EVALUATION OF OPERATIONAL AND SAFETY IMPACTS OF PART-TIME USE OF THE INSIDE SHOULDER

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ABSTRACT

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The Michigan Department of Transportation (MDOT) introduced its first application of dynamic part-time shoulder use (D-PTSU) on the US-23 corridor in November 2017 to mitigate recurring congestion. This project referred to as the Flex route involved widening the left shoulder, which now serves as a temporary travel lane during between M-14 and M-36 during periods of heavy congestion. As the application of D-PTSU is relatively novel in the United States, especially the use of the left shoulder, this study evaluates the operational and safety performance of the US-23 Flex route and provides guidance for future implementation of similar facilities in Michigan and elsewhere.

The evaluation assessed various metrics, including average travel time, travel time reliability, driver compliance, and incident clearance times. The findings show that operations of the US-23 Flex route have improved significantly, especially in the southbound direction. While the northbound direction also showed better performance after the Flex lane opened in general, some of the prior congestion has shifted to the end of the Flex route in the northbound direction due to a bottleneck that was introduced at the end terminal. Fortunately, this problem is expected to be alleviated by the planned extension of the Flex lane to I-96 in 2024. The operational analyses also showed improved operations when special events occurred such as football games and holidays. Incident clearance times largely decreased after the Flex route was opened. Part-time shoulder running also provided an additional travel lane during peak periods, such as University of Michigan home football games, reducing such non-recurrent congestion.

Crash data were compared for a period of five years (i.e., 2012 to 2016) before the construction of the Flex route, and two years (i.e., 2018 and 2019) after its completion. After considering increases in traffic volume, crashes were reduced by 17 percent when considering all times of day, including 34 percent in the southbound direction. During the peak operational periods, reductions of approximately 50 percent were experienced in the southbound direction. In contrast, total crashes were comparable in the northbound direction and actually increased by approximately 24 percent during the peak traffic periods. However, much of this increase is attributable to the lane drop that occurs at the northern terminus of the Flex route. The planned extension to I-96 should remedy the existing safety issues.

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CHAPTER 1 INTRODUCTION

1.1 Background

Traffic congestion has become one of the most detrimental effects of the popularity of automobile transportation. Seven significant causes of congestion were usually observed, including physical bottlenecks, traffic incidents, bad weather, work zones, poor signal timing, and other special events (FHWA, 2005). In 2019, Americans lost 99 hours per year on average because of congestion. This resulted in $88 billion lost in total, which breaks down to an average of $1,377 per driver (INRIX, 2020). Under congestion, drivers typically experience slower speeds, longer travel times, queueing, and stop-and-go traffic. Besides the inconvenience of wasting time crawling through a traffic jam, congestion also increases the risk of crashes and costs through increased fuel use. More fuel use directly translates to vehicle emissions such as greenhouse gases and particulate matter. Road agencies and environmental groups advocate for reducing traffic congestion to mitigate its adverse effects on mobility and quality of life.

One of the traditional approaches is to “build out” of the congestion by introducing additional travel lanes. The downsides to this approach are that it is prohibitively expensive, there is limited right-of-way available, and these additional lanes would be fully utilized during only certain high-volume periods. Fortunately, there are multiple strategies have developed to mitigate the problems. Active traffic management (ATM) is one of the strategies to improve the efficiency and reliability of the transportation system, which utilizes dynamic management to control traffic demand and capacity. It generally includes variable speed limit, queue warning, dynamic lane use, and dynamic part-time shoulder use (D-PTSU). The variable speed limit allows the agencies to speed limit accordingly in terms of traffic conditions; The principle of queue warning is to inform travelers of advanced traffic conditions by using warning and message signs; Dynamic lane use refers to closing or opening of individual travel lanes to motorists based on the traffic conditions. It also provides advanced warning for drivers to safely merge to an adjacent lane; D-PTSU typically indicates left or right shoulder can be open or closed for traffic in response to the traffic congestions (Kuhn et al., 2017).

The potential benefits of ATM strategies were proved to be varied. For instance, the systems were found to be 1) more throughput and capacity; 2) less primary and secondary incidents; 3) less severe incident; 4) more uniform speeds; 5) smaller headways; 7) more uniform driver behaviors; 8) more trip reliability; and 9) less fuel use (Mirshahi et al., 2007; Sorrell, 2014). In 2012, more than 18 states in the United States have implemented at least one ATM strategy such as dynamic speed limits or dynamic lane use control (FHWA, 2012). Within that, a few states have installed other strategies, especially D-PTSU. By 2018, only five states (Washington, Colorado, Illinois, Georgia, and Michigan) that used the shoulders as a dynamic travel lane (Jenior et al., 2016; Jenior et al., 2019).

1.2 Overview of D-PTSU in Michigan

Michigan Department of Transportation (MDOT) has widened and opened 11 feet inside shoulder as an alternative travel lane during peak hours along the US-23 between M-14 (mile marker 45.6) and M-36 (mile marker 53.2) with a length of 8.5 miles since November 2017 (Figure 1-1).

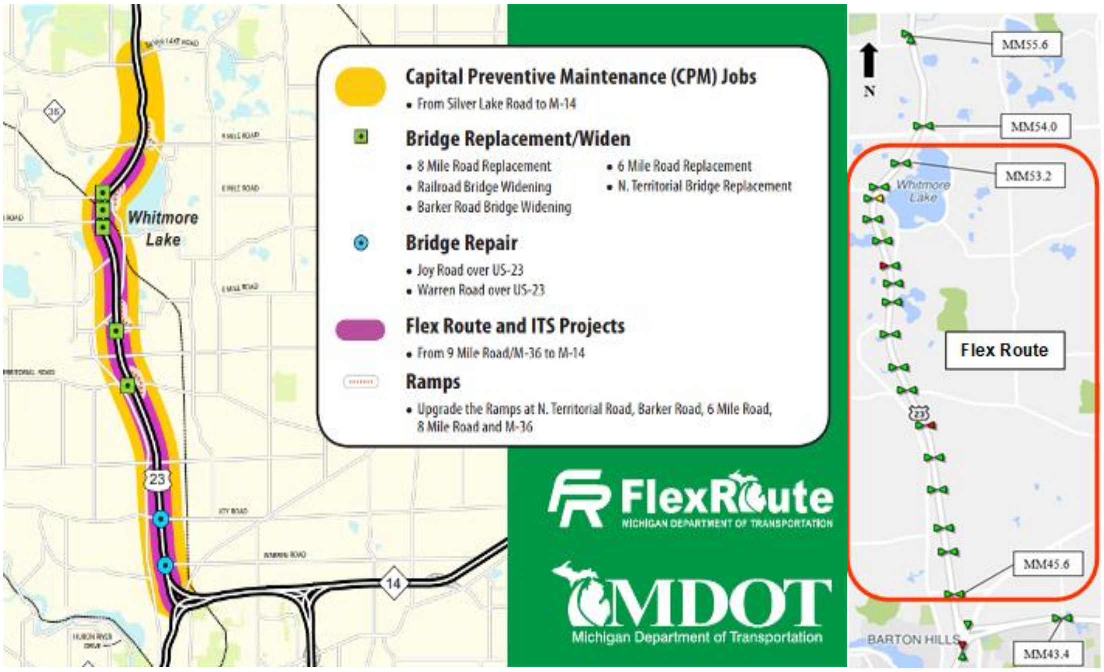


Figure 1-1 Location and layout of US-23 Flex route

Meanwhile, multiple intelligent transportation systems (ITS) equipment were installed to accommodate the uses of several ATM strategies: dynamic shoulder use, dynamic lane control, variable speed advisories, queue warning, real-time truck parking information and management systems (TPIMS) and over-height vehicle detection system (Figure 1-2). This is the first installation of ATM system in Michigan, which is also known as “US-23 Flex route”. In southbound direction, the route starts at M-36 (MM 53.2). There is an auxiliary lane for traffic that’s exiting the US-23. At this point, the left shoulder is widened out and become a third travel lane under those highly congested periods. It ends at MM 45.6 prior to the M-14 interchange. In northbound direction, the Flex route starts at MM 45.6 (M-14). It has three lanes at the beginning section. However, at the end of the route at MM 53.2, a bottleneck occurs because the travel lane drops from three to two lanes when the Flex route is under operation.

Figure 1-2 Example of over-height gantry on US-23 Flex route

US-23 Flex route is generally operated during peak hours (Southbound: 6-9:30 am and Northbound: 3-7 pm). In addition to the peak hours, it is also operated when large events (e.g., football games) and constructions occur, or in the occurrence of a crash and traffic need to be detoured to avoid second crashes. While the left shoulder lane is open, an advisory speed with a maximum value of 60 mph (posted speed limit is 70 mph) will be displayed on the dynamic message board to inform and warn the drivers (Foley, Steffen, & Palmer, N.A).

1.3 Research Objectives

Since deployments of D-PTSU are relatively new in the United States and Michigan, the primary objectives of this study are to evaluate the operational and safety performance of part-time use of inside shoulder. To accomplish the goal of the study, the following tasks were completed:

1. Travel time reliability was evaluated and compared before and after the installation of D-PTSU;
2. Speed-volume relationship was estimated after construction of D-PTSU;

3. Lane (Shoulder) compliance rate and advisory speed compliance rate were calculated and evaluated ;
4. Typical performance of D-PTSU under special events such as University of Michigan football games and holidays;
5. Incident cleared time was compared before and after the implantation of D-PTSU;
6. Safety performance of D-PTSU was also analyzed in terms of crash frequency and crash rate before and after D-PTSU operated.

The corresponding speed, travel time, volume, and crash data were provided by MDOT and Michigan Police Department. This study can provide better understanding of the current D-PTSU also provide guidance for future projects in Michigan and elsewhere.

1.4 Dissertation Structure

The reminder of this document provides the review of existing research literature, describe the data and methodology utilized, discuss the critical findings from the results concerning the objectives of the study, and summarize the findings. Brief descriptions of each chapter are as follows:

- CHAPTER 2: Literature Review – this chapter is organized into two sections to summarize the extant literature review regarding the impacts of D-PTSU on operational and safety performance.
- CHAPTER 3: Operational Impacts – this chapter provides a high-level overview of speed, travel time, and volume data of US-23 Flex route from different databases. Meanwhile, the operational performance of US-23 Flex route are examined in terms of travel time reliability, speed-volume relationship, drivers' compliance, performance during special events, and incident clearance time.

- CHAPTER 4: Safety Impacts – this chapter contains a high-level overview of crash data of US-23 Flex route. The safety performance of US-23 Flex route are evaluated by before and after comparisons in terms of crash rate and severity.
- CHAPTER 5: Conclusions – This chapter summarizes the key findings of the research. It also includes a discussion of limitations and recommendations for future research.

CHAPTER 2 LITERATURE REVIEW

Part-time shoulder use is one of transportation system management and operation (TSM&O) strategy that open left or right shoulder as temporary travel lanes during some hours of the day (FHWA, 2016). It is also part of Active Traffic Management (ATM) system and known as hard shoulder running (HSR). It always follows two other strategies: advisory variable speed limits (AVSLs) and lane use control signals (LUCS) in the ATM system (Dutta, Boateng, & Fontaine, 2018). The general purpose of this strategy is to cost-effectively reduce congestion and improve reliability of a transportation system. It is appropriate for the locations where have limited right-of-way, budgets, or other restrictions such as undesirable roadway geometrics to add new lanes to increase the capacity during the certain hours of a day. As Federal Highway Administration (FHWA) (2016) indicates that part-time shoulder use is primarily implement on freeways and several factors need to be considered before implementation: "the location of the shoulder (left/right shoulder options) used, vehicle-use options (e.g., bus only, high-occupancy vehicle (HOV) only, all vehicles except trucks). Operating schedule, and special speed controls." In addition to these factors, the minimum geometric clearances, visibility, pavement requirements and impacts on safety also need to be considered. All the minimum requirements should be met and traffic safety should be ensured ahead part-time shoulder use.

2.1 Operational Impacts

There are extensive numbers of examples of part-time shoulder use in Europe. The part-time shoulder use first time installed in the freeway section in German was the late 1990s. By 2010, approximately 250 km (155 miles) of the freeway had used shoulders as temporary travel lanes (BMWI, 2010). Part-time shoulder use was proved to increase throughout traffic, reduce traffic congestion, and increase trip reliability during peak hours (Geistefeldt, 2012; Fuhs & Brinckerhoff, 2010; Kuhn, 2010).

For example, Geistefeldt (2012) analyzed the operational performance of two three-lane major freeways in the German federal state of Hesse before and after the implementation of part-time shoulder use. The study showed that if the right shoulder was used as a temporary travel lane during the peak hours, the capacity of the three-lane freeways increased 20% to 25%, and the total duration of congestion decreased by up to 90%. Truck drivers had a higher percentage of acceptance for part-time shoulder use than passenger car drivers. Another example of successful part-time shoulder use is along Munich area freeways in Germany, which has resulted in a 20% increase in capacity during rush hour (Fuhs & Brinckerhoff, 2010). The Dutch employed a narrow median dynamic lane in the Netherlands, similar to the US-23 corridor. This lane was constructed in addition to the outside hard shoulder running and is used when there is an increase in traffic volume. However, the temporary shoulders are only used with variable speeds to minimize congestion and increase capacity by 7% to 22% (Kuhn, 2010).

