I-70 is the fourth corridor in the morning peak, but it goes to the sixth corridor in the afternoon and for the combined peak times. These results present that each corridor has different delay characteristics, and the characteristics are also affected by the time of day.

Note that this method is derived using AADTT due to data limitations, and thus some variations in results are expected, especially when the hourly truck-volume distributions are significantly different for corridors. When truck volumes for certain time intervals are available, a more accurate delay analysis would be feasible.

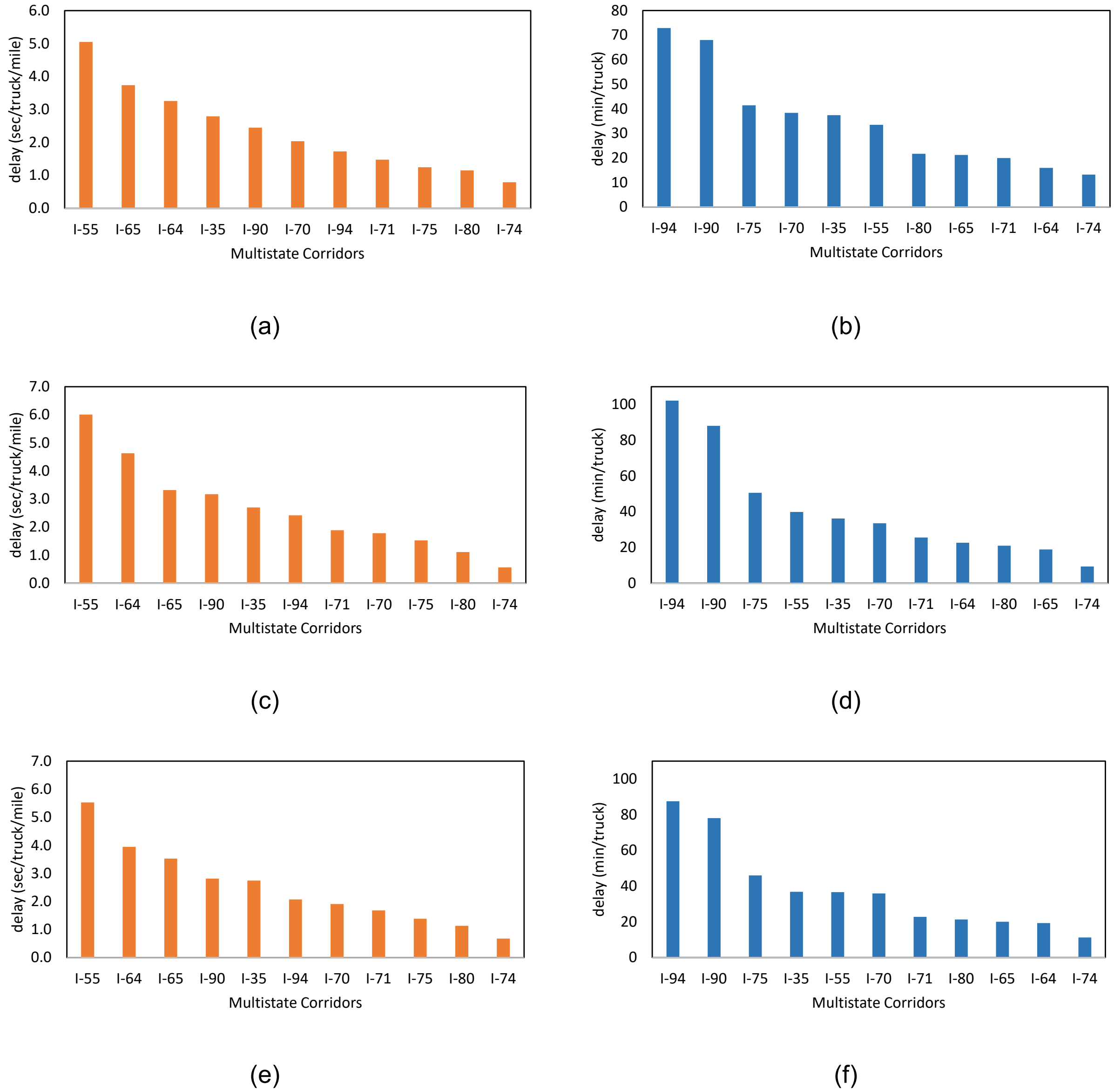


Figure 4-2. (a) Delay for Unit Length in the Morning Peak; (b) Delay for Corridor in the Morning Peak; (c) Delay for Unit Length in the Afternoon Peak; (d) Delay for Corridor in the Afternoon Peak; (e) Delay for Unit Length in Both Peaks; (f) Delay for Corridor in Both Peaks

4.3. Examples of Avoiding Bottlenecks

This section provides examples of avoiding bottlenecks and the benefits. Avoidance can be achieved through both the time (e.g., changing departure time) and space (e.g. selecting another route) domains.

4.3.1. Example 1: Travel Time Difference by Departure Time

The first example is travel from the Twin Cities (MN) to Chicago (IL) via I-94 (eastbound) with about 430 miles of travel length. In this example, we compare the travel time by various departure times to see the impact of bottleneck activation.

Firstly, using NPMRDS, travel times for each TMC are derived, and based on that, total travel time is estimated as the sum of TMC travel times for different departure times. Note that, considering time change over travel, the time window to estimate travel time is also changed. For example, when the sum of travel time for the first 50 TMCs reaches one hour, we move to the next time window (e.g., departure time +1) to estimate travel time for following TMCs. For the reference travel time, we derive the minimum travel time regardless of the time window from the minimum travel time for each TMC. The estimated reference travel time is 402 min. It is assumed that a truck travels without stopping only for illustration purposes. The general analysis framework applies to more realistic scenarios of intermediate stopping.

This travel route passes three major areas: the Twin Cities, Milwaukee, and Chicago, as presented in Figure 4-3. Each area has multiple bottlenecks with different activation times. Specifically, in the Twin Cities, I-94 (eastbound) has bottlenecks near interchanges with I-394 and I-35W, and the activation times of the bottlenecks vary from AM07 to PM06. Another bottleneck activation is also observed near the interchange with I-35E in the evening rush hour (PM03–PM05). In the Milwaukee area, on the other hand, the bottlenecks activate in the morning (AM07–AM08) and evening (PM03–05) rush hours near multiple interchanges and ramps along I-94 (eastbound). I-94 (eastbound) in the Chicago area suffers a long traffic congestion event between US-41 and I-290 during AM06–PM08 with some mitigation during AM10–AM11. Please see the time-space diagram for I-94 (eastbound) in the Appendix for details.

Figure 4-4 shows the estimated travel time (black bar) and delay as compared to the reference time (red line) for each departure time. Clearly, the delays vary between 8 minutes (2.0% of the reference time) to 36 minutes (9.0% of the reference time). The results show that, depending on the departure time, traffic would encounter congestion from bottlenecks or pass certain areas without suffering from congestion. For example, when trucks depart at AM05, they pass the Milwaukee and Chicago areas around AM10 and AM11, respectively, and do not suffer serious traffic congestion events. On the other hand, trucks that depart at PM12 will suffer significant traffic congestion in the Milwaukee area at PM05 and encounter a long traffic queue in the Chicago area during the PM06–PM07 timeframe, which increases the travel time. Thus, this example shows that traffic congestion from bottlenecks can be avoided through proper travel time planning.

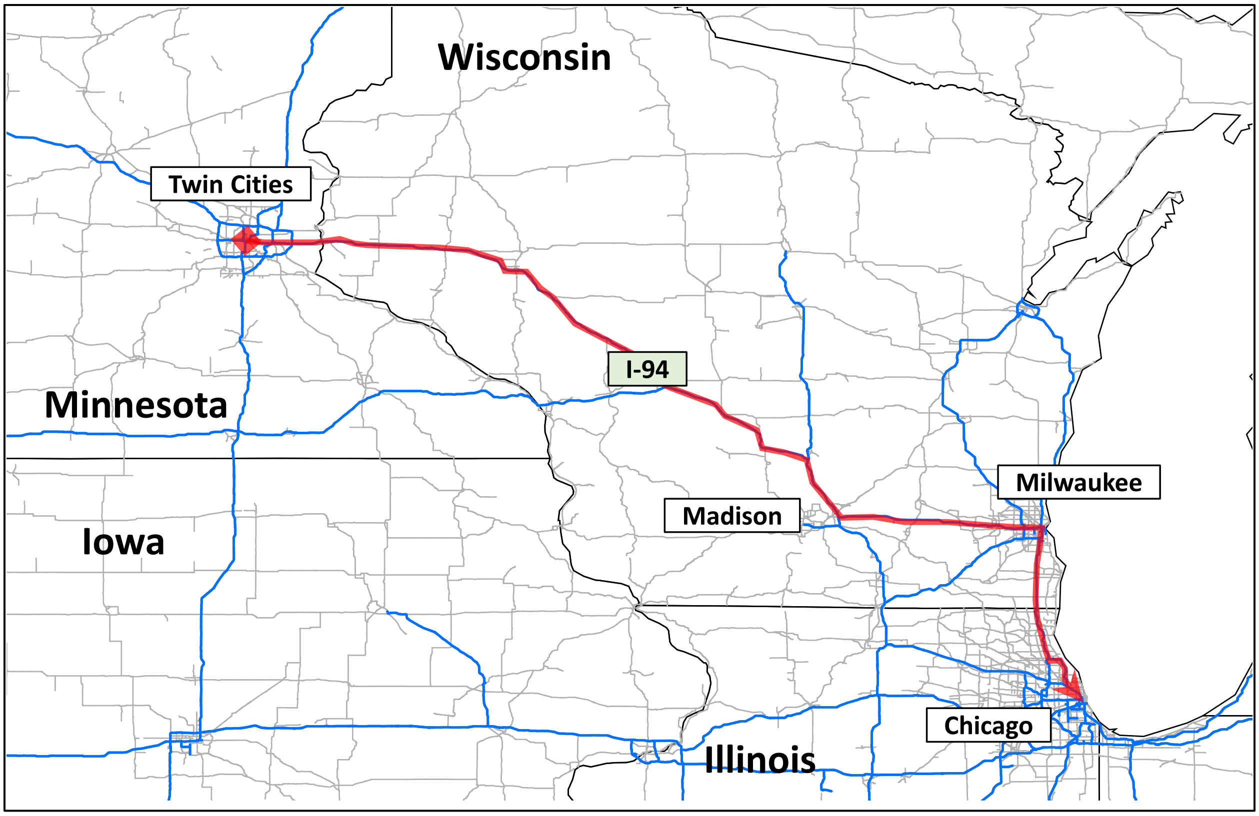


Figure 4-3. Travel Route for Example 1

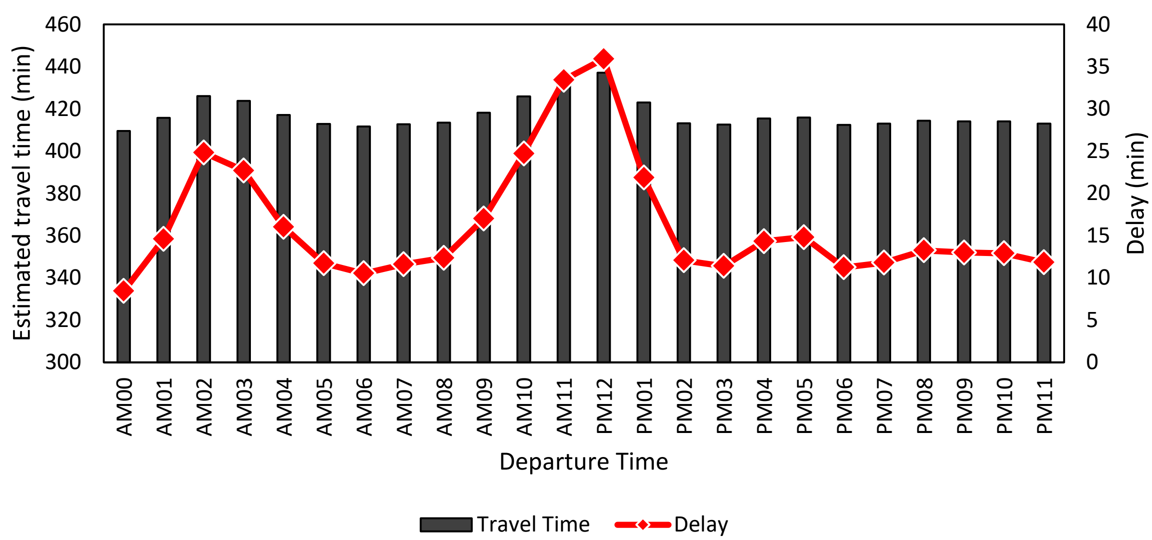


Figure 4-4. Estimated Travel Time and Delay to Reference Time for Each Departure Time of Example 1

4.3.2. Example 2: Route Choice Considering Bottleneck Activation

The second example presents the effect of route choice considering various bottleneck activation times. The travel is from Madison (WI) to O'Hare airport (IL), and there are two travel routes, I-90 and I-94/I-294, as presented in Figure 4-5. The route of I-90 (130 miles) is a little shorter than I-94/I-294 route (135 miles). Using the same method as in Example 1, the travel times for each route with different departure times are estimated. Figure 4-6 shows the travel time for I-90 (green bars at left) and I-94 (red bars at right), and the travel time difference between the two routes (blue line with diamond marker). The travel times using I-90 are smaller in most time windows, but the I-94 route is faster in the morning (e.g., departure at AM05–AM06). This result comes from avoiding congestion on I-90 near the interchange with I-290 in the morning. On the other hand, the I-94 route has more travel time, up to 4.5 minutes, in the afternoon (e.g., departure at PM04–PM06) due to the bottleneck activation both in the Milwaukee area and at I-294. This example shows that avoiding bottleneck activation is feasible through route choice that also takes into consideration the departure (or travel) time.

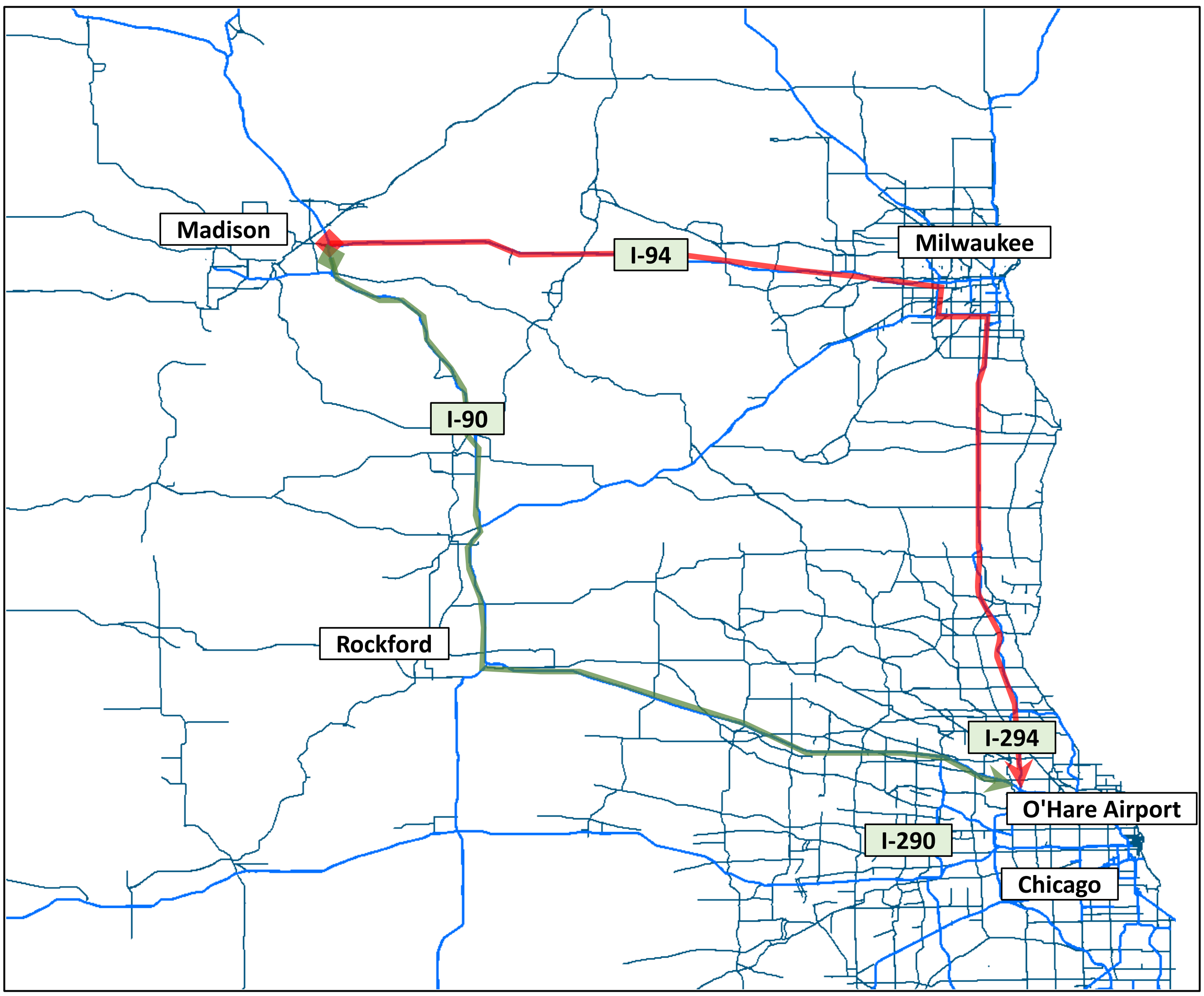


Figure 4-5. Travel Route for Example 2

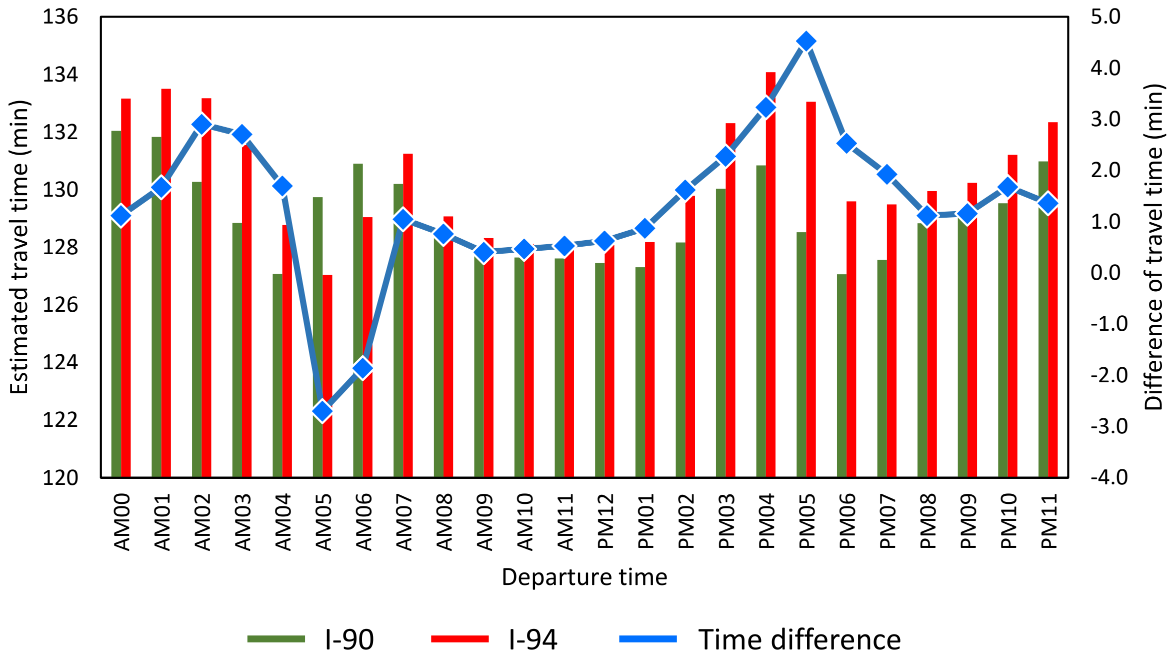


Figure 4-6. Estimated Travel Times for Two Routes and Travel Time Differences for Example 2

5. MARINE BOTTLENECK IDENTIFICATION

This section describes the methodology to identify marine highway bottlenecks in the MAASTO region. Section 5.1 defines the marine highway network under this study and describes the data used for the analysis. Section 5.2 depicts the methodology adopted to characterize the bottlenecks. Finally, Section 5.3 presents the findings and locations of the bottlenecks.

5.1. Network and Data

5.1.1. Marine Highway Network

The marine highway network under this study in the MAASTO region is shown in Figure 5-1. Essentially, in the region, five major marine corridors are present: M-35, M-55, M-70, M-29, and M-90. These corridors connect the waterways of the Mississippi, Missouri, Ohio, and Illinois rivers. Specifically, M-35 connects the Upper Mississippi River with M-55, which extends from the Gulf of Mexico to the Illinois River. M-70 and M-29 extend across the 10 states connecting the Ohio, Mississippi, and Missouri rivers. M-90 connects the Great Lakes to the East Coast.

Locks and dams, present across every corridor, are considered for this study. Throughout the waterway network, 59 locks and dams are identified and studied. There are 22 locks and dams present in the combined M-70 and M-29 corridors, and there are 26 locks and dams in M-35, 11 in M-55, and four in M-90.

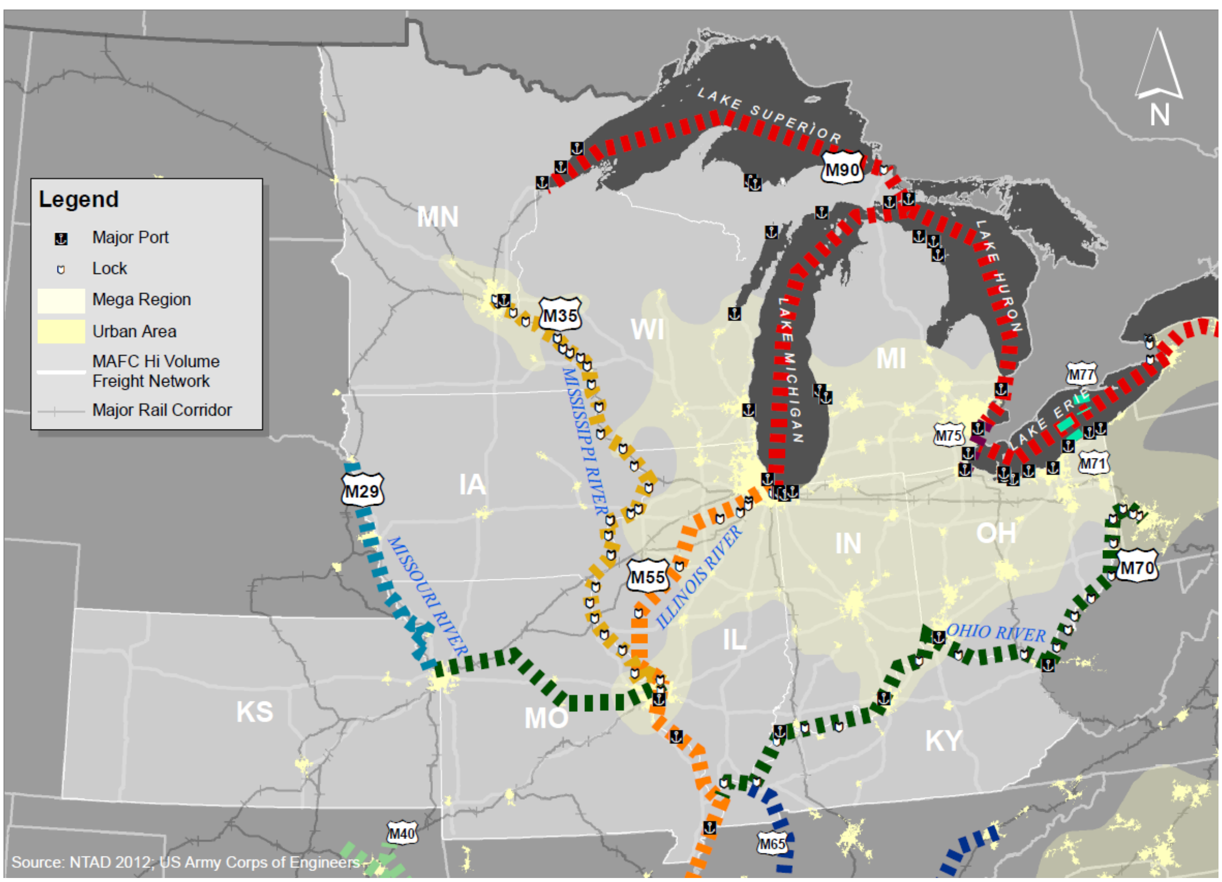


Figure 5-1. Marine Corridors in the MAASTO Region

5.1.2. Data

The data used to characterize marine highway bottlenecks is taken from the US Army Corps of Engineers (USACE) – Lock Performance and Monitoring System (LPMS). The data published by LPMS is an archived database of data from 1993 to 2016 collected from all locks and dams operated by the Corps. The data includes information on the total number of vessels and barges locked, vessel type, size and date of lockage, commodity carried, and tonnage, along with the duration of unavailability *(17)*. This data is typically used to analyze the performance and characteristics of locks and dams. Performance is associated with delay, operations, availability, and the number of vessels processed, while assessing the type and tonnage of commodities processed provides the lock and dam characteristics that help determine their economic value.