In the US, the D-PTSU showed similar impacts (Jenior et. al., 2019; Kuhn, 2010; Balogh, 2012; Coffey et. al., 2018; Chun & Fontaine, 2016; Dutta et. al., 2019). For instance, part-time shoulder use on I-5 in Washington has increased throughput and reduced travel times by 8 to 10 minutes (Kuhn, 2010; Balogh, 2012). Coffey, Park, and Bhavsar (2018) also evaluated the operational performance of part-time shoulder use over I-476 in Philadelphia regarding travel time and speed under different scenarios. The results indicated that part-time shoulder use improved the overall operational performance. The maximum travel time and speed improvements were 60 % and 200%, respectively. Moreover, the Colorado Department of Transportation (CDOT) also found that after the implementation of part-time shoulder use, the throughput increased by 14%, and travel time improved by 38% in the general purpose lane. The average travel speed increased across all lanes (Jenior et. al., 2019). Additionally, Dutta et.al (2019) investigated the operational performance of part-time shoulder use, but they also considered the whole ATM system on I-66 in Virginia, including variable speed limits, lane use control signals, and dynamic hard shoulder running. The results from ATM utilization and average travel time analyses presented that the ATM system improves the operational performance significantly, especially dynamic hard shoulder running (Chun & Fontaine, 2016; Dutta et. al., 2019).

2.2 Safety Impacts

There was limited research investigated the impacts of part-time shoulder use on traffic safety. Dutta et.al (2018) evaluated the safety performance of ATM system on I-66 as well by conducting Empirical Bayes analysis. There was a significant reduction in crash on hard shoulder running section.

A study from Virginia showed opposite results. The researchers collected 3 years crash data of a portion of freeway after implementation of inside lane use for HOVs and part-time right shoulder use during peak hours. The annual average daily traffic (AADT) volume correlated to specific lane types were also included in the study. A negative binomial model was utilized to investigate the effects of relevant factors on the difference of crash frequency before and after part time shoulder use was active. The results indicated that no significant difference of crash frequency when considered all type of lanes. However, for right shoulder specific analysis, motorists' aggressive lane change behaviors at the merge and diverge areas during adverse light conditions were found to be significant. The crashes were also found to increase 38% in these areas (Lee, Dittberner, & Sripathi, 2007).

Another study conducted by FHWA in Minneapolis showed that the crash frequency slight increase after implementation of part-time shoulder use. The Empirical Bayes analysis was performed and the results that the total annual crash rate on I-35 W in Minnesota increased 28.4% after using the shoulder as a travel lane. MnDOT stated that a possible reason for an increase in crash rates might related to the removal of an upstream bottleneck while the part-time shoulder use was introduced. Then, the researchers applied SHRP 2 L07 models to the same segment and found that the crash rate was expected to increase 22% while the congestion increased. Thus, based on the results from the Empirical Bayes and SHRP 2 LO7 models, after implementation of part-time shoulder use correlated to an increase of 6.4% in crash rates occurred on the I-35W (FHWA, 2014).

NCHRP Project 17-89 examined the safety performance of part-time shoulder use on various freeways across the United States (Jenior et al., 2021). The project involved the development of safety performance functions for fatal-and injury (FI) crashes and property-damage-only (PDO) crashes for freeway segments, ramp entrance speed-change lane sites, and ramp exit speed-change lane sites. The study also resulted in a series of severity distribution functions that can be used to predict the distribution of crashes at various injury severity levels. The analysis included traffic and geometric characteristics, as well as details of the features of associated transition zones (i.e., locations upstream, downstream, or between portions of a freeway with a PTSU typical section) and turnouts (i.e., paved areas adjacent to a shoulder used for PTSU that function as refuge areas for disabled vehicles).

The results showed that higher FI crashes were observed on urban freeway segments with PTSU operations, especially on those segments where PTSU was in operation for longer periods of the day. Segments with turnouts or lane widths of 12 feet tended to experience fewer FI crashes.

Interestingly, the results showed that the total number of crashes was 137 percent higher during times when the shoulder was open for use versus when it was closed. The report noted that no significant difference was observed in crash risks between right- and left-shoulder PTSU, which is due in part to the fact that there were limited numbers of cases where left-side shoulders were used by state DOTs. Total crashes were 7.3 percent lower at facilities that had converted from static PTSU to dynamic PTSU (e.g., activation based on volumes rather than fixed time periods).

CHAPTER 3 OPERATIONAL IMPACTS

This chapter details a series of analyses focused on assessing the operational performance of the US-23 Flex route. A before-after comparison is conducted to quantify changes in speeds and travel times along the corridor after the median shoulder was converted to a temporary travel lane. This includes an evaluation of changes in average speeds/travel times, as well as various travel time reliability measures. Additional investigations were conducted to examine Flex route performance on the dates of special events (i.e., University of Michigan home football games and holidays), incident clearance times, and driver response to gantry messages.

3.1 Data

Several data sources were utilized to assess the operational performance of the Flex route. This includes probe vehicle data, microwave vehicle detection systems (MVDS) reports, permanent traffic recorder (PTR) data, ATM reports, and incident clearance data. The following sections provide an overview of each data source and describe how and where these data were used for analysis purposes.

3.1.1 Probe Vehicle Data

Probe vehicle data are collected from global positioning system (GPS) equipment that is installed in a wide variety of vehicles and devices, including commercial vehicle fleets, connected passenger vehicles, and cell phones. The GPS devices send and receive signals from earth-orbiting satellites. A control center converts information from the GPS signal to display real-time position and speed data for the probe vehicles. The corresponding travel time can be determined from the travel speed and distance (Barichello & Knickerbocker, n.d.; Turner et al., 1998).

In Michigan, probe vehicle data from INRIX is available through the Regional Integrated Transportation Information System (RITIS). RITIS is a secure data platform that integrates existing operational data from transportation agencies. It has a variety of uses for transportation officials, first responders, planners, and researchers to assess operational performances of roadways, evaluate active operations, perform long-range planning and capital programming, conduct research, improve executive leadership, and obtain traveler information (CATT Lab, 2021).

The Michigan INRIX data is available dating back to January 1, 2016 and includes real-time travel time information for each eXtreme Definition (XD) segment along the Flex route at various time intervals (1-minute, 5-minute, 10-minute, 15-minute, and 1-hour). Data are also available at the Traffic Message Channel (TMC) level. In comparison to a typical TMC segment, the XD segments generally have more granularity and allow for more detailed investigations as to how travel times/speeds vary over the road network (INTRIX, 2021). For the purposes of the Flex route evaluation, this is the only data source that provides travel speed and time information during the periods both before (i.e., 2016) and after (2018 onward) the route went into operation.

Ultimately, the data used as a part of this evaluation covered 8.76 miles of the US-23 corridor in the southbound direction and 8.49 miles in the northbound direction (based upon XD segmentation). Figure 3-1a shows the target area of INRIX probe vehicle data on the Flex route. A detailed quality assurance/quality control (QA/QC) review was conducted on these data at the onset of the analysis. This review of data available through RITIS showed that 1.75 miles of data were missing in the southbound direction from 12:00 am, January 1, 2016, to 2:00 pm, October 8, 2019. This area is highlighted in Figure 3-1b. In addition, there were also a few other minor issues with the data, including a few instances of missing or duplicate data. Ultimately, the data from the missing 1.75 miles were obtained directly from INRIX. Duplicate data were removed and there were a small number of cases where gaps existed in the final dataset, though these did not have a substantive impact on the analysis.

Initially, the operational evaluation was going to compare changes in speed/travel time data between 2016 and 2018-2020. However, a few issues were identified for the latter time period. A significant inflection point was observed from speed profiles as shown in Figure 3-2 for both the southbound (Figure 3-2a) and northbound (Figure 3-2b) directions. In both instances, all speeds increased significantly in early June of 2019. This was due to changes in the fleet data that is used by INRIX to provide the travel time estimates. From this point forward, there was a large increase in the relative proportion of passenger vehicle data (as compared to large trucks). This resulted in increases of 5 mph or more. In addition, it is also important to note that data from March 2020 onward were atypical as substantive changes in travel patterns occurred due to travel restrictions imposed by the coronavirus disease 2019 (COVID-19) pandemic. The impacts of pandemic will be introduced in the later sections.

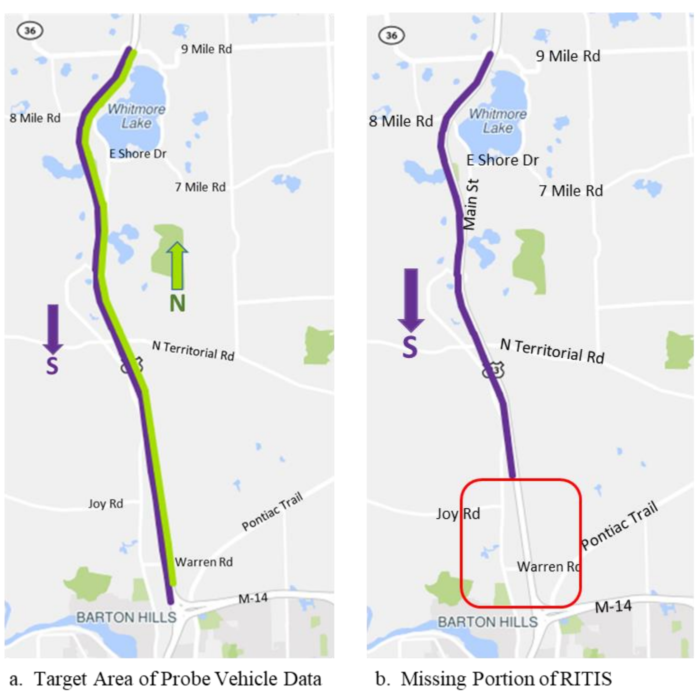
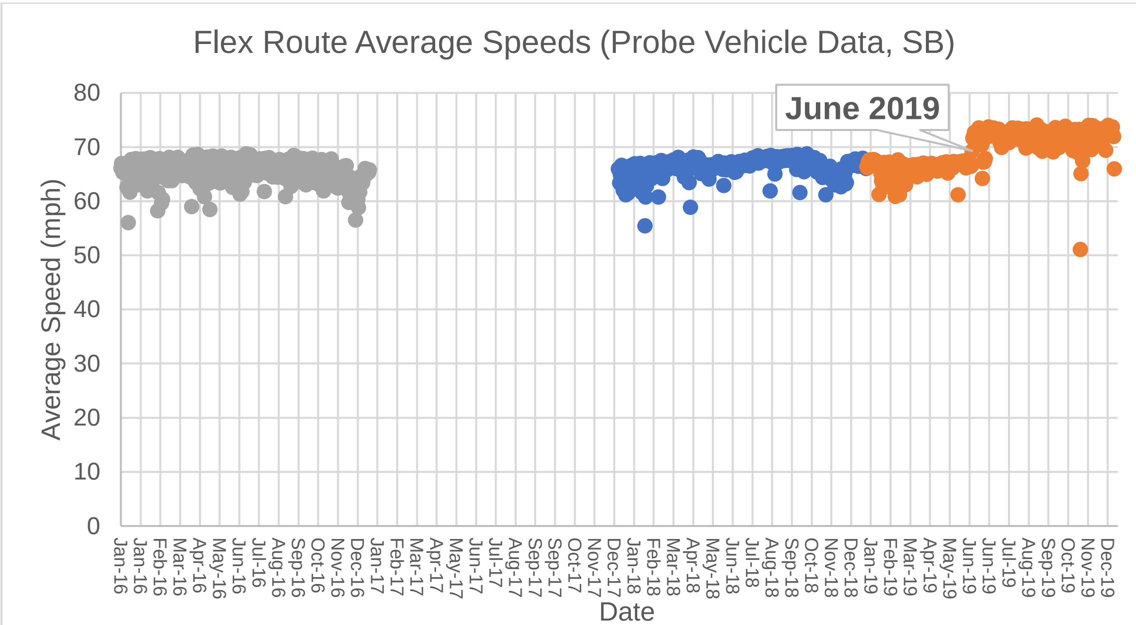
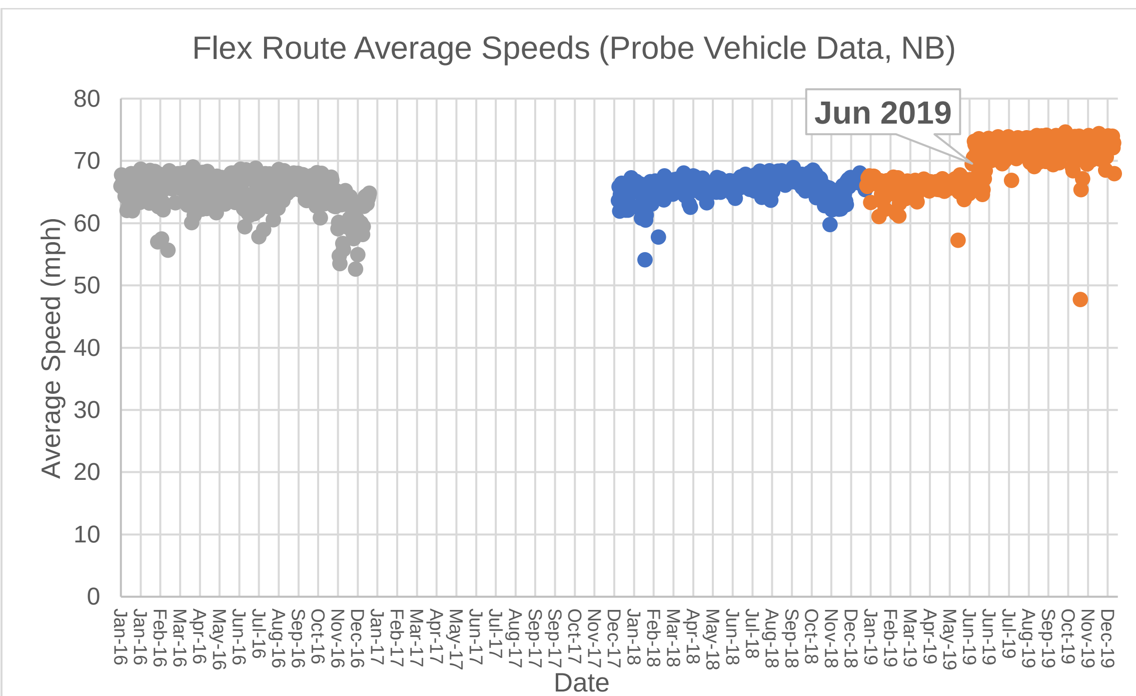