For this study, the data of significance are: vessel traffic, number of tows and barges, average delay time of tows, chambers, unavailable timings, and a list of locks and dams of every waterway. Data used for this study comes from the latest version of summary sheets reported by the USACE in 2016 (January – December) and sorted by lock and dam for every waterway.

The data was processed and compiled for the marine highway corridors under this study and reported as shown in Table 5-1.

Table 5-1. Example of Compiled Data for Marine Corridors

M-35								
Location	Total Lockages	Tows		Average Delay (hrs.)		Total Delay (hrs.)	Scheduled Unavailable Time (hrs.)	Unscheduled Unavailable Time (hrs.)
		All	Delayed	All Tows	Delayed Tows			
Lock and Dam 2	3394.00	1597.00	1283.00	1.08	0.96	1335.15	2354.92	8.60
Lock and Dam 3	4891.00	1558.00	1328.00	1.31	0.98	1489.05	2280.00	0.00
Lock and Dam 4	3826.00	1496.00	785.00	1.00	1.39	1101.00	1920.00	53.20

The definitions of terms used in the above data example are adopted from USACE *(18)*:

- Lockages: The movement through a lock of either vessel(s) or extraneous matter such as debris, manatees, etc. Each lockage has a unique ID.
- Tow: A towboat with a barge or barges.
- Average Delay of All Tows: The average delay time, expressed in hours, for all tows which passed through a lock chamber.

5.2. Methodology

Identification of bottlenecks in marine highways is limited to assessing the areas of obstruction to the flow of vessels; otherwise vessels travel freely with optimal speed. When it comes to marine highways, obstruction is dominated by locks and dams where vessels are forced to stop for some time and undergo some process, whether it be lockage, loading, unloading, or inspection. Thus, this stoppage contributes to delay experienced by vessels traversing the waterway.

Consequently, to identify the locations of bottlenecks along the marine highway networks in the MAASTO region, we first considered the five major marine corridors: M-70, M-29, M-90, M-55, and M-35. Locks and dams across every corridor were identified to obtain the delay experienced at every lock and dam. Then, US Army Corps of Engineers data was used to extract the average delay experienced by tows and unavailability timings. Towing is associated with vessels carrying barges, thus reflecting freight delay experienced at locks and dams. The average delay of all tows was calculated, and bottlenecks were characterized as the location where the average delay of all tows exceeded 1.5 hours. In addition, a survey was done to obtain the causes of delay at each lock and dam.

It is worthwhile to note here some limitations on the availability of data pertaining to bottleneck characteristics. For instance, as discussed in Section 1, bottlenecks in marine highways can be attributed to weather conditions, operational mechanisms, and traffic congestion. There is significant variability in the causes of delay at locks and dams. Thus, fully characterizing a bottleneck would require a complete understanding of infrastructure conditions, weather variability, geometric features, and the causes of vessel delay. However, the data available from USACE provides the average delay experienced by all tows traversing the lock with no information on the cause of such delay (whether it is attributed to operational failure, unexpected high water levels, etc.). Although an aggregate statistic on the total scheduled/unscheduled unavailability timing is presented in the data, it fails to provide sufficient information to perfectly characterize the bottleneck and attribute a specific cause behind a vessel's delay.

Thus, deciding on a criterion for identifying bottlenecks is challenging, as average delay is a relative value imbedding a lot of variability. Bearing this in mind, we found that an average delay of 1.5 hours as a threshold is reasonable.

5.3. Results

Based on the criterion above, two types of delays are identified: Congestion and Operational. Congestion refers to the average delay of all tows above 1.5 hours with insignificant unscheduled unavailable timing. In such cases, delay could be attributed to high vessel traffic through the lock. Operational delay reflects conditions where average delay is above 1.5 hours yet there is a significant unscheduled unavailable timing. This reflects that a sudden closure or failure in operation is contributing to the delay experienced. Table 5-2 presents a list of bottlenecks identified in this study, along with their location and average delay.

Table 5-2. Marine Highway Bottlenecks Identified[1]

Marine Highway	BN No.	Lockage\ Dam Name	Chamber	River\ Waterway	District	Delay Type	Average Delay of All Tows (hours)
M-70 & M-29	1.1	Emsworth Lock and Dam	2	Ohio	Pittsburgh	Operational	3.18
M-70 & M-29	1.2	Montgomery Lock and Dam	1	Ohio	Pittsburgh	Operational	1.74
M-70 & M-29	1.3	Montgomery Lock and Dam	4	Ohio	Pittsburgh	Operational	8.55
M-70 & M-29	1.4	Greenup Locks and Dams	4	Ohio	Huntington	Congestion	2.09
M-70 & M-29	1.5	Robert C Byrd	2	Ohio	Huntington	Congestion	1.72
M-70 & M-29	1.6	Lock and Dam 52	1	Ohio	Louisville	Congestion	4.16
M-70 & M-29	1.7	Lock and Dam 52	`5	Ohio	Louisville	Congestion	3.01
M-70 & M-29	1.8	Lock and Dam 53	1	Ohio	Louisville	Congestion	3.38
M-35	2.1	Lock and Dam 8	1	Mississippi	St. Paul	Congestion	1.81
M-35	2.2	Lock and Dam 14	1	Mississippi	Rock Island	Congestion	2.50
M-35	2.3	Lock and Dam 15	1	Mississippi	Rock Island	Congestion	2.26
M-35	2.4	Lock and Dam 16	1	Mississippi	Rock Island	Congestion	2.10

[1] While Emsworth and Montgomery Lock and Dam are located just outside the MAASTO region, they were added for proximity and system impacts

M-35	2.5	Lock and Dam 17	1	Mississippi	Rock Island	Congestion	2.34
M-35	2.6	Lock and Dam 18	1	Mississippi	Rock Island	Congestion	1.65
M-35	2.7	Lock and Dam 20	1	Mississippi	Rock Island	Congestion	2.98
M-35	2.8	Lock and Dam 21	1	Mississippi	Rock Island	Congestion	1.69
M-35	2.9	Lock and Dam 22	1	Mississippi	Rock Island	Congestion	3.90
M-35	2.10	Lock and Dam 24	1	Mississippi	St. Louis	Congestion	2.73
M-35	2.11	Lock and Dam 25	1	Mississippi	St. Louis	Congestion	3.66
[2]***M-35 & M-55 & M-70**	3.1	Chain of Rocks Lock and Dam 27	1	Mississippi	St. Louis	Congestion	2.52
***M-35 & M-55 & M-70**	3.2	Chain of Rocks Lock and Dam 27	4	Mississippi	St. Louis	Congestion	1.77
***M-35 & M-55 & M-70**	3.3	Mel Price	1	Mississippi	St. Louis	Congestion	2.39
M-55	4.1	Marseilles Lock and Dam	1	Illinois Waterway	Rock Island	Congestion	3.52
M-55	4.2	Starved Lock and Dam	1	Illinois Waterway	Rock Island	Congestion	2.32
M-55	4.3	LaGrange Lock and Dam	1	Illinois Waterway	Rock Island	Congestion	1.65

[2] *Chain of Rocks and Mel Price locks are considered part of M-35, M-55, and M-70 highways as they are located in the St. Louis area (an intersection of the three marine highways)

The results indicate that, in total, 22 bottlenecks exist in the marine highway network according to our criterion. Specifically, the M-35 corridor currently endures the highest number of bottlenecks with 13 total bottlenecks. There are eight bottlenecks in the M-70/M-29 corridor and five bottlenecks in M-55, while no bottlenecks were found in the M-90 (Great Lakes) corridor. Figure 5-2 represents the share of bottlenecks within the major corridors.

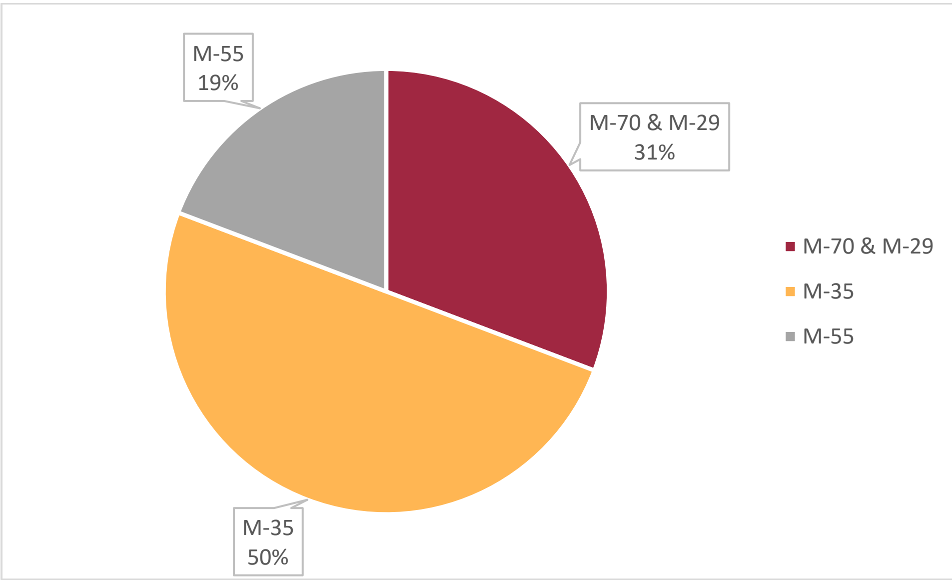


Figure 5-2. Distribution of Bottlenecks Along Marine Corridors

Yet, if we consider total hours of delay experienced in all five corridors, we notice that M-70/M-29 experiences the highest overall delay, attributable to delays at Locks and Dams 52 and 53. Figure 5-3 shows the total delay experienced in each corridor, while Figure 5-4 and Figure 5-5 present the total and average delay, respectively.

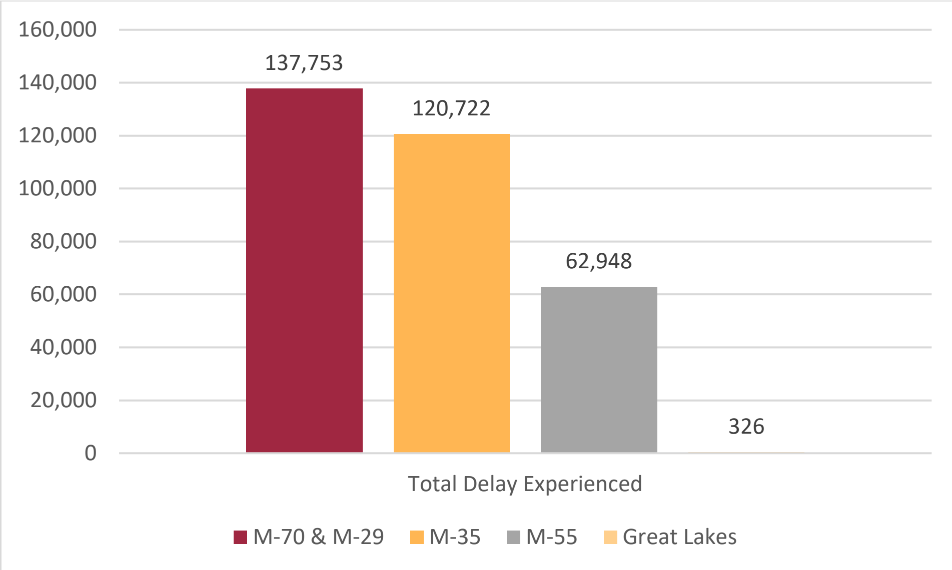


Figure 5-3. Total Delay Experienced in Marine Corridors

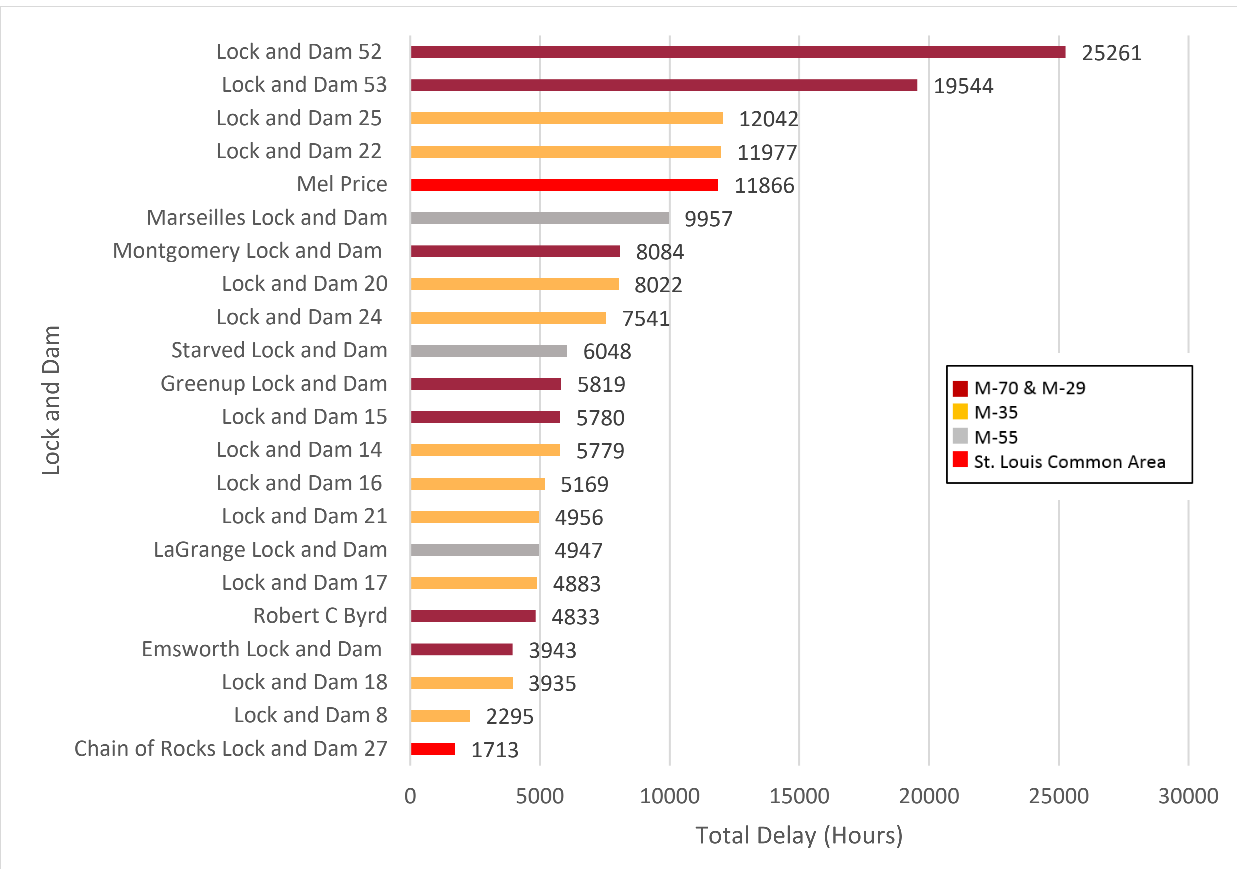


Figure 5-4. Total Delay at Locks and Dams with Bottleneck

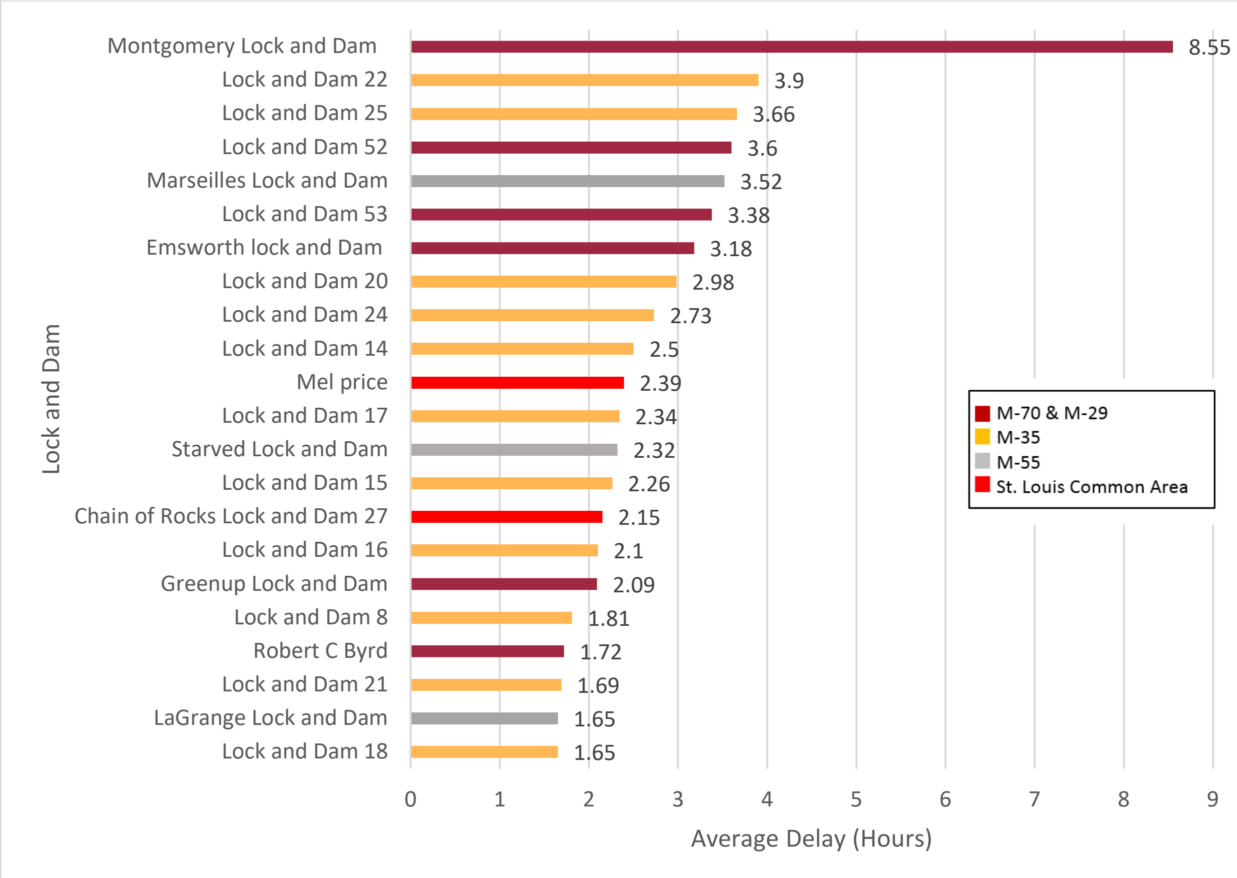


Figure 5-5. Average Delay for Locks and Dams with Bottleneck

As expressed before, delays at locks and dams can be attributed to variabilities in infrastructure, operation, and weather conditions, thus high delay might not indicate high congestion. Figure 5-6 shows that a significant percentage of unavailability timing is attributed to unscheduled unavailability, meaning a sudden break in operation (maintenance/repair, mechanical malfunctions, etc.) or unexpected weather conditions (water levels, storms, etc.) is adding to the delay of vessels at the bottleneck locations.

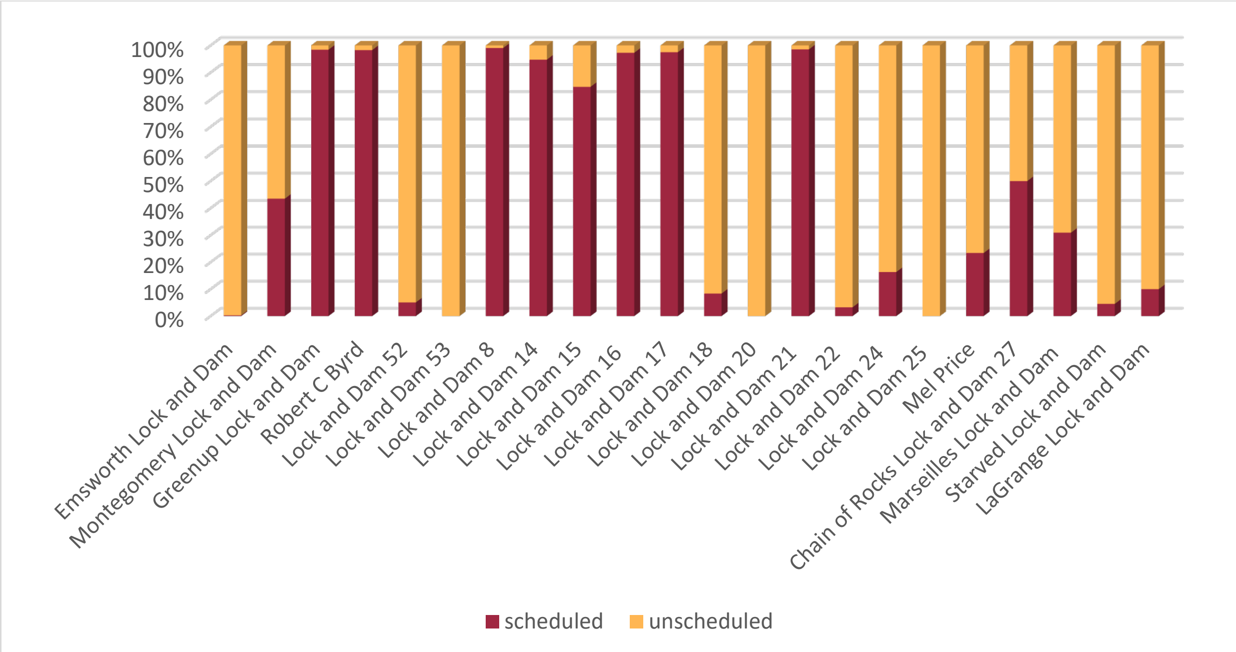


Figure 5-6. Scheduled vs. Unscheduled Unavailable Timing

6. EFFORTS FOR FREIGHT BOTTLENECKS MITIGATION

This section provides currently used and planned efforts to mitigate freight bottlenecks on roadways. The presented methods include roadway improvement, traffic control strategies (e.g., ramp metering, and variable speed limit), and providing real-time traffic information. This section also provides examples for each method collected from state DOTs and through state-by-state searches of projects and studies. There are other potential solutions to address freight bottlenecks such as traffic demand management, congestion pricing or truck-lane dedication that are not presented in this report. Note that there is no simple process to decide the “best” practice, but recent research *(19)* proposes to consider the following factors when selecting a solution:

- The causes of the delays
- The geographic and geometric attributes of that location
- The operational characteristics of the roadway
- The organization of the agencies working on that facility and other facilities that influence the operation of that roadway
- The operational systems currently implemented on the road
- The type of funding available

6.1. Highway Improvement

Highway improvement projects could help address freight bottlenecks by increasing road capacity and/or removing geometric restrictions. This method includes road expansions, adding travel lanes, interchange improvements, or building a new roadway to increase road capacity to better meet high demand. Though significant improvement is expected through these efforts, issues such as funding availability, environmental impact, or social agreement can pose significant challenges to this approach.