Figure 3-1 Coverage of INRIX probe vehicle data from RITIS

Consequently, to allow for a more appropriate comparison between the pre- and post-implementation periods, data from 2019 onward were removed from the analysis. As such, the before-after analyses focused exclusively on data from calendar years 2016 and 2018.



a. Southbound



b. Northbound

Figure 3-2 Yearly speed profile of INRIX probe vehicle data

3.1.2 Microwave Vehicle Detection System (MVDS) Reports

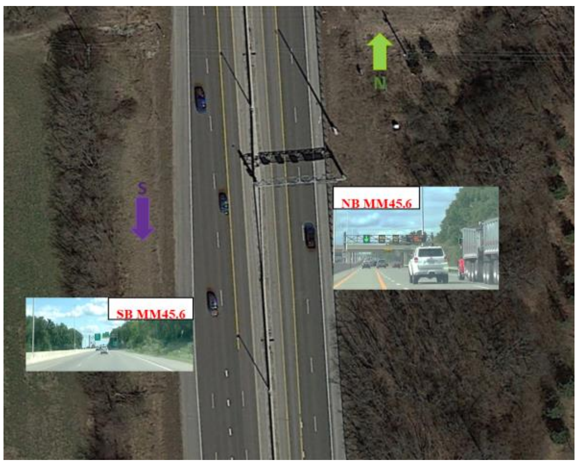
Microwave vehicle detection systems (MVDS) are a noninvasive means of collecting data from above ground sidefire microwave sensors. The data collection equipment consists of a radar detection unit pole-mount assembly, mounting hardware, Underwriters Laboratories (UL) approved power supply, lightning and surge protection, cables, and communications patch rods (MDOT, 2017). The system transmits microwave energy toward vehicles and the reflected signal can be used to determine vehicle volume counts and speeds in each travel lane based on the waveform that is transmitted by the radar sensor (Gordon & Tighe, 2005).

For the purposes of this study, two years of MVDS reports for the Flex route were provided by MDOT. These reports included directional speed and volume data for each lane at every mile marker (MM) along the Flex route at one-minute intervals. Unfortunately, these data are only available from January 1, 2018 onward. Since no data are available prior to when the Flex route went into operation, the MVDS reports were used for a series of analyses that focused on the in-service performance after the hard shoulder running was introduced in November 2017.

The Flex route is located between MM 45.6 and MM 53.2 as shown in Figure 3-3. In the southbound direction, the route starts at MM 53.2 and ends at MM 45.6 prior to the M-14 interchange (Figure 3-3a). The Flex lane is introduced near an auxiliary lane in this direction and the temporary travel lane terminates directly at the M-14 interchange without a lane drop (the shoulder lane converts to a general purpose lane just north of the M-14 interchange in the vicinity of Warren Road)

In the northbound direction, the Flex route starts at MM 45.6, where a third travel lane is introduced. One important difference as compared to the southbound direction is that a lane drop from three to two lanes occurs at the termination of the northbound Flex Lane near MM 53.2. This introduces a bottleneck as vehicles from the leftmost (shoulder) lane attempt to merge into the subsequent two-lane section (Figure 3-3b).

In addition to the data along the extents of the Flex route, the MVDS reports also contain partial upstream and downstream data at MM 43.4, MM54.0, and MM 55.6. These data are available from August 28, 2018 to December 31, 2019 and provide additional information that allow for an in-depth investigation of impacts immediately upstream and downstream of the Flex route, including the northbound bottleneck. Figure 3-4 displays a coverage map of where the MVDS sensors are installed.



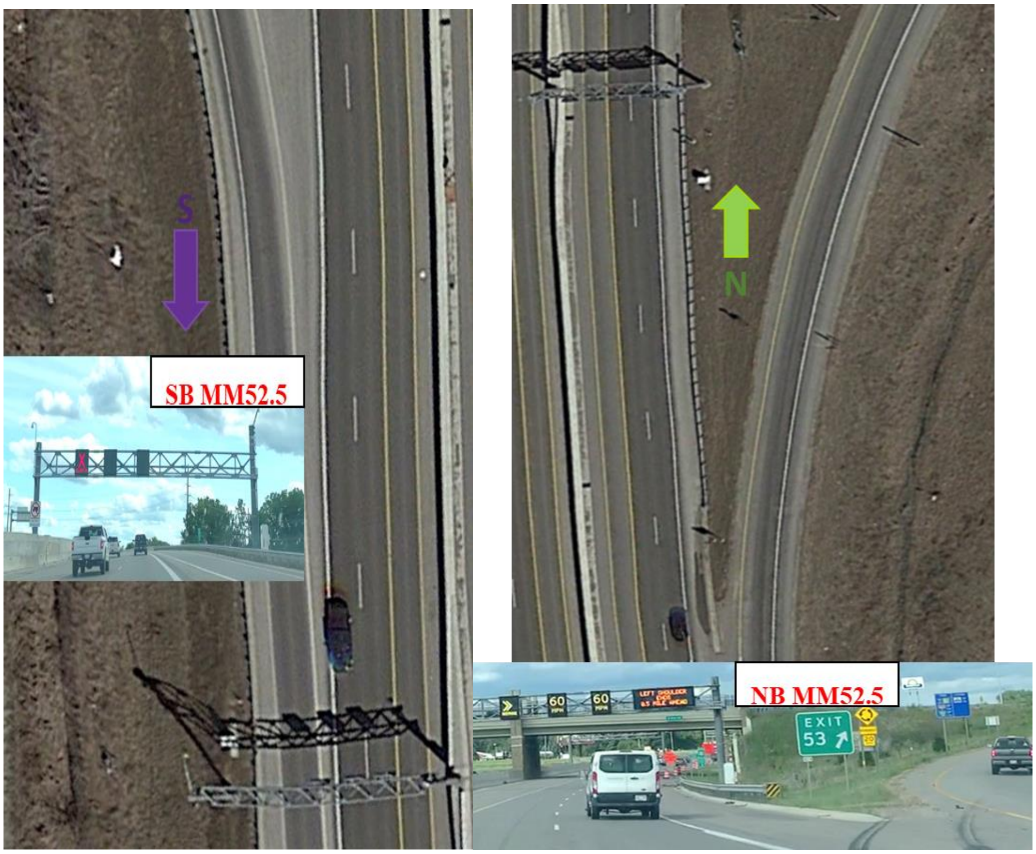
a. MM 45.6

b. MM 53.2

Figure 3-3 Starting and ending mile markers of the US-23 Flex route

Figure 3-4 Map of MVDS sensor locations

As with the probe vehicle data, QA/QC reviews were conducted before analyzing the data. Several points should be noted regarding a few issues that were identified as a part of these reviews. In general, data are provided for three lanes in each direction along the Flex route. This includes the left shoulder, left lane, and right lane. However, additional data were available for the auxiliary lane at MM 52.5 in both directions. A deceleration lane is also located in the southbound direction at MM 52.5 Consequently, four lanes of data were anticipated at this location. However, data for only three lanes were provided in the MVDS reports. An investigation suggests that data from the inside shoulder (Flex lane) were missing at this location. Figure 3-5 shows pictures of the gantries at each of these locations, which illustrate the presence of additional acceleration/deceleration lanes at MM 52.5, as well as a deceleration lane at MM 53.2.



a. MM 52.5

b. SB MM 53.2

Figure 3-5 Pictures of mile marker 52.5 and 53.2 on US-23 Flex route

3.1.3 Permanent Traffic Recorder (PTR) Data

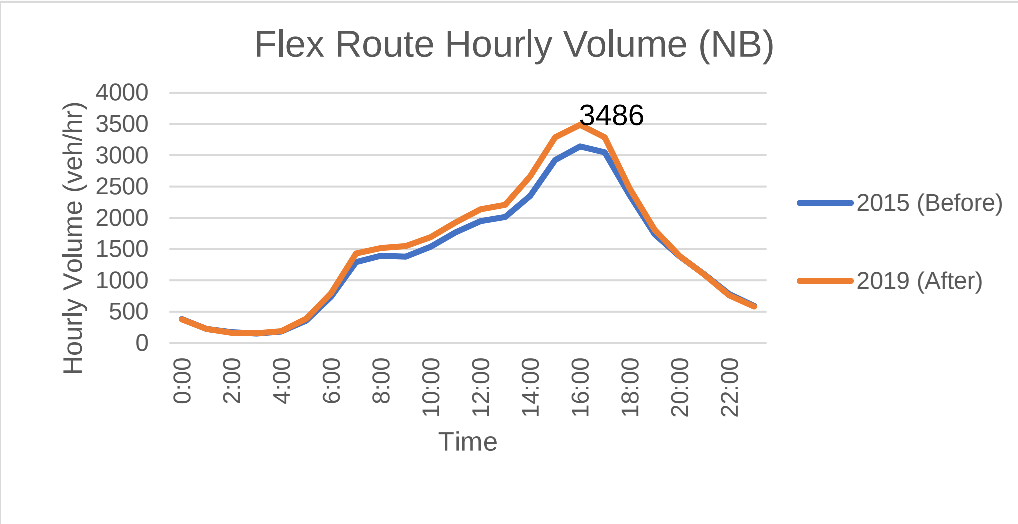
As noted above, the only operational data available prior to January 1, 2018 were from RITIS/INRIX. While this information includes travel time and speed information, there were no volume data available. The only source of detailed volume data is from the MVDS.

Consequently, estimates of the hourly traffic volume for the period prior to Flex route implementation were obtained from permanent traffic recorder (PTR) stations. PTR stations are installed throughout Michigan as a part of the MDOT traffic monitoring program. Permanent electronic sensors are installed in the pavement and continuously record the passage of vehicles over a specific portion of roadway over time. The resultant reports provide hourly data for each day of the month, in addition to summary average daily traffic (ADT) counts for every Saturday, Sunday, weekday, and month (MDOT, n.d.-b).

MDOT provided PTR reports for the period from 2014 through 2020. The PTR data for the Flex route were specifically obtained for PTR Station 8239, which is located 0.5 miles south of Barker Road. These data include hourly volume count and travel speeds from 2014 through 2017. The volume and speed data are available at 15-minute intervals after 2017. However, data inspection showed a number of time gaps, including the periods from January to February 2016 and January 2017 to June 2018. Consequently, 2015 and 2019 PTR data were utilized in the study as these were the years for which full data were available as near to the implementation date of the Flex route as possible. A summary of the PTR data is shown in Table 3-1 and details of changes in hourly volumes between 2015 and 2019 are included in Figure 3-6. The results showed that the maximum throughput in the northbound direction increased by 11.0 percent and in the southbound direction by 35.4 percent.

Table 3-1 Descriptive statistics of PTR volume data

Direction	Period	Year	Min.	Max.	Mean	Std. Dev.
NB (veh/hr.)	Before	2015	149.7	3141.62	1372.87	943.23
	After	2019	154.6	3486.16	1482.23	1050.21
SB (veh/hr.)	Before	2015	112.29	2502.29	1371.89	838.32
	After	2019	122.14	3388.63	1524.99	995.58



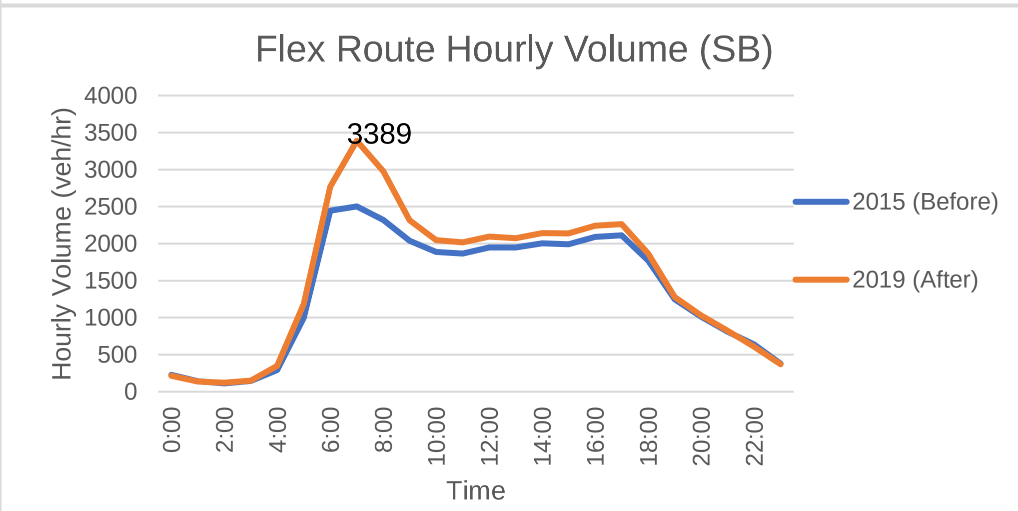


Figure 3-6 Hourly volume of US-23 Flex route

3.1.4 Active Traffic Management (ATM) Reports

As a part of the active traffic management (ATM) system, a series of dynamic message signs (DMS) are installed on the overhead gantries at each milemarker which are spaced at approximately every 0.5 miles along the Flex route. These signs display different messages, such as whether the shoulder or a specific travel lane is opened or closed, as well as variable advisory speeds, queue warnings, overheight vehicle warnings, etc. An example photo of a gantry with four DMS from the Flex route is shown in Figure 3-7. There are 16 and 18 gantries installed in the southbound and northbound directions, respectively, of the US-23 Flex route. Among these, five gantries in the southbound and four gantries in the northbound direction include a sequence of four DMS as shown in Figure 3-7. The other gantries include three DMS, exclusive of the large text-based sign that appears over the right shoulder.