Example: Clear Path 465 in Indiana DOT

The Clear Path 465 project aims to address insufficient capacity near the interchange between I-465 and I-69 on the northeast side of Indianapolis, Indiana. Note that this interchange is presented as a major freight bottleneck, number 11-2 in Section 3.3.11. Figure 6-1 shows the location and overview of this project. There are several reasons for this project, including (i) insufficient mainline capacity of I-465 and I-69, (ii) undesirable movement on the ramp with long queues, and (iii) frequent incidents from weaving movements (over 1,100 crashes between 2011–2013). This project plans to add travel lanes on I-465 and to modify the interchange between I-465 and I-69. The purpose of this project is to improve traffic operations by increasing road capacity and to improve safety to reduce incidents. The detailed contents and progress are presented on the Indiana DOT website (https://www.in.gov/indot/3654.htm).

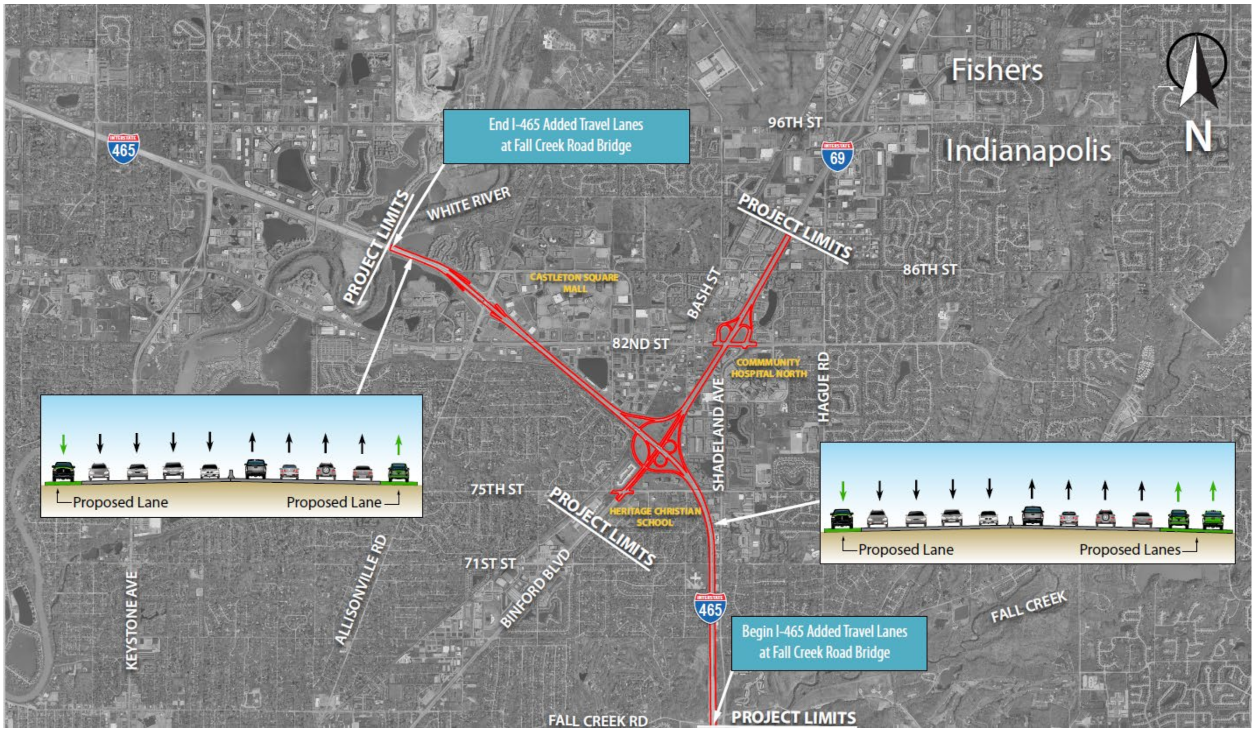


Figure 6-1. Overview of the Clear Path 465 Project

6.2. Ramp Metering

Ramp metering is a popular freeway control method that regulates the number of vehicles entering (or leaving) the freeway, thereby achieving better freeway operation. Ramp metering control is usually applied with traffic signals that are installed on highway on-ramps to control vehicle entry. Many studies and real-world applications demonstrate the benefits of ramp metering, such as reducing congestion, increasing throughput, achieving reliable travel times, and reducing collisions on the highway *(20)*. As presented in Figure 6-2, many large cities in the US have adopted this ramp metering method to mitigate the bottlenecks caused by ramps. In this research, we found merge ramps to be one of the most significant causes of freight bottlenecks. Additionally, advanced ramp metering algorithms, using real-time information and coordinated with the highway network, have been widely adopted recently *(20)* and demonstrate increased benefits.

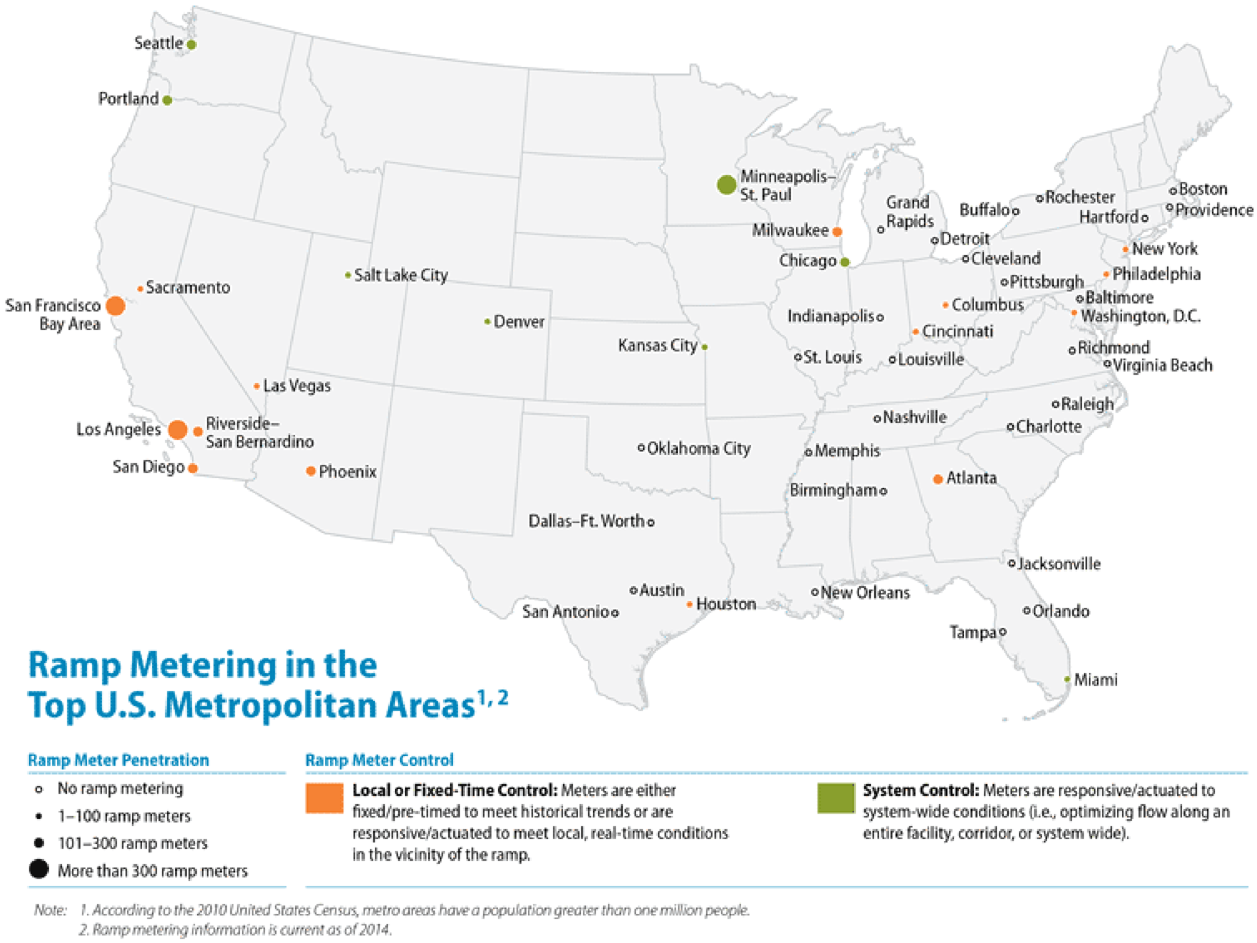


Figure 6-2. Ramp Metering in the Top US Metropolitan Areas (adopted from *(20)*)

6.3. Variable Speed Limit

The ramp metering in Section 6.2 is an effective method, but it also has limitations. For example, ramp metering provides little benefit when the mainline demand is high, and thus the required metering rate is very small *(21)*. Additionally, ramp metering can cause queues on metered ramps that can become excessively long and spill over to adjacent arterial roads. Alternatively, the method of variable speed limit (VSL) is designed to control mainline flow by actively changing the speed limit in response to traffic congestion, incidents, or weather conditions. The purpose of VSL is to decrease flow rate with low travel speed, and thus prevent the activation of bottlenecks in advance and/or resolve current traffic congestion faster. VSL control also provides a more homogenous travel speed between vehicles, which can reduce stop-and-go traffic and thereby reduce the probability of traffic incidents. VSL has been applied in Europe since the 1960s, and this method is also applied in several states in the US including Washington, New Jersey, Florida, and Georgia. In this research, we found that the most significant causes of freight bottlenecks are interchanges between highways, a situation where ramp metering is not an ideal solution. Thus, VSL could be a promising solution to address bottlenecks near interchanges. Note that integrative control strategies of both VSL and ramp metering are also developed to maximize bottleneck operations *(22, 23)*.

Example: VSL Application on the Top End of I-285 in Atlanta, GA.

In 2014, the Georgia DOT implemented VSL control on the north side of I-285, referred to as the I-285 Top End, by increasing the base speed limit to 65 mph from 55 mph. The map of the VSL-applied area is presented in Figure 6-3. The VSL is only applied on the north part where the traffic volume is higher than other sections. The VSL system can adjust the speed limit in 10-mph increments to a minimum speed of 35 mph from the base speed limit of 65 mph in response to traffic congestion, incidents, or weather conditions. To this end, the Transportation Management Center monitors the roadway in real-time and controls the speed limit using active traffic management software. There are 176 electronic speed limit signs in 88 locations spaced ½ to 1½ miles apart. Multiple benefits are expected, including reduced congestion, reduced traffic delay, and enhanced driver safety—even with the higher base speed limit.