The ATM reports provided by MDOT included timestamps (to the nearest second) and corresponding messages whenever a gantry message changes. Similar to the MVDS reports, the ATM reports were available from January 1, 2018 onward. As with the previously described datasets, the analyses in this project was from January 1, 2018 to December 30, 2019, avoiding pandemic related traffic anomalies.

The typical messages shown on each of the four DMS are summarized below:

- **DMS 1:**
    - Red X, Green Arrow, Merge Right
- **DMS 2 and DMS 3:**
    - Various advisory speeds (e.g., 60/50/40/30 mph)
    - Red X, Green Arrow, Merge Right or Merge Left
- **DMS 4:**
    - Detailed messages to guide drivers: slow traffic warning, lane closure, crash warning, left shoulder is open/closed etc.

Figure 3-7 An example of gantry messages on the US-23 Flex route (NB MM46.8)

3.1.5 Incident Clearance Data

Unexpected and non-recurring incidents (e.g., crashes, debris, disabled vehicles) generally cause frustration for motorists, introduce considerable delay, and create additional adverse impacts such as wasted fuel. In response to these issues, MDOT established a Freeway Courtesy Patrol (FCP) in 1994 to assist motorists who encountered such issues on select freeways in Southeast Michigan, including the US-23 corridor. The FCP operates 24 hours per day, seven days a week. The primary goals of the FCP are to reduce the delay caused by these types of incidents and improve the operations of the freeway system. The FCP services include (MDOT, n.d.-a):

- servicing disabled vehicles by providing fuel, oil, and other system fluids;
- clearing stranded vehicles and debris from driving lanes;
- changing or inflating tires;
- making minor mechanical repairs;
- securing the area around your vehicle;

- transporting motorists to a safe location;
- providing cell phone assistance;
- transporting stranded motorists; and,
- providing directions.

For the purposes of this study, data from the FCP data was obtained in order to better understand the impacts of the Flex route on the operational and safety performance of the corridor. To this end, incident clearance data from the FCP was obtained for periods before (January 2015-December 2016) and after (January 2018 – March 2019) implementation of the US-23 Flex route. After March 2019, the vendor of this data changed from the MDOT FCP to a third-party contractor. Thus, additional data for the rest of 2019's months were obtained from this contractor. The data involved traffic management information such as locations of events, types of events and services, FCP arrival time, and the incident clearance time, etc. The incident clearance time is defined as the time when the traffic fully recovers after incidents.

3.1.6 Data Integration

The datasets described previously were integrated for analysis purposes. As a part of the operational analyses, three primary datasets were utilized: microwave vehicle detection system (MVDS) reports; permanent traffic recorder (PTR) data; and INRIX probe vehicle data.

Data at the highest level of fidelity were obtained from the MVDS reports, which provide traffic volume and average speed information at each mile marker in one-minute intervals. These data became available once the ITS infrastructure was installed and, consequently, these data are only available for the period after the Flex route went into operation. Before period Flex Route volumes were assumed to be proportional (across XD segments) to the after period volumes. Consequently, the 2016 traffic volumes were estimated using the ratio of annual average daily traffic (AADT) between the before and after periods. Data for the 2016 and 2018 AADT were collected from MDOT's Traffic Data Management System (TDMS). The TDMS provides continuous count data from PTR stations. The segment-specific 2016 volumes were estimated by multiplying the 2018 MVDS volume data by the ratio of 2016 AADT to 2018 AADT. To be consistent with the INRIX probe vehicle data, all MVDS traffic volumes was aggregated into 15-minute intervals.

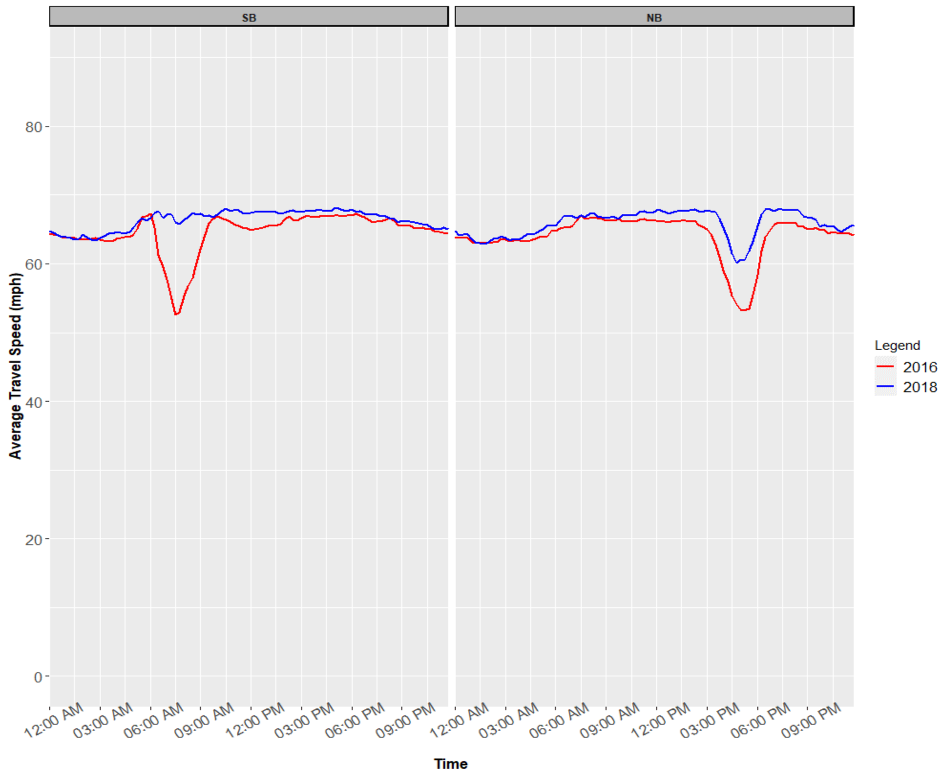
As noted previously, the travel times for each XD segment before (2016) and after (2018) construction of the Flex route were available from INRIX probe vehicle data. The travel time was calculated based on the average vehicle speed and length of each XD segment (i.e., segment length divided by average speed). The INRIX travel time data are available at the segment level, but the MVDS traffic volume data are available at the point level. To join the two datasets, the shapefiles for the Michigan INRIX XD segments, 2015 sufficiency file, and Michigan mile marker database were obtained from MDOT. The XD segment shapefiles include the coordinates of the starting points and ending points for each segment hours. The sufficiency file provides the physical road (PR) number, as well as the beginning mile points (BMP) and ending mile points (EMP) for each Michigan trunkline segment. It also serves as the base map for the Michigan government. The mile marker shapefile indicates the locations of specific mile markers along the US-23 corridor, along with the corresponding physical road (PR) number and mile points. The following steps outline the integration procedures for these databases:

1. The Flex route segments, as well as the upstream and downstream segments, were aggregated such that they were approximately one mile in length based on PR numbers, as well as BMPs and EMPs from the sufficiency file. This resulted in a total of nine segments in the southbound direction and eight segments in the northbound direction.

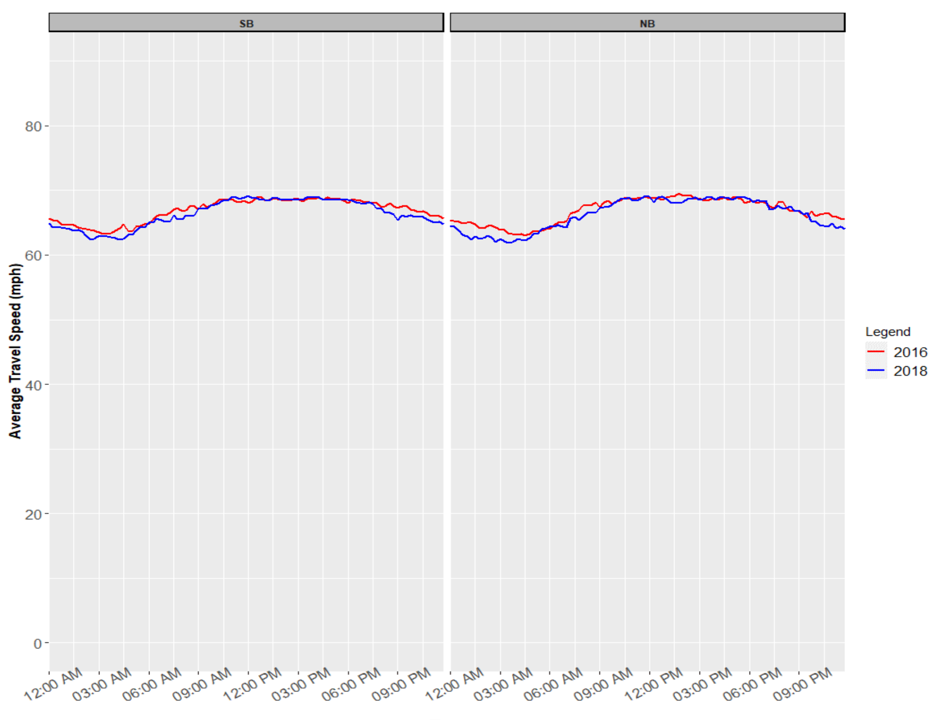
2. A linear referencing tool was used in ArcMap to locate the starting and ending points of XD segments along the Flex route. These points were matched with the sufficiency file to determine the corresponding PR numbers and mile points.
3. The XD segments were aggregated into approximately one-mile lengths based on PR numbers, BMPs, and EMPs as detailed in Step 1. Travel times were calculated for these segments from the INRIX probe vehicle data.
4. The traffic volume was calculated at the segment level using the PR numbers and mile points from the mile marker shapefile.
5. Vehicle miles traveled (VMT) were calculated by multiplying these volumes by the adjusted segment lengths.
6. VMT-weighted travel times were then calculated for each segment.

3.2 Impacts on Travel Time and Reliability

The INRIX probe vehicle data were used to examine changes in travel time and speed data before and after implementation of the Flex route. Figure 3-8 shows trends in average travel speeds between the before and after periods. Average travel speeds increased significantly during weekdays, especially during the peak hours. In contrast, no significant difference was found during the weekends. In addition, Figure 3-9 presents changes in the average speeds moving in each direction along the Flex route. These data generally show increasing speeds in both the southbound and northbound directions, except for the northernmost extent in the northbound direction at the lane drop.



a. Weekdays



b. Weekends

Figure 3-8 US-23 Flex route average travel speed over time

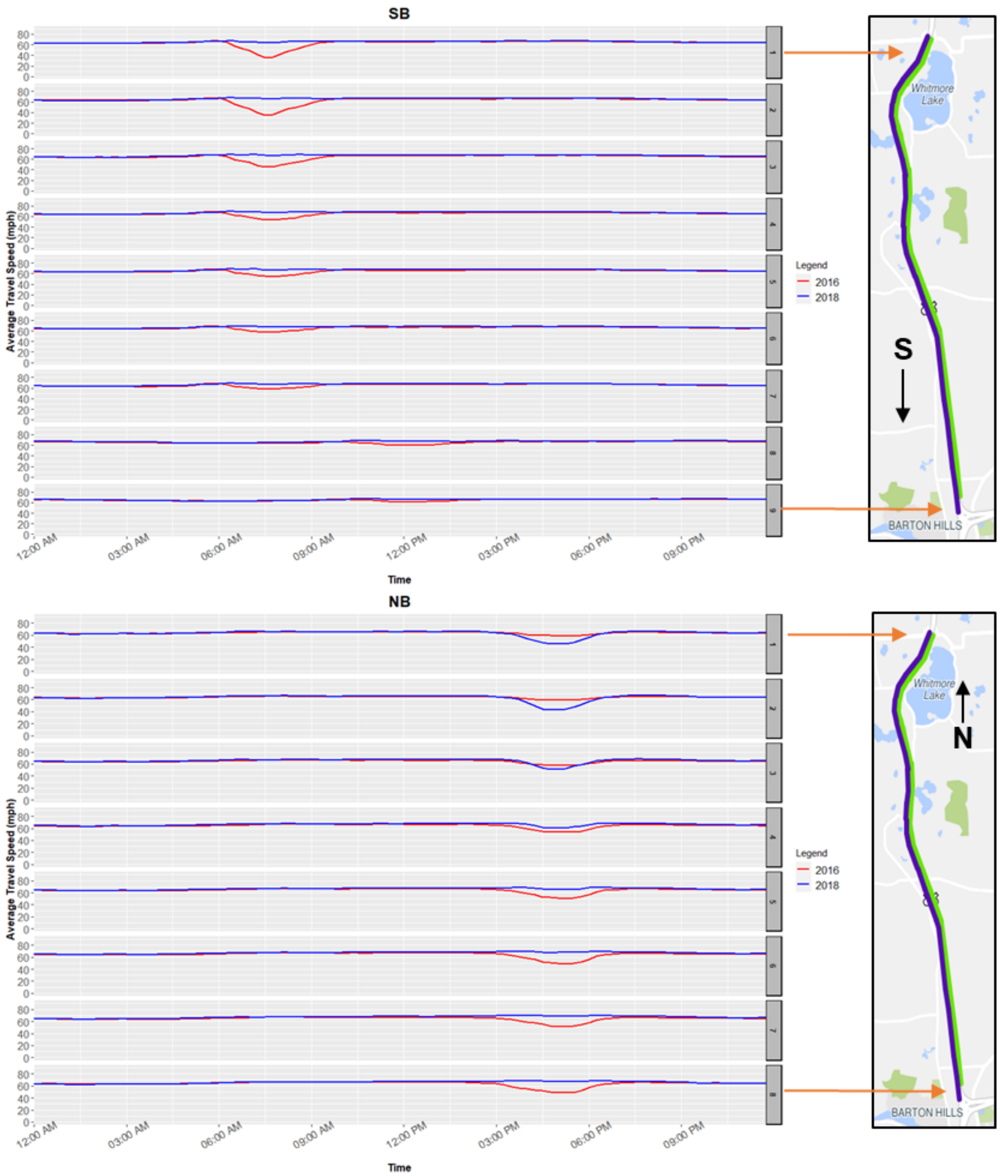


Figure 3-9 US-23 average travel speed over time at segment-level

3.2.1 Travel Time Reliability Definitions

Travel time reliability is one of the key factors to evaluate the operational performance of a transportation system. According to the FHWA, travel time reliability is “the consistency or dependability in travel times, as measured from day-to-day and/or across different times of times of the day” (Office of Operations, 2005). Reliability is crucial to both motorists and freight carriers.