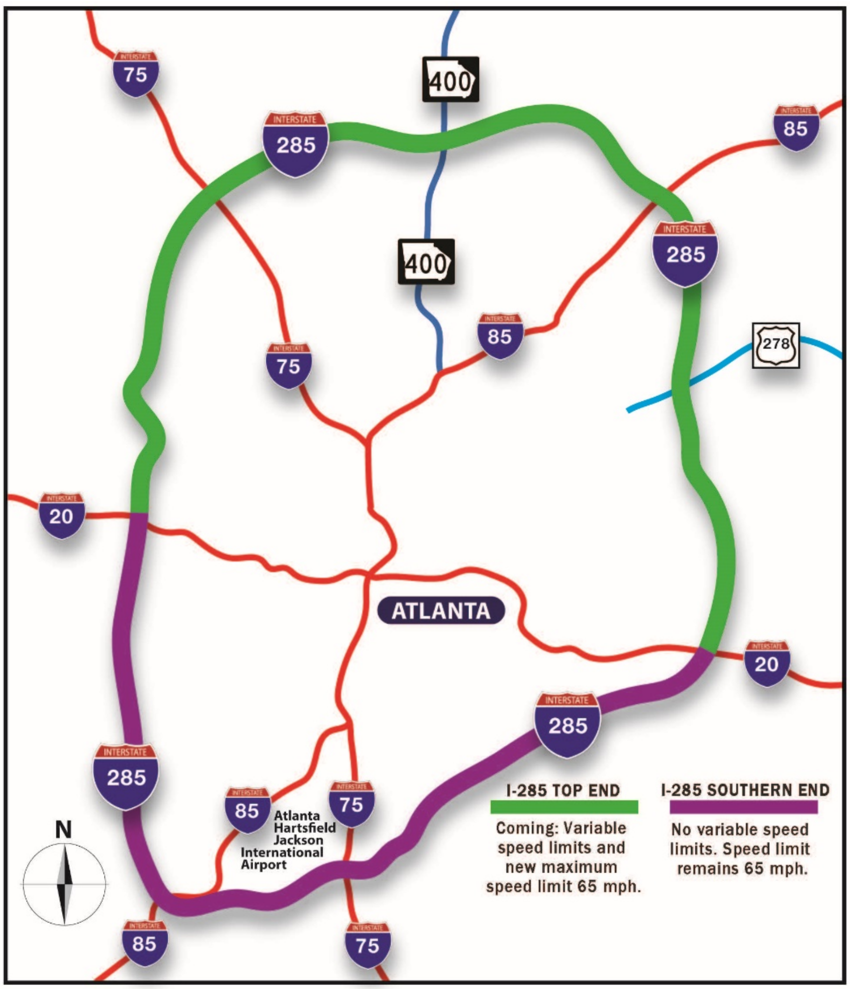


Figure 6-3. VSL Application on the Top End of I-265, Atlanta, GA (adopted from *(24)*)

6.4. Real-Time Traffic Information

As presented in the examples in Section 4.3, developing optimal travel planning considering bottleneck locations and their activation times are critical to avoiding traffic congestion. However, travel planning derived only from typical traffic patterns could be inaccurate since the patterns could vary significantly. In addition, non-recurrent traffic events, such as an incident or a work zone, would cause more variability. Thus, providing real-time traffic information is important both before and during travel. With the advent of new technologies to collect traffic data, there are many resources to provide real-time traffic information. For example, in public areas, the FHWA and state DOTs provide the 511 traffic system that provides real-time traffic information including highway conditions, incidents, road closures, and weather alerts. This system can be accessed by phone, website, or smartphone app. Figure 6-4 shows an example of the 511 system in Wisconsin, which shows traffic speeds, incidents, roadwork, and truck information. In addition, there are numerous private/private-sector sources of traffic information, such as map services (e.g., Google Maps), navigation, or on-board vehicle systems. One interesting recent effort in traffic information is traffic forecasting using cutting-edge data processing algorithms, such as deep learning *(25, 26)*.

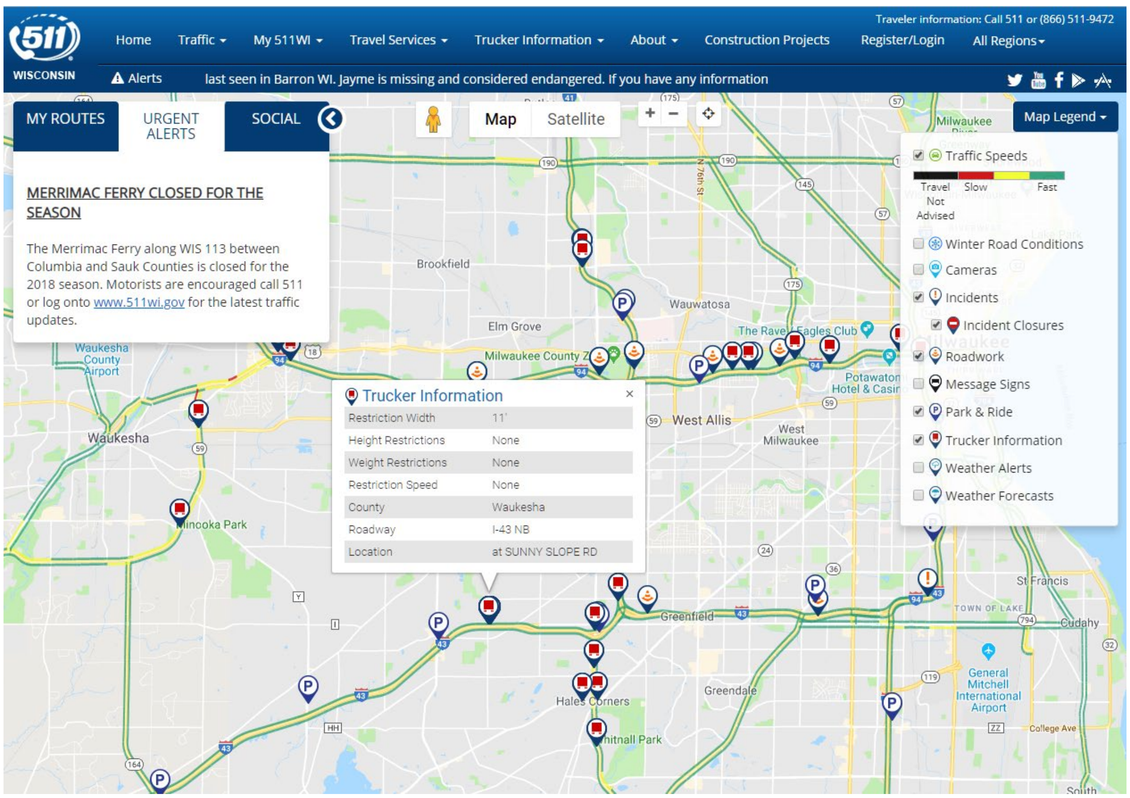


Figure 6-4. Example of the Traffic 511 System in Wisconsin

7. CONCLUSION

This research investigated major freight bottlenecks in the MAASTO region's multistate and multimodal freight network, including both the roadway and marine highway networks. For the highway freight bottlenecks, the NHFN, which carries the majority of truck volume, was identified as the freight network to be investigated. For data, NPMRDS, which provides speed and travel time at the TMC level, was selected. For a measure to define freight bottlenecks, TTI was used with the criterion of TTI >1.4. From the highest value of TTI for each TMC, using GIS analysis, 14 areas in the MAASTO region near large cities were identified as potential regions where freight bottlenecks occur. By constructing time-space diagrams of TTI for corridors in each region, locations and activation times of freight bottlenecks were identified. The possible causes of bottlenecks were also investigated through location research using GIS and satellite maps. The results show that bottlenecks typically occurred near major interchanges and ramps near large cities, and their activation times and queue lengths vary. The bottlenecks are also presented for multistate corridors that have been identified as the most valuable freight corridors in the MAASTO region. A delay analysis for multistate corridors was conducted, taking into consideration bottleneck activations that cause traffic delay and truck volume, in order to prioritize the corridors to be improved. The results show that I-94, I-90, and I-75 have high delays in terms of the AADTT weighted average delay along the entire corridor length, while I-55, I-64, and I-65 have high average delay per unit mile. Possible solutions to mitigate freight bottlenecks, including highway improvement projects, ramp metering, variable speed limit, and real-time traffic information, were provided with examples.

This research also investigated bottlenecks attributed to marine corridors. The analysis was done utilizing the data published by USACE reporting the average delay, total number of vessels, unavailable timings, and lockage system. In order to characterize the bottlenecks in each corridor, the average delay in each lock and dam was considered, and bottlenecks were characterized for locations experiencing an average delay for all tows of 1.5 hours and above. The results show that, in total, 22 bottlenecks are present along the five corridors. M-35 currently endures the highest number of bottlenecks with 13, the combined corridor of M-70 and M-29 experiences the highest total delay, and M-55 faces five bottlenecks. No bottlenecks exist in M-90.

There are several issues that merit future research. To identify highway freight bottlenecks, we used TTI as a measure using data from NPMRDS. Since this approach does not reflect truck volumes, identified bottlenecks do not address the effect of truck volume such as total delay. Thus, to characterize bottleneck severity more comprehensively, truck volume data should be considered. To overcome this, we used AADTT to weigh the delay for each TMC in our delay analysis of multistate corridors. However, this approach is also subject to errors when the truck volume distributions by time differ significantly between corridors. Thus, more detailed information for truck volume distribution is required to perform a more accurate delay analysis. In addition, while characterizing bottlenecks in marine corridors requires a thorough realization of the environmental conditions, infrastructure operation, and causes of delay, currently data availability poses a barrier to such analysis. Although we used scheduled/unscheduled unavailability data to better understand the cause of bottlenecks, this is not enough to fully characterize bottlenecks. Thus, more specific information on the delay timing and cause of every vessel traversing the lock and dam is needed to derive a more accurate analysis.

REFERENCES

1. Hooper, A. *Cost of Congestion to the Trucking Industry: 2018 Update*. 2018.
2. Chao, E. L., J. Rosen, P. Hu, and R. Schmitt. *Freight Facts and Figures*. 2017.
3. Federal Highway Administration. Traffic Congestion and Reliability: Linking Solutions to Problems. 2004.
4. MARITIME ADMINISTRATION, D. O. T. 46 Code of Federal Regulations, Chapter II. https://ecfr.io/Title-46/cfrv8.
5. Marathon, N. *Economic Impacts Analysis of Inland Waterways Disruption on the Transport of Corn and Soybeans*. 2016.
6. Guo, J., Q. Gong, and A. Obernesser. *Assessment of Multimodal Freight Bottlenecks and Alleviation Strategies for the Upper Midwest Region*. 2010.
7. Yu, T.-H., D. A. Bessler, and S. W. Fuller. Effect of lock delay on grain barge rates: examination of upper Mississippi and Illinois Rivers. *The Annals of Regional Science*, Vol. 40, No. 4, 2006, pp. 887–908.
8. Morgiotta, R., H. Cohen, and P. DeCorla-souza. Speed and Delay Prediction Models for Planning applicatioins. 1999.
9. Liao, C. *Measure of Truck Delay and Reliability at the Corridor Level*. 2018.
10. MNDOT, and Metropolitan_Council. *Twin Cities Metropolitan Region Freight Study*. St. Paul, 2013.
11. MNDOT. *Minnesota Statewide Freight Bottlenecks*. 2018.
12. IADOT. *IOWA STATE FREIGHT PLAN*. 2018.
13. FHWA. *Truck Freight Bottleneck Reporting Guidebook*. 2018.
14. Han, Y., E. Perry, S. Ahn, G. Vohres, and W. Kontar. *Identification and Characterization of the MAASTO Region's Multimodal Freight Network*. 2018.
15. Schuman, R., S. Turner, and J. Corrales. National Performance Management Research Data Set (NPMRDS) Descriptive Metadata Document. 1–20. https://npmrds.ritis.org/analytics/help/#npmrds. Accessed Dec. 3, 2018.
16. Google Map_Street View. https://www.google.com/maps/@44.9620892,-93.269236,3a,75y,355.43h,80.95t/data=!3m6!1e1!3m4!1sCu0_5xJsrfiR-ZwRJZSyIA!2e0!7i13312!8i6656. Accessed Dec. 4, 2018.
17. US Army Corps of Engineers. Lock Performance and Monitoring System (LPMS). http://corpslocks.usace.army.mil/lpwb/f?p=121:1:9536601039637.
18. US Army Corps of Engineers. Definition of Terms. http://cwbi-ndc-nav.s3-website-us-east-1.amazonaws.com/lpms.html .
19. Ahanotu, D., R. Margiotta, B. Eisele, M. Hallenbeck, A. Goodchild, and E. McCormack. *Guide for Identifying, Classifying, Evaluating, and Mitigating Truck Freight Bottlenecks*. 2017.
20. Mizuta, A., K. Roberts, L. Jacobsen, and N. Thompson. Ramp Metering: A Proven, Cost-Effective Operation Strategy - A primer. *Fhwa-Hop-14-020*, 2014.
21. Hegyi, A., B. De Schutter, and H. Hellendoorn. Model predictive control for optimal

coordination of ramp metering and variable speed limits. Vol. 13, 2005, pp. 185–209.

22. Hegyi, A., B. De Schutter, and H. Hellendoorn. Model predictive control for optimal coordination of ramp metering and variable speed limits. *Transportation Research Part C: Emerging Technologies*, Vol. 13, No. 3, 2005, pp. 185–209.

23. Lu, X.-Y., P. Varaiya, R. Horowitz, D. Su, and S. Shladover. Novel Freeway Traffic Control with Variable Speed Limit and Coordinated Ramp Metering. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2229, 2011, pp. 55–65.

24. GDOT. Variable Speed Limits (VSL). http://www.dot.ga.gov/DriveSmart/SafetyOperation/Pages/VSL.aspx#tab-2. Accessed Dec. 17, 2018.