Consistent, reliable travel times allow travelers to assess their time and make better use of it. Similarly, freight carriers rely on predictable travel times to stay competitive in the market. Travel time reliability has also become a widely used measure for evaluating the effectiveness of countermeasures, such as hard shoulder running (Office of Operations, 2005). Therefore, to understand the effectiveness of the US-23 Flex route, various travel time reliability measures were calculated for the periods before and after implementation. This section introduces several of these measures and details the methodology used to calculate each using the data described previously.

According to the FHWA, reliability can be quantified in the following ways (Office of Operations, 2005):

- Free-flow travel time: The free-flow travel time was calculated as the 85th percentile travel time during the off-peak period (Office of Operations, 2015). For the purposes of the Flex route, this period is defined as Monday through Friday, from 9 am to 4 pm and 7 pm to 10 pm, as well as Saturday and Sunday from 6 am to 10 pm.
- Travel time index: The travel time index is the ratio of the average travel time required as compared to the free-flow travel time and is calculated as shown in Equation 1.

$$\textbf{Travel Time Index} = \frac{\textbf{Average Travel Time}}{\textbf{Free Flow Travel Time}} \qquad \textbf{Equation 1}$$

- Planning time (or 95th percentile travel time): The planning time provides an upper bound, or near worst-case scenario, for the travel time. This is calculated as the 95th percentile travel time.
- Planning time index: The planning time index represents how much larger the 95th percentile travel time is as compared to the ideal or free-flow travel time. Equation 2 shows the calculation of the planning time index.

$$\textbf{Planning Time Index} = \frac{\textbf{95th Percentile Travel Time}}{\textbf{Free Flow Travel Time}} \qquad \textbf{Equation 2}$$

- Buffer time: The buffer time denotes the extra time (beyond the average travel time) required by drivers in order to traverse a segment in no greater than the 95th percentile travel time. Equation 3 shows the calculation of buffer time.

$$\boldsymbol{Buffer\ Time = 95th\ Percentile\ Travel\ time - Average\ Travel\ Time} \quad \textbf{Equation 3}$$

- Buffer time index: The buffer time index expresses the buffer time as a proportion of the average travel time as shown in Equation 4.

$$\boldsymbol{Buffer\ Time\ Index = \frac{Buffer\ Time}{Average\ Travel\ Time}} \qquad \textbf{Equation 4}$$

3.2.2 Travel Time Reliability Results

Summary data for each of the travel time reliability measures were calculated over the Flex route limits and are included in Table 3-2, Table 3-3, and Table 3-4. First, Table 3-2 presents reliability measures on a daily basis for weekdays. Separate estimates are provided for the periods before and after the Flex route went into operation. Table 3-3 presents these same quantities for weekends.

Table 3-2 Results of travel time reliability during weekdays (24 hours)

Direction	Period	Year	Free Flow Travel Time (mins)	Average Travel Time (mins)	95th percentile Travel Time (mins)	Buffer Index	Planning Time Index	Travel Time Index
Southbound	Before	2016	8.2	8.4	11	0.3	1.3	1
	After	2018	8.2	8	8.6	0.1	1.1	1
Northbound	Before	2016	8	8.3	11.4	0.4	1.4	1
	After	2018	8	7.9	9	0.1	1.1	1

Collectively, these data show that the average travel times on the Flex route reduced from 8.4 to 8 minutes in both southbound and northbound directions when considering the entire day. The 95th percentile travel time decreased 2.4 minutes (21.5 percent) regardless of direction. The corresponding indices improved as well. Other than that, the free-flow travel time and average travel times on the Flex route ranged from 7.8 to 8.0 minutes during weekends when considering the entire day. These times (and the associated free-flow speeds) were virtually unchanged between the before and after periods. Similarly, the other metrics tended to be quite similar when averaging over the entire day.

Table 3-3 Results of travel time reliability during weekends

Direction	Period	Year	Free Flow Travel Time (mins)	Average Travel Time (mins)	95th percentile Travel Time (mins)	Buffer Index	Planning Time Index	Travel Time Index
Southbound	Before	2016	8.2	8.0	8.6	0.1	1.0	1.0
	After	2018	8.2	8.0	8.8	0.1	1.1	1.0
Northbound	Before	2016	8.0	7.7	8.4	0.1	1.0	1.0
	After	2018	8.0	7.8	8.7	0.1	1.1	1.0

These same quantities were calculated separately for the peak and off-peak hours on weekdays and are detailed in Table 3-4. Table 3-4 is of particular interest as this illustrates the changes that occurred during the peak traffic periods when the Flex route is in operation. After the Flex route went into operation, average travel times during the peak periods were reduced by 16.5 percent and 11.2 percent in the southbound and northbound directions, respectively. Similarly, reductions of 37.3 percent and 20.8 percent in the 95th percentile travel times were observed southbound and northbound, respectively. These reductions led to improvements in the corresponding trip planning time and buffer time metrics, as well. Furthermore, drivers were able to save additional time during the off-peak hours, though these savings were relatively small.

Table 3-4 Results of travel time reliability during weekdays (peak vs. off-peak hours)

Direction	Period	Year	Free Flow Travel Time (mins)	Average Travel Time (mins)	95th percentile Travel Time (mins)	Buffer Index	Planning Time Index	Travel Time Index
Peak Hour								
Southbound 6:00–9:30 am	Before	2016	8.2	9.7	14.2	0.5	1.7	1.2
	After	2018	8.2	8.1	8.9	0.1	1.1	1.0
Northbound 3:00–7:00 pm	Before	2016	8.0	9.8	17.3	0.8	2.2	1.2
	After	2018	8.0	8.7	13.7	0.6	1.7	1.1
Off-Peak Hour								
Southbound	Before	2016	8.2	8.2	8.7	0.1	1.1	1.0
	After	2018	8.2	8.0	8.6	0.1	1.1	1.0
Northbound	Before	2016	8.0	8.0	8.6	0.1	1.1	1.0
	After	2018	8.0	7.8	8.5	0.1	1.1	1.0

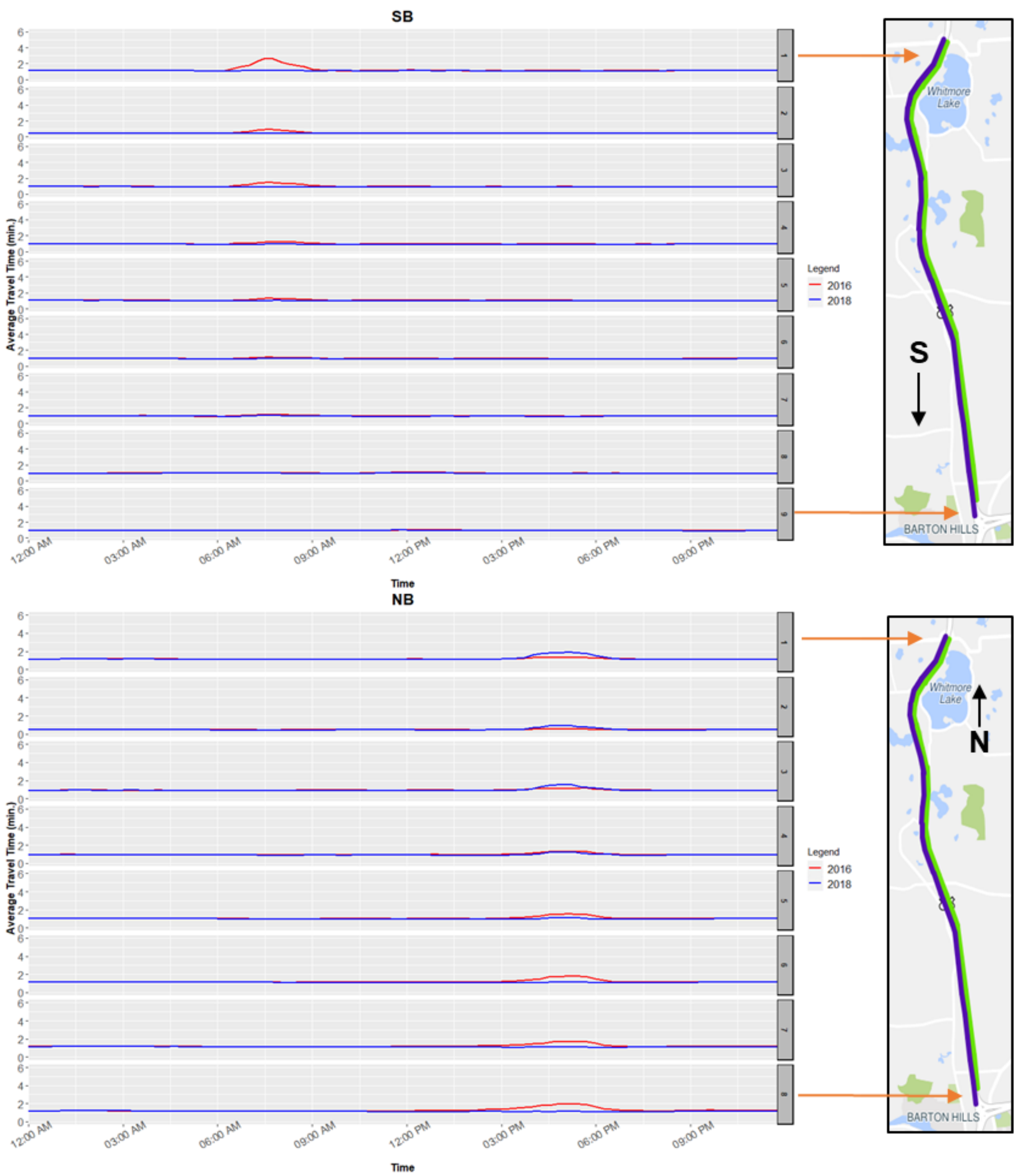
In general, motorists in the southbound direction tended to save more time than in the northbound direction. This is largely due to a bottleneck that is present at the northbound terminus of the Flex route where the left (inside shoulder) lane terminates in a lane drop condition.

In addition to the overall performance, travel time reliability was also examined at the individual segment-level. As discussed previously, the southbound and northbound directions were comprised of nine segments and eight segments, respectively. The average and 95th percentile travel time, buffer time index, planning time index, and travel time index were calculated for each segment during weekdays and weekends.

To allow for a visual assessment of changes in travel times over time and space, the target variables were plotted for each segment by time-of-day and are shown in Figure 3-10 and Figure 3-11. Since the trends of planning time and travel time index were similar to the trends of average and 95th percentile travel time, the plots of planning time and travel time index can be found in Appendix A.

Figure 3-10 shows gradual, but persistent, improvement in average annual travel times during weekday peak hours in both directions. These benefits were more pronounced in the southbound direction. In contrast, travel times actually increased downstream near the Flex route terminus in the northbound direction. This was again due to the bottleneck that occurs at the lane merge at the Flex Route termination point. The planned extension of the Flex route to I-96 should address this issue and result in improvements that are consistent across the corridor.

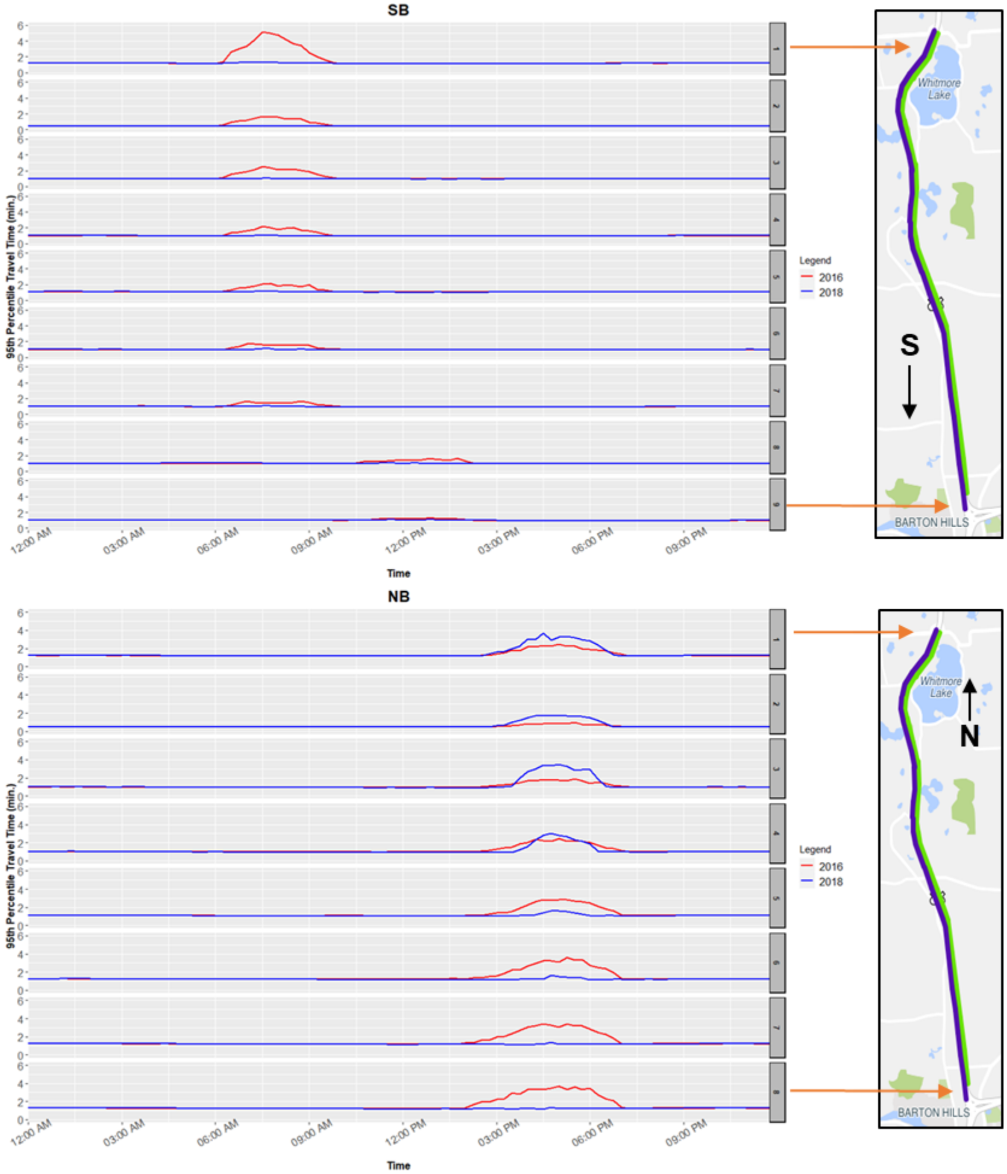
Figure 3-11 provides a similar graphical summary for changes in average annual travel times during weekends. These results show that travel times remained quite stable during weekends after Flex route implementation. This is reflective of the lower traffic volumes that are generally experienced during the weekends and the fact that the Flex route is generally not in operation at these times. The one exception would be for special events, such as home football games at the University of Michigan. This special case is covered subsequently in this chapter of the report. Beyond average travel times, 95th percentile travel time, buffer time index, planning time index, and travel time index all showed similar trends and the associated plots can be found in Appendix A.



a. Plot of average travel time during weekdays

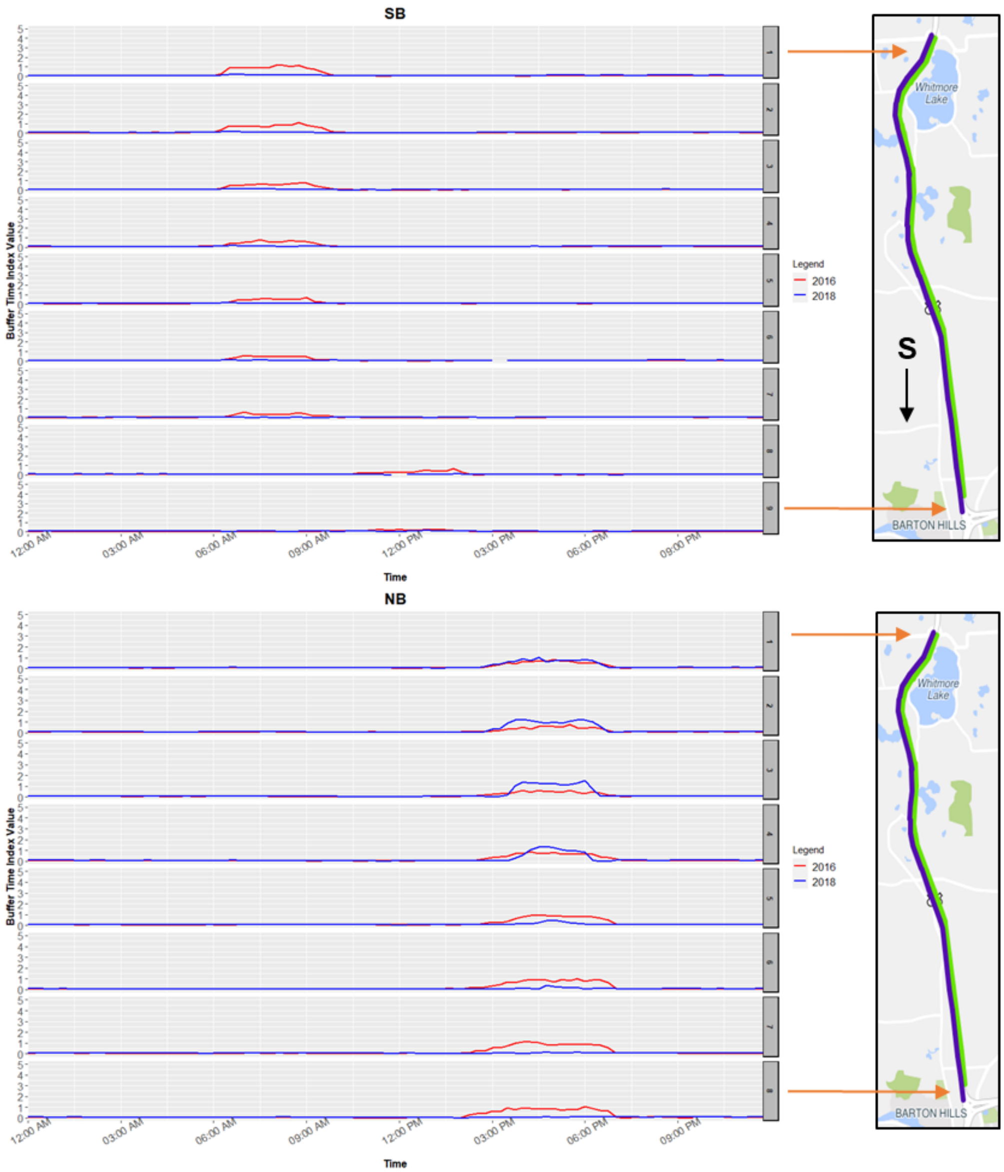
Figure 3-10 Plots of travel time reliability over time at segment-level during weekdays

Figure 3-10 cont'd



b. Plot of 95th travel time during weekdays

Figure 3-10 cont'd



c. Plot of buffer time index during weekdays

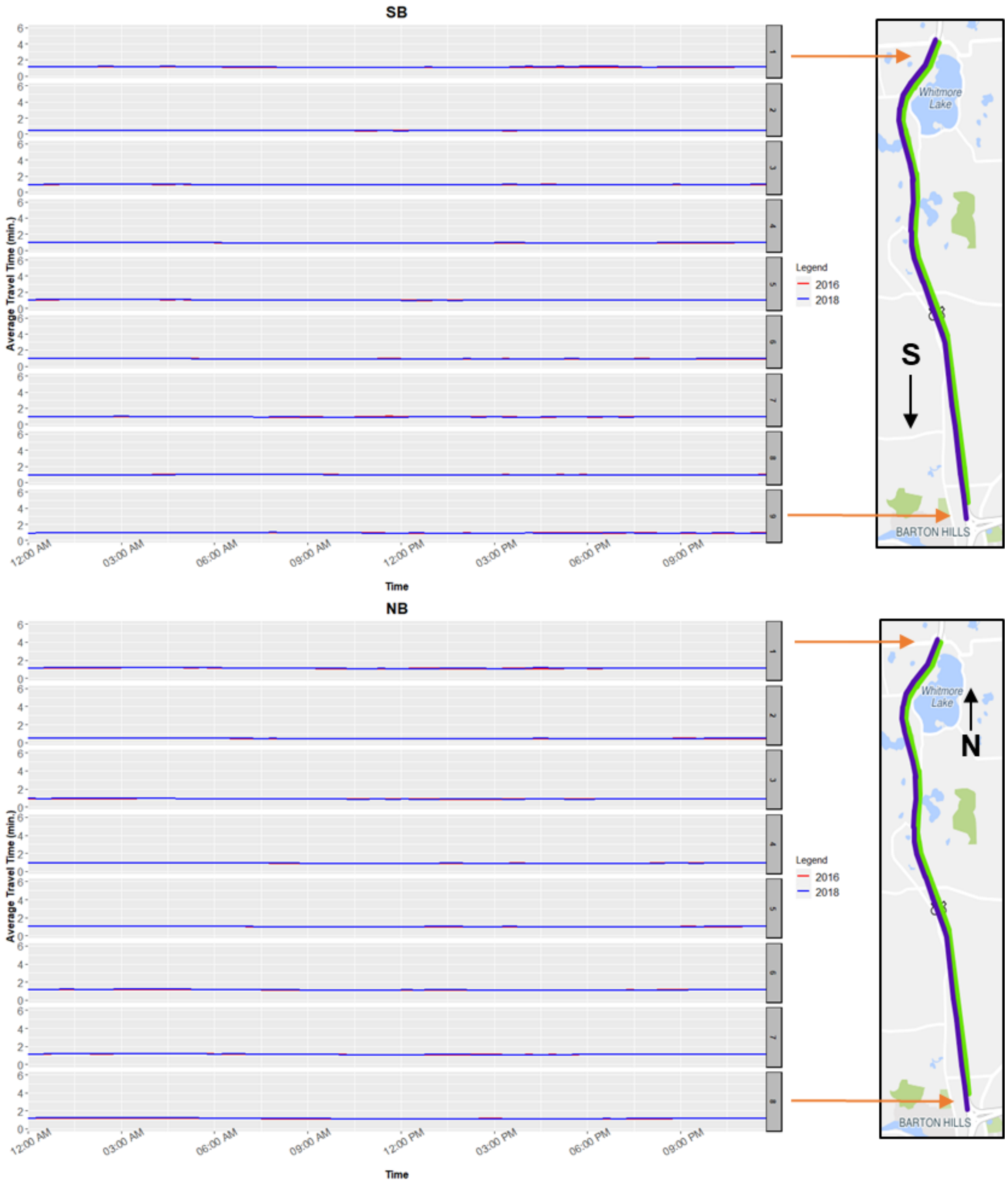


Figure 3-11 Plot of average travel time at segment-level during weekends

3.2.3 Level of Travel Time Reliability (LOTTR)

As part of the Moving Ahead for Progress in the 21st Century (MAP-21) level of travel time reliability (LOTTR) was introduced as a preferred service measure by the FHWA. The LOTTR is defined as the "the ratio of the 80th percentile travel to the normal travel time (i.e., the 50th percentile occurring throughout a full calendar year)" (Culotta et al., 2019). The LOTTR is required to be estimated for four different time periods based on the Highway Performance Monitory System (HPMS) Field Manual Supplemental Guidance (i.e., am peak, pm peak, midday, and weekend) (Office of Highway Policy Information, 2018b). The default time periods from the FHWA were adjusted for this study based on the operational periods of the Flex route. The four time periods of interest for this study are:

1) AM peak hours in weekdays (6:00 – 9:30 AM);
2) midday in weekdays (9:30 AM– 3:00 PM);
3) PM peak hours in weekdays (3:00 – 7:00 PM); and
4) weekend (6:00 AM – 7:00 PM).

Table 3-5 displays summary results of LOTTR for these time periods, for the periods before (2016) and after (2018) the Flex route went into operation, including separate estimates for each of the aforementioned periods.

Research generally suggests that values of LOTTR less than 1.50 can be considered to be reliable (Boston Region Metropolitan Planning Organization, 2018; Taylor & Change, 2017). Overall, the US-23 Flex route met this reliability threshold during both the pre- and post-implementation periods. However, it should be noted that the LOTTR values were close to the 1.50 threshold prior to implementation in both the northbound (LOTTR=1.42) and southbound (LOTTR=1.36) peak periods. In addition to the entire corridor, LOTTR values were also calculated at the segment-level and are presented in Figure 3-12. Consistent with the metrics detailed previously, LOTTR was also found to generally improve from the upstream to downstream Flex route segments in both the northbound and southbound directions. The exception was again the northernmost sections in the northbound direction, which was unreliable as per the 1.50 threshold after the Flex route went into operation.