25. Vlahogianni, E. I., M. G. Karlaftis, and J. C. Golias. Short-term traffic forecasting: Where we are and where we're going. *Transportation Research Part C: Emerging Technologies*, Vol. 43, 2014, pp. 3–19.

26. Polson, N. G., and V. O. Sokolov. Deep learning for short-term traffic flow prediction. *Transportation Research Part C: Emerging Technologies*, Vol. 79, 2017, pp. 1–17.

APPENDIX A. BOTTLENECKS FOR MULTISTATE CORRIDORS IN THE MAASTO REGION

1. I-35 (I-35W, I-35E)

Direction	State	Area	BN No.	Location	Type	Time	Max Queue
North	KS	Kansas City	3-3	@Switzer Bypass	Interchange	AM7-8	1.69
	KS	Kansas City	3-4	@Switzer Bypass	Interchange	PM4-5	1.69
	KS	Kansas City	3-5	@I-29	Multiple	PM4-5	1.28
	KS	Kansas City	3-6	@I-70	Multiple	PM4-5	0.8
South	KS	Kansas City	3-7	@Shawnee Mission Pkwy	Multiple	AM07	1
	KS	Kansas City	3-8	@ S 7th St	Multiple	PM4-5	4.9
North (I-35E)	MN	Twin Cities	1-1	@MN-62	Merge	AM7	1.19
	MN	Twin Cities	1-2	@I-94	Interchange	PM3-5	1.07
	MN	Twin Cities	1-3	@I-694	Interchange	PM4-5	0.81
	MN	Twin Cities	1-4	@MN-62	Merge	PM5	1.24
South (I-35E)	MN	Twin Cities	1-5	@Cayuga St.	Merge	AM7	2.35
	MN	Twin Cities	1-6	@MN-62, MN-5	Merge	PM4-5	2.69
North (I-35W)	MN	Twin Cities	1-7	@MN-13	Merge	AM6-8	3.42
	MN	Twin Cities	1-8	@I-94	Interchange	AM7-8	3.34
	MN	Twin Cities	1-9	@I-694	Interchange	PM3-5	3.20
	MN	Twin Cities	1-10	@I-94	Interchange	PM3-6	3.55
South (I-35W)	MN	Twin Cities	1-11	@I-694	Interchange	AM6-7	5.24
	MN	Twin Cities	1-12	@I-94	Interchange	AM7-8	14.60
	MN	Twin Cities	1-13	@MN-62	Merge	AM8	1.40
	MN	Twin Cities	1-14	@I-94	Interchange	PM1-6	4.02
	MN	Twin Cities	1-15	@MN-13	Merge	PM4-5	1.15

2. I-55

Direction	State	Area	BN No.	Location	Type	Time	Max Queue
North	IL	Chicago	6-17	@US-41	Interchange	AM6-10	1.16
	IL	Chicago	6-18	@Kedzie Ave, IL-50m Harlem Ave	Multiple	AM6-9	6.34
	IL	Chicago	6-19	@US-41	Interchange	PM1-6	1.16
	IL	Chicago	6-20	@Harlem Ave	Merge	PM3-6	5.31
	IL	Chicago	6-21	@IL-83	Interchange	PM4-5	5.45
	MO	St. Louis	7-7	@ I-64	Multiple	PM3-5	0.9
South	IL	Chicago	6-22	@Kedzie Ave	Merge	AM6-7	1.23
	IL	Chicago	6-23	@Kedzie Ave,I-90	Multiple	PM12-6	6.53
	IL	Chicago	6-24	@IL-83	Interchange	PM2-5	5.85
	IL	Chicago	6-25	@I-355	Interchange	PM4-5	1.54
	MO	St. Louis	7-8	@ I-70	Multiple	AM7	1.18

3. I-64

Direction	State	Area	BN No.	Location	Type	Time	Max Queue
East	MO	St. Louis	7-9	@I-170	Multiple	AM7-8	1.69
	MO	St. Louis	7-10	@I-170	Multiple	PM4-5	1.69
	MO	St.Louis	7-11	@I-55 & I-70	Multiple	PM 4-5	2.2
	KY	Louisville	14-7	@I-65	Interchange	PM4-5	1.5
	KY	Louisville	14-8	@I-265	Interchange	PM5	1.73
	KY	Louisville	14-9	@Mellwood Ave	Merge	PM5	0.3
West	MO	St. Louis	7-12	@Hampton Avenue	Multiple	AM7	2.5
	MO	St. Louis	7-13	@Hampton Avenue	Multiple	PM4-5	4.32
	MO	St. Louis	7-14	@I-55 & I-70	Multiple	AM7	1.58
	KY	Louisville	14-10	@I-71	Interchange	AM8	0.8
	KY	Louisville	14-11	@I-71	Interchange	PM3-6	4.39

4. I-65

Direction	State	Area	BN No.	Location	Type	Time	Max Queue
North	KY	Louisville	14-12	@I-64	Interchange	PM3-5	3.45
South	IN	Indianapolis	11-2	@I-70	Interchange	PM4-5	1.68
	KY	Louisville	14-13	@I-64	Interchange	AM7-8	1.99
	KY	Louisville	14-14	@KY-61,Oak St	Multiple	PM4-5	1.58
	KY	Louisville	14-15	@I-64	Interchange	PM4-5	1.09

5. I-70

Direction	State	Area	BN No.	Location	Type	Time	Max Queue
East	KS	Kansas City	3-13	@I-435	Multiple	PM4-5	3.44
	KS	Kansas City	3-14	@I-35	Multiple	PM4-5	3.95
	MO	St. Louis	7-15	@I-55 & I-64	Multiple	PM4-5	1.8
	OH	Columbus	12-7	@I-71	Interchange	PM4	1.21
	OH	Columbus	12-8	@I-270	Interchange	PM4-5	5.56
West	OH	Columbus	12-9	@I-270	Interchange	AM7	1.21
	OH	Columbus	12-10	@US-33	Merge	AM7	0.55
	OH	Columbus	12-11	@I-71	Interchange	PM4-5	1.68

6. I-71

Direction	State	Area	BN No.	Location	Type	Time	Max Queue
North	OH	Cleveland	10-10	@I-90	Interchange	AM6-9	2.56
	OH	Columbus	12-12	@I-70	Interchange	PM4	1.21
	OH	Columbus	12-13	@I-670	Interchange	PM4-5	2.35
	KY	Cinncinnati	13-5	@KY-8, US-25	Multiple	AM7-8	5.86
	OH	Cinncinnati	13-6	@McMillan St	Merge	PM4-5	4.88
	KY	Louisville	14-16	@I-265	Interchange	PM5	4.1
South	OH	Columbus	12-14	@I-670	Interchange	PM3-5	0.84
	OH	Columbus	12-15	@I-270	Interchange	PM4-5	2.01
	OH	Columbus	12-16	@I-70, I-70	Multiple	PM4-5	0.87
	OH	Cinncinnati	13-7	@OH-126	Merge	AM7	1.61
	OH	Cinncinnati	13-8	@I-75,I-471	Multiple	PM3-6	3.01
	KY	Cinncinnati	13-9	@KY-8	Merge	PM4-5	1.49
	OH	Cinncinnati	13-10	@OH-126	Merge	PM5	1.61
	KY	Louisville	14-17	@I-64	Interchange	AM8	1.92
	KY	Louisville	14-18	@I-64, I-65	Multiple	PM4-5	2.7

7. I-74

Direction	State	Area	BN No.	Location	Type	Time	Max Queue
East	IA	Davenport/ Moline	2-1	@US-67	Merge	AM7-8	0.16
	IA	Davenport/ Moline	2-2	@US-67	Merge	PM4-5	0.33
	OH	Cincinnati	13-11	@US-27	Interchange	AM7	1.3
West	IL	Davenport/ Moline	2-3	@River Dr.	Merge	PM4-5	0.16

8. I-75

Direction	State	Area	BN No.	Location	Type	Time	Max Queue
North	MI	Detroit	8-8	@MI-10	Interchange	AM7-8	0.8
	MI	Detroit	8-9	@I-696	Interchange	AM8	0.91
	MI	Detroit	8-10	@I-696	Interchange	PM3-6	6.19
	MI	Detroit	8-11	@I-94	Interchange	PM5	0.8
	MI	Detroit	8-12	@MI-24	Interchange	PM6	3.4
	OH	Toledo	9-1	@ Washington St.	Merge	PM4-5	0.92
	KY	Cinncinnati	13-12	@KY-8, US-25	Multiple	AM7-8	5.86
	OH	Cinncinnati	13-13	@I-275	Interchange	PM4-5	2.1
	OH	Cinncinnati	13-14	@Paddock Rd, OH-562	Multiple	PM4-5	4.96
South	MI	Detroit	8-13	@I-94, MI-102,I-696	Multiple	AM7-8	11.56
	MI	Detroit	8-14	@I-696	Interchange	PM4-5	4.02
	OH	Cinncinnati	13-15	@I-275	Interchange	AM7	2.6
	OH	Cinncinnati	13-16	@OH-126	Interchange	AM7-8	2.58
	OH	Cinncinnati	13-17	@I-71	Interchange	PM3-6	2.04
	OH	Cinncinnati	13-18	@OH-126	Interchange	PM3-6	3.78
	KY	Cinncinnati	13-19	@KY-8	merge	PM4-5	1.49

9. I-90

Direction	State	Area	BN No.	Location	Type	Time	Max Queue
East	IL	Chicago	6-29	@I-290, Ohio St, IL-64, Kimball Ave, I-94, IL-171, I-190, I-294	Multiple	AM6-PM10	16.78
	IL	Chicago	6-30	@I-94	Interchange	PM2-6	3.74
	OH	Cleveland	10-13	@I-71	Interchange	AM7-8	4.73
West	IL	Chicago	6-31	@Bryn Mawr Ave, I-94, IL64, Ohio St	Multiple	AM11-PM7	11.57
	IL	Chicago	6-32	@I-290, I55	Interchange	AM6-8	5.22
	IL	Chicago	6-33	@Bryn Mawr Ave, I-94	Multiple	AM6-9	8.11
	IL	Chicago	6-34	@I-290	Interchange	AM9-PM7	1.90
	IL	Chicago	6-35	@Devon Ave	Merge	PM4-5	1.01
	OH	Cleveland	10-14	@I-77, US-20	Multiple	PM3-5	3.12

10. I-94

Direction	State	Area	BN No.	Location	Type	Time	Max Queue
East	MN	Minneapolis	1-35	@I-394	Interchange	AM7-8	2.41
	MN	Minneapolis	1-36	@I-394	Interchange	PM2-5	3.43
	MN	Minneapolis	1-37	@I-35E	Interchange	PM3-5	3.14
	MN	Minneapolis	1-38	@MN-280	Merge	PM5	0.25
	WI	Milwaukee	5-8	@I-41	Interchange	AM7	2.63
	WI	Milwaukee	5-9	@St.Paul Ave, WI-175	Merge	AM7-8	3.79
	WI	Milwaukee	5-10	@I-43	Interchange	PM3-5	2.51
	WI	Milwaukee	5-11	@I-41	Interchange	PM4-5	2.63
	WI	Milwaukee	5-12	@St.Paul Ave, WI-175	Merge	PM5	1.12
	IL	Chicago	6-36	@I-55, I-290, Ohio St, IL-64, Kimball Ave, I-90, Lake Ave, US-41	Multiple	AM10-PM10	23.52
	IL	Chicago	6-37	@I-290, Ohio St, IL-64, Kimball Ave, I-90	Multiple	AM6-9	11.31
	IL	Chicago	6-38	@130th St, US-20, I-57, I-90	Multiple	PM2-6	13.71
	MI	Detroit	8-15	@I-96	Interchange	AM7-8	3.96
	MI	Detroit	8-16	@I-75, I-96	Multiple	PM3-5	7.2
	MI	Detroit	8-17	@US-23	Interchange	PM4-5	1.52
	MI	Detroit	8-18	@I-696	Interchange	PM4-5	2.02
West	MN	Minneapolis	1-39	@I-35E	Interchange	AM7	3.39
	MN	Minneapolis	1-40	@MN-280	Merge	AM7	0.88
	MN	Minneapolis	1-41	@I-35W	Interchange	AM7-8	1.43
	MN	Minneapolis	1-42	@I-394, I-35W	Multiple	PM2-6	4.19
	MN	Minneapolis	1-43	@I-494	Interchange	PM4-5	1.77
	WI	Milwaukee	5-13	@Holt Ave	Merge	AM7	2.71
	WI	Milwaukee	5-14	@I-41	Interchange	AM7	3.17
	WI	Milwaukee	5-15	@I-41	Interchange	PM3-5	3.64
	IL	Chicago	6-39	@I-290, I-55	Interchange	AM6-10	5.22
	IL	Chicago	6-40	@Skoki Blvd, IL-58, Touhy Ave, US-14, I-90	Multiple	AM6-8	14.12
	IL	Chicago	6-41	@I-90, I-57, US-20	Multiple	AM6-8	7.16
	IL	Chicago	6-42	@IL-64, Ohio St, I-290, I-55	Multiple	PM12-7	5.35
	IL	Chicago	6-43	@I-90	Interchange	PM1-6	4.72
	IL	Chicago	6-44	@I-90	Interchange	PM1-6	5.64
	MI	Detroit	8-19	@I-75, local road	multiple	AM7-8	8.3
	MI	Detroit	8-20	@US-23	Interchange	AM7-8	1.77
	MI	Detroit	8-21	@I-96	Interchange	PM3-5	1.76

APPENDIX B. TIME-SPACE DIAGRAM FOR CORRIDORS

*The length and file size of Appendix B precludes it from being included here. It is posted at:
https://uwmadison.box.com/s/mkneo69b43p3hs2gqf3jp6dck5elgg8d

APPENDIX C. MARINE HIGHWAY DATA

M-70 & M-29								
Location	Total Lockages	Tows		Average Delay (hrs.)		Total Delay (hrs.)	Scheduled Unavailable Time (hrs.)	Unscheduled Unavailable time (hrs.)
		All	Delayed	All Tows	Delayed Tows			
Emsworth Lock and Dam - Chamber 1	2428.00	2055.00	682.00	0.54	1.41	935.58	3.08	1143.95
Emsworth Lock and Dam - Chamber 2	2804.00	1036.00	384.00	3.18	2.74	3943.03		
Deshields Lock and Dam - Chamber 1	2901.00	2544.00	833.00	1.01	3.09	2368.42	3.03	216.78
Deshields Lock and Dam - Chamber 4	1522.00	874.00	932.00	0.35	1.24	143.32		
Montgomery Lock and Dam - 1	3510.00	3601.00	2158.00	1.74	2.07	4542.63	2109.13	2740.87
Montgomery Lock and Dam - 4	1399.00	541.00	345.00	8.55	7.74	3540.98		
New Cumberland Lock and Dam - 1	3231.00	2942.00	1110.00	1.04	2.16	2748.95	1.55	247.07
Pike Island - 1	2945.00	2936.00	964.00	0.29	0.88	861.93	0.00	188.93
Pike Island - 4	1300.00	788.00	52.00	0.05	0.33	21.45		
Hannibal - 1	3438.00	3426.00	1663.00	0.57	1.17	1955.25	5.70	42.05
Hannibal - 4	808.00	561.00	50.00	0.11	0.66	34.18		
Belleville - 2	3293.00	3288.00	1971.00	0.99	1.72	3249.50	22.50	234.50
Belleville - 4	589.00	311.00	94.00	0.08	0.18	21.02		
Racine - 2	3375.00	3335.00	1541.00	0.79	1.69	2535.65	13.72	104.13
Racine - 4	498.00	317.00	28.00	0.17	1.30	38.33		
Greenup - 2	2162.00	2147.00	1117.00	1.24	2.31	2520.73	4311.78	69.23

Greenup - 4	2574.00	1622.00	1224.00	2.09	2.17	5818.63		
Capt Ant Meldahl - 2	3799.00	3586.00	1589.00	0.53	1.16	1865.32	6796.50	6.13
Capt Ant Meldahl - 4	214.00	50.00	6.00	0.03	0.15	1.85		
Robert C Byrd - 2	2968.00	2960.00	1110.00	1.72	4.12	4832.77	2320.38	41.18
Robert C Byrd - 4	276.00	202.00	14.00	0.07	0.55	15.67		
Willow Island - 2	3276.00	3199.00	1170.00	0.79	1.93	2583.13	4.58	574.12
Willow Island - 4	655.00	282.00	20.00	0.04	0.32	11.40		
Markland - 2	3465.00	3398.00	1507.00	0.54	1.20	1830.72	0.00	39.68
Markland - 4	1039.00	242.00	21.00	0.05	0.25	12.57		
Mcalpine - 1	2645.00	2489.00	769.00	0.47	1.56	1379.28	18.47	96.53
Mcalpine - 2	2293.00	2203.00	598.00	0.44	1.47	925.43		
Lock and Dam 52 - 1	6559.00	6607.00	2304.00	4.16	6.41	23684.98	3.33	56.55
Lock and Dam 52 - 5	595.00	585.00	538.00	3.01	2.95	1577.07		
Lock and Dam 53 - 1	6507.00	6388.00	5706.00	3.38	3.43	19543.90	0.00	23.53
Cannelton - 2	4320.00	4276.00	3275.00	0.83	1.08	3546.45	8.90	157.70
Cannelton - 4	854.00	324.00	158.00	0.21	0.37	57.47		
Newburgh - 2	5058.00	5007.00	3659.00	0.88	1.20	4384.97	9.67	60.32
Newburgh - 4	944.00	525.00	225.00	0.39	0.68	125.00		
John T Myers - 2	4143.00	4041.00	2380.00	0.73	1.23	2924.03	168.53	157.52
John T Myers - 4	1289.00	299.00	73.00	0.12	0.30	24.42		
Smithland - 1	3036.00	2895.00	1220.00	0.63	1.33	1804.67	2.00	180.78
Smithland - 2	3066.00	2967.00	1389.00	0.74	1.41	1997.43		

The Great Lakes								
Location	Total Lockages	Tows		Average Delay (hrs.)		Total Delay (hrs.)	Scheduled Unavailable Time (hrs.)	Unscheduled Unavailable Time (hrs.)
		All	Delayed	All Tows	Delayed Tows			
Black Rock Lock - 1	1781	113	28	0.18	0.06	4.23	5433.73	0.00
Chicago Lock - 1	11,218	261	309	0.31	0.08	26.03	4.07	13.18
Alanson Lock	5521	0	0	0	0	0	3654.98	0.00
St. Mary's Lock - 1	2789	455	169	0.41	0.27	47.83	6233.00	2379.53
St. Mary's Lock - 2	3059	561	265	0.54	0.9	247.92		

M-35								
Location	Total Lockages	Tows		Average Delay (hrs.)		Total Delay (hrs.)	Scheduled Unavailable Time (hrs.)	Unscheduled Unavailable Time (hrs.)
		All	Delayed	All Tows	Delayed Tows			
Lock and Dam 1	935.00	11.00	0.00	0.00	0.00	0.00	2400.00	0.00
Lock and Dam 2	3394.00	1597.00	1283.00	1.08	0.96	1335.15	2354.92	8.60
Lock and Dam 3	4891.00	1558.00	1328.00	1.31	0.98	1489.05	2280.00	0.00
Lock and Dam 4	3826.00	1496.00	785.00	1.00	1.39	1101.00	1920.00	53.20
Lock and Dam 5	3340.00	1497.00	1380.00	1.19	0.92	1276.12	4536.77	0.00
Lock and Dam 6	3552.00	1528.00	1275.00	0.94	0.87	1229.07	2016.92	14.30
Lock and Dam 7	3755.00	1955.00	1284.00	1.08	0.85	1255.80	0.00	0.00
Lock and Dam 8	3302.00	1529.00	1093.00	1.81	2.05	2295.28	2354.03	22.43
Lock and Dam 9	3832.00	1585.00	1217.00	1.09	1.10	1508.92	2304.00	24.80
Lock and Dam 10	3887.00	1938.00	1563.00	0.94	0.92	1559.63	2.73	8.20
Lock and Dam 11	4176.00	1984.00	1839.00	1.03	0.88	1735.80	0.00	42.67
Lock and Dam 12	3953.00	2045.00	1324.00	1.16	1.48	2177.08	0.00	19.78
Lock and Dam 13	4006.00	2083.00	1409.00	1.19	1.45	2272.62	0.00	20.65
Lock and Dam 14 - 1	4089.00	2418.00	2070.00	2.50	2.50	5778.90	1517.30	83.93
Lock and Dam 14 - 4	972.00	0.00	0.00	0.00	0.00	0.00		
Lock and Dam 15 - 1	3971.00	2542.00	2433.00	2.26	2.03	5731.17	1925.00	347.20
Lock and Dam 15 - 4	651.00	129.00	97.00	0.75	0.52	49.58		

Lock and Dam 16	4726	3199	2684	2.1	1.75	5169.07	2040.23	56.82
Lock and Dam 17	4235	2603	1718	2.34	2.86	4882.65	1961.00	50.28
Lock and Dam 18	4483	2679	2606	1.65	1.42	3934.53	6.48	70.85
Lock and Dam 19 - 1	2643	2377	2202	0.9	0.89	2056.9	0.53	37.60
Lock and Dam 20 - 1	4780	2770	2675	2.98	2.63	8022.37	0.00	90.35
Lock and Dam 21 - 1	4979	2856	2166	1.69	1.94	4956.2	1525.52	22.77
Lock and Dam 22 - 1	4887	2707	2688	3.9	3.65	11,977.22	2.63	78.15
Lock and Dam 24 - 1	4953	2716	1982	2.73	3.87	7540.82	28.93	148.13
Lock and Dam 25 - 1	4937	2697	2192	3.66	4.09	12,042.23	0.00	9.33

St. Louis Intersection Between M-35 and M-55 and M-70								
Location	Total Lockages	Tows		Average Delay (hrs.)		Total Delay (hrs.)	Scheduled Unavailable Time (hrs.)	Unscheduled Unavailable Time (hrs.)
		All	Delayed	All Tows	Delayed Tows			
Mel Price - 1	5767	5524	4323	2.39	3.02	11,865.58	11.50	35.88
Mel Price - 4	521	256	109	1.30	1.82	306.37		
Chain of Rocks Lock and Dam 27 - 1	7148	7112	6410	2.52	2.62	16,614.07	0.82	1.07
Chain of Rocks Lock and Dam 27 - 4	686	493	407	1.77	1.36	559.15		

M-55								
Location	Total Lockages	Tows		Average Delay (hrs.)		Total Delay (hrs.)	Scheduled Unavailable Time (hrs.)	Unscheduled Unavailable Time (hrs.)
		All	Delayed	All Tows	Delayed Tows			
Harvey Lock	4101	4535	3778	1.10	0.65	2,819.43	0.00	26.28
Old River Lock - 1	3071	3294	3161	0.61	0.44	1,395.15	0.00	11.17
Kaskaskia River Navigation Lock - 1	939	731	6	0.06	1.54	37.90	27.00	15.42
Thomas J. O'Brien Lock - 1	4637	1492	246	0.07	0.34	95.42	38.07	32.43
Lockport Lock - 1	3782	3748	2222	1.05	1.35	3,267.37	34.00	57.47
Brandon Road Lock and Dam - 1	3738	3518	1776	0.97	1.41	2,674.58	18.50	13.72
Dresden Island - 1	3859	3076	2971	1.49	1.30	4,022.30	95.33	46.98
Marseilles Lock and Dam - 1	3851	3012	2349	3.52	3.69	9,957.32	25.68	57.25
Starved Rock Lock and Dam	3839	3032	2887	2.32	2.10	6,047.50	1.42	29.82
Peoria Lock and Dam	3363	2832	967	0.95	2.07	2,553.12	0.57	27.83
LaGrange Lock and Dam - 1	3588	2909	1313	1.65	2.77	4,947.33	2.73	18.78

www.midamericafreight.org

Mid-America Freight Coalition
Ernest Perry, PhD, Program Manager
University of Wisconsin–Madison
College of Engineering
Department of Civil and Environmental Engineering
1415 Engineering Drive, 2205 EH
Madison, WI 53706
ebperry@wisc.edu
(608) 890-2310