Table 3-5 Results of LOTTR

Direction	Year	Time Period	80th Percentile Travel Time (min.)	50th Percentile Travel Time (min.)	LOTTR
Southbound	2016	AM Peak	11.40	8.40	1.36
Southbound	2016	Midday	8.20	7.90	1.04
Southbound	2016	PM Peak	8.10	7.80	1.03
Southbound	2016	Weekend	8.00	7.70	1.05
Southbound	2018	AM Peak	8.10	7.80	1.04
Southbound	2018	Midday	8.00	7.80	1.03
Southbound	2018	PM Peak	8.00	7.80	1.03
Southbound	2018	Weekend	8.10	7.70	1.05
Northbound	2016	AM Peak	8.00	7.70	1.04
Northbound	2016	Midday	7.90	7.60	1.04
Northbound	2016	PM Peak	11.40	8.00	1.42
Northbound	2016	Weekend	7.80	7.40	1.05
Northbound	2018	AM Peak	7.90	7.70	1.03
Northbound	2018	Midday	7.80	7.60	1.03
Northbound	2018	PM Peak	9.10	7.70	1.19
Northbound	2018	Weekend	7.90	7.50	1.05

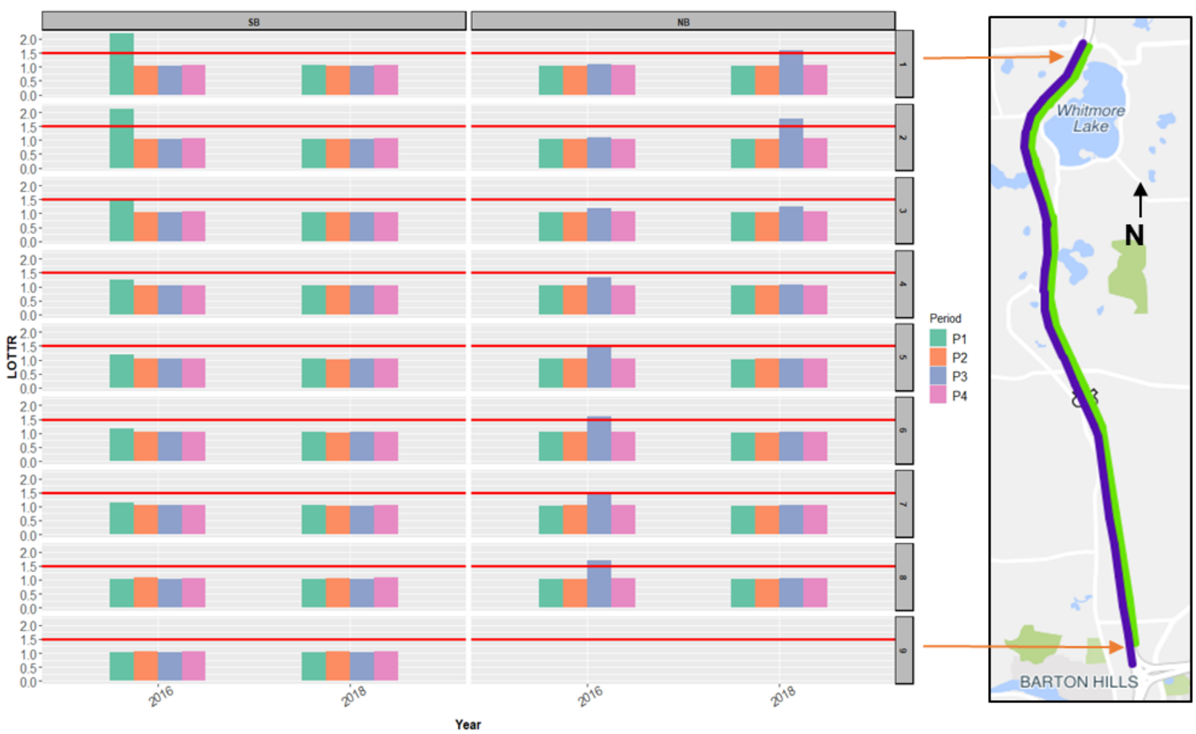


Figure 3-12 Results of LOTTR at segment-Level

3.2.4 Worst Hour Performance

In addition to the travel time reliability measures detailed previously, this study also involved an investigation of the worst-case scenarios from an operational perspective. To that end, a one-hour sliding window method was utilized to identify the one-hour periods over the course of the calendar year that showed the highest travel times (and lowest speeds). The results are shown in Figure 3-13. Looking at the data from this perspective shows particular improvements in the southbound direction, where the longest travel time was observed from 7:15 am to 8:15 am during the periods before and after the Flex route went into operation. During the post-installation period, the average travel time decreased 27.3 percent from 11.36 minutes to 8.26 minutes on average. In the northbound direction, travel times were reduced by 10 percent under these worst-case scenarios. Interestingly, there were also shifts in the period during which these worst-case scenarios occurred after introduction of the Flex route. During 2016, the worst-hour occurred between 4:45 PM and 5:45 PM. Afterwards, this shifted up to 4:30 PM to 5:30 PM.

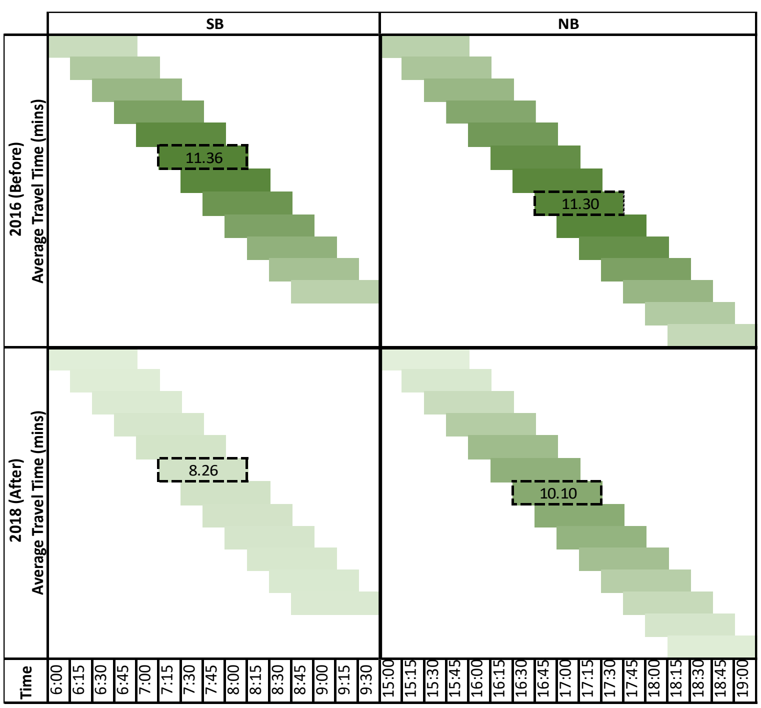


Figure 3-13 Peak hours performance

3.3 Speed-Volume Relationships for Flex Route

3.3.1 Evaluation of Annual Operational Data

The MVDS reports include both speed and traffic volume information on a lane-by-lane basis. These data allow for an evaluation of the speed-flow relationships, as well as the potential estimation of capacity on a directional and/or lane-by-lane basis.

To better understand the nature of driver behavior along the Flex route, the speed and flow relationships along the Flex route are detailed in this section of the report. While MVDS reports were reviewed for both 2018 and 2019, the discussion focuses on the 2019 data as the results are very similar between the two years. The results from 2018 are included in Appendix B.

A summary of the speed and volume data during weekdays and weekends from 2019 for the entire Flex route is shown in Table 3-6. In addition, a similar table was developed for peak hour and off-peak hour, as well (Table 3-7). These results show that average travel speeds on the Flex route were approximately 70 mph regardless of the time-of-day and day-of-week. The northbound direction showed lower travel speeds and higher variability as compared to the southbound direction, which is again attributable largely to the bottleneck in the northbound direction.

Table 3-6 Descriptive statistics for speed and volume over 24-hour period by day-of-week and direction

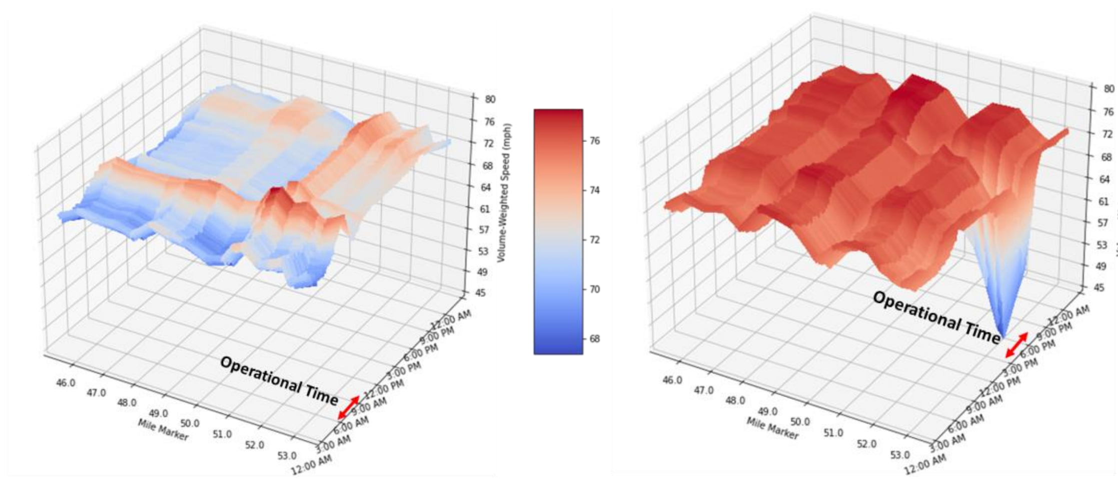
Day	Direction	Variable	Min	Max	Mean	Std. Dev.
Weekdays	Southbound	Volume-Weight Speed (mph)	50.97	77.73	71.61	2.18
		Flow Rate (veh/h)	89.61	5054.18	1669.74	1202.84
	Northbound	Volume-Weight Speed (mph)	41.03	75.88	70.56	4.05
		Flow Rate (veh/h)	109.87	4900.95	1602.84	1145.67
Weekends	Southbound	Volume-Weight Speed (mph)	65.36	78.59	73.05	1.67
		Flow Rate (veh/h)	74.83	3677.60	1296.96	857.43
	Northbound	Volume-Weight Speed (mph)	65.77	76.97	72.62	1.99
		Flow Rate (veh/h)	97.58	3564.80	1260.23	836.02

Table 3-7 Descriptive statistics for speed and volume during peak and off-peak periods by direction

Time Period	Direction	Variable	Min	Max	Mean	Std. Dev.
Peak Period	Southbound (6:00 AM - 9:30 AM)	Volume-Weight Speed (mph)	50.97	77.59	71.21	3.77
		Flow Rate (veh/h)	1862.04	5054.18	3687.10	722.50
	Northbound (3:00 PM - 7:00 PM)	Volume-Weight Speed (mph)	41.03	75.88	67.25	7.91
		Flow Rate (veh/h)	1800.79	4900.95	3453.80	591.96
Off-Peak Period	Southbound (6:00 AM - 9:30 AM)	Volume-Weight Speed (mph)	65.79	77.73	71.67	1.76
		Flow Rate (veh/h)	89.61	3945.56	1323.39	887.09
	Northbound (3:00 PM - 7:00 PM)	Volume-Weight Speed (mph)	63.49	75.86	71.22	2.12
		Flow Rate (veh/h)	109.87	3944.38	1230.80	823.95

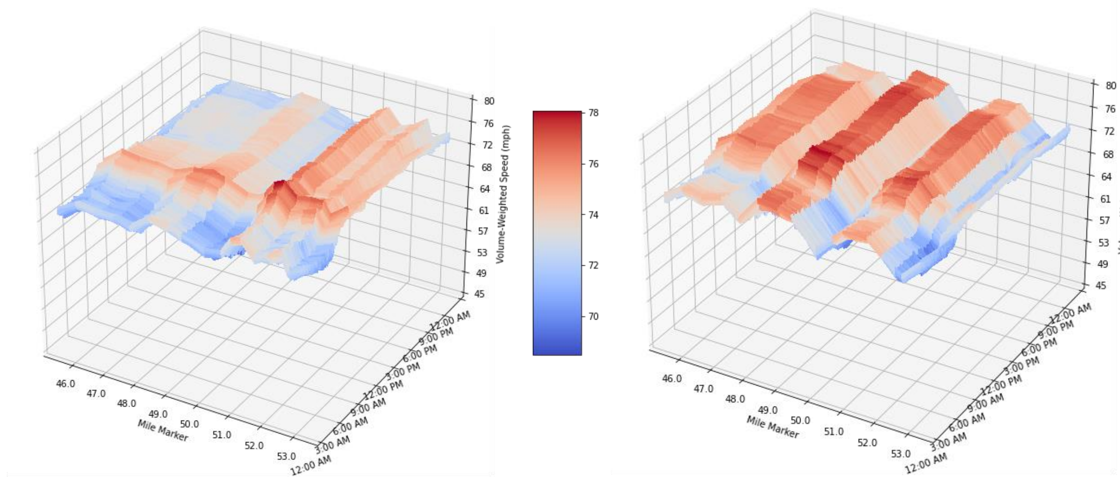
A series of speed profiles were developed to provide a graphical overview of how travel times/speeds varied, both overall and within specific travel lanes. These profiles provide insights as to where and when congestion was most pronounced and when speed reductions occurred. Figure 3-14 and Figure 3-15 provide these speed profile plots in both directions for weekdays and weekends, respectively. Travel speeds tended to be fairly consistent in the southbound direction during weekdays, generally operating at or near free-flow conditions. The northbound direction also generally showed consistently high travel speeds, with the exception of the northernmost sections leading up to the lane drop as illustrated by the sharp drop during the PM peak period between milemarkers 51 and 53 specifically.

Speeds during weekends were also relatively stable regardless of the direction. There were some minor drops in speeds in the northbound direction. Once again, these occurred leading into the terminus of the Flex lane where the number of lanes is reduced from three to two. The planned extension of Flex route to I-96 is expected to largely mitigate the speed reductions during all operational periods.



a. Southbound b. Northbound

Figure 3-14 Average travel speed over time and mile marker for US-23 Flex route (weekdays)

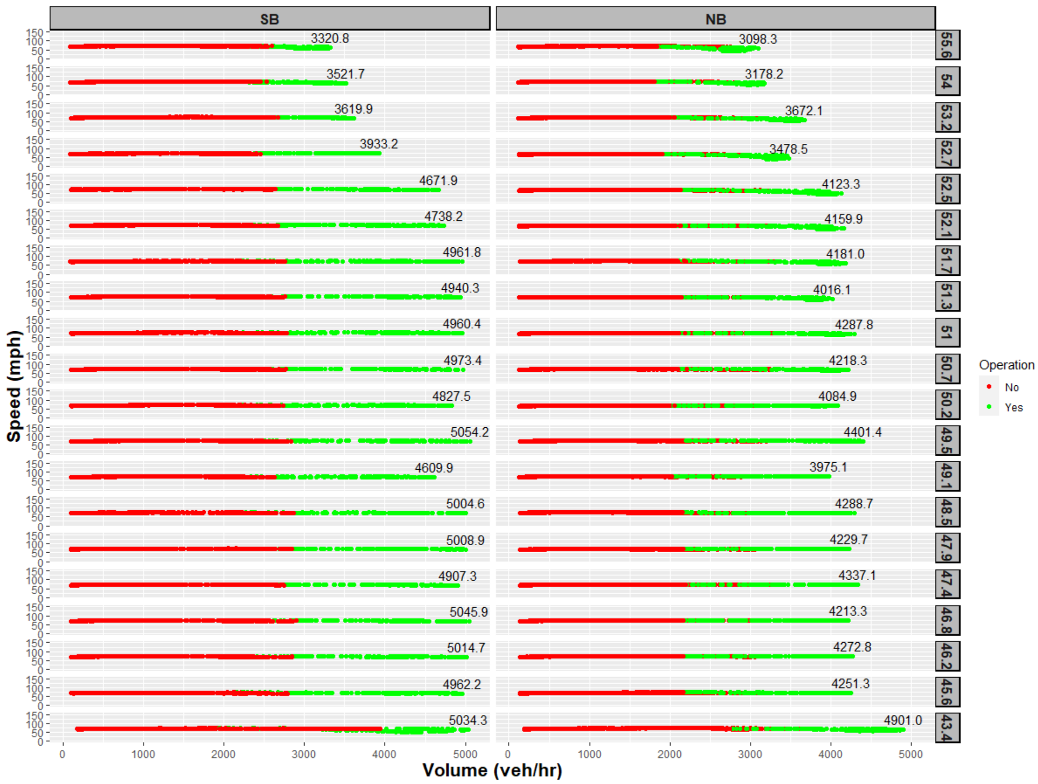


a. Southbound b. Northbound

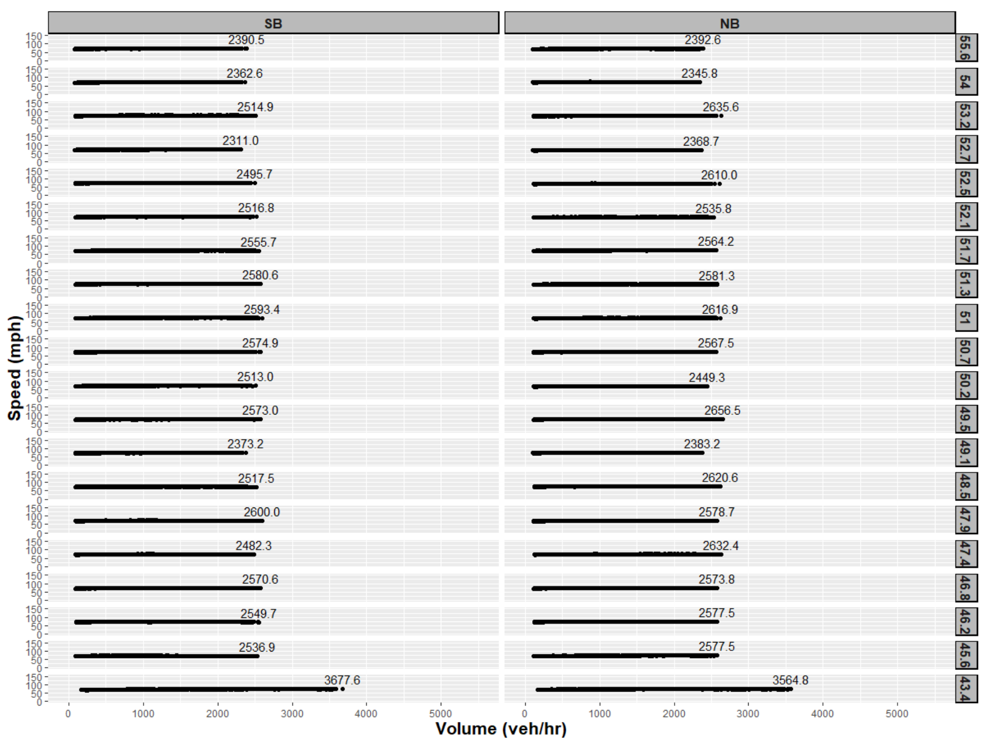
Figure 3-15 Average travel speed over time and mile marker for US-23 Flex route (weekends)

The speed and flow relationships during weekdays for the entire corridor (averaged across all travel lanes) are plotted in Figure 3-16a. The speed and volume data were differentiated by the fixed operational time of the Flex route. The green color is reflective of speeds and volumes while the Flex lane is in operation (i.e., southbound from 6:00 AM - 9:30 AM; northbound from 3:00 PM - 7:00 PM). The red color indicates periods when the Flex lane was not in operation. As the figure shows, speeds were largely consistent across most flow rates. Generally speaking, the corridor operated at traffic volumes that were significantly less than capacity.

The exception is the northernmost section of northbound US-23, where speeds begin to decline as congestion begins to occur, particularly near MM 52.7 and MM 53.2, leading up to the lane drop. In general, the southbound direction experienced very limited congestion once the Flex route went into operation. Speed-flow curves were also developed for weekends (Figure 3-16b) and the trends were consistent in both directions and throughout the course of the day.



a. Weekdays



b. Weekends

Figure 3-16 Speed-flow curve during weekdays and weekends (one year) for US-23 Flex route

In addition to the preceding plots that detail total volumes and average speeds in each direction, speed-flow curves were also generated on a lane-by-lane basis. Figure 3-17 provide a summary of these data for calendar year 2019 for the left shoulder, left lane, and right lane during the periods when the Flex lane was open for motorists. Appendix B includes similar plots for 2018 as the data were again very consistent between the two years.

These plots are largely consistent with the total directional data detailed previously. Speeds and flow rates were largely consistent, with the exception of the northernmost extents in the northbound direction. Comparing the lane-by-lane data, volumes tended to be highest in the middle (i.e., left) lane as compared to the right lane. Volumes also tended to be higher in the southbound direction as compared to northbound. The Flex route ends near MM 53.2 northbound and this is where the lowest speeds and flow rates are found on the left shoulder.

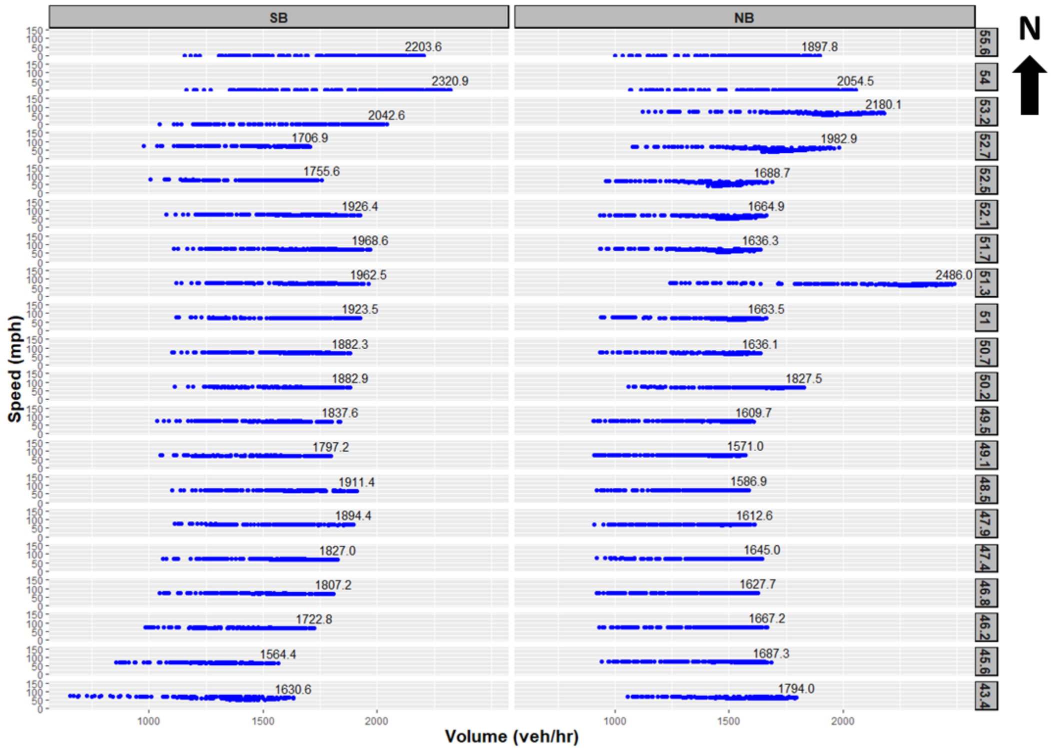
Some issues were observed in the data, including an unusual trend at MM 51.3 northbound, where significantly lower flow rates and speeds were recorded on the left shoulder, while higher flow rates and speeds occurred on the middle (left) lane. As Figure 3-17a shows, this section is generally similar to the other three-lanes sections. It appears there are sensor alignment and/or classification issues here.

a. i) Left shoulder (Flex lane)

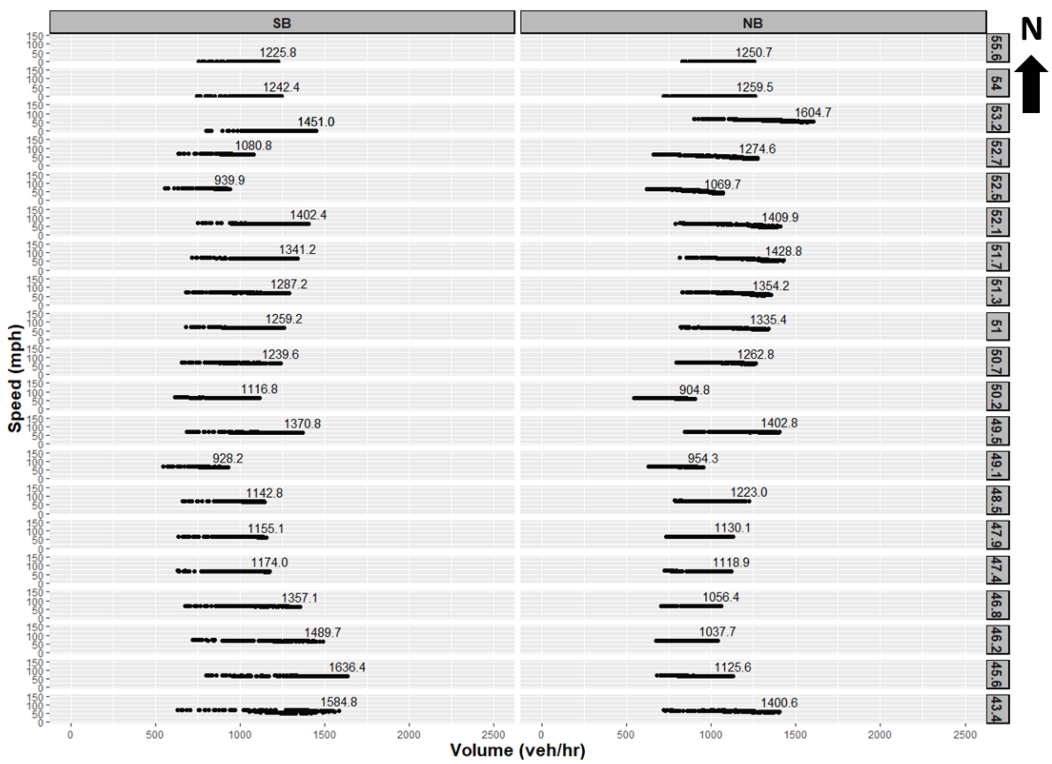
a. ii) Gantry at MM 51.3 northbound

Figure 3-17 Speed-flow curves for US-23 Flex route during peak hours on lane-by-lane basis

Figure 3-17 cont'd



b. Left lane



c. Right lane

3.3.2 *Evaluation of Sample Data from Normal Week*

This section provides a more detailed assessment of speed-flow relationships using sample data for a one-week period during which there were no crashes or other sources of non-recurrent congestion based upon a review of available ATM, speed, crash, and incident data.

3.3.2.1 Data Integration

As a part of this investigation, the gantry messages that were displayed were identified from the ATM report. Travel speed and volume data were drawn from the MVDS reports and were integrated with the ATM information based on the associated timestamps and milemarkers to determine specific times when the Flex route was open. As the milemarkers for the gantry messages do not match directly with the operational data, some manual adjustment was required to align the nearest milemarker for the MVDS and ATM data. The milemarkers for all ATM and MVDS data are detailed in Table 3-8.

Table 3-8 Comparison of mile marker between MVDS reports and ATM reports

Direction	Mile Marker		Direction	Mile Marker	
	MVDS	ATM		MVDS	ATM
SB	43.4		NB	43.4	45.3
SB	45.6	45.6	NB	45.6	45.6
SB	46.2	46.2	NB	46.2	46.2
SB	46.8	46.8	NB	46.8	46.8
SB	47.4	47.4	NB	47.4	47.4
SB	47.9	47.9	NB	47.9	47.9
SB	48.5	48.5	NB	48.5	48.5
SB	49.1	49.1	NB	49.1	49
SB	49.5	49.5	NB	49.5	49.5
SB	50.2	50	NB	50.2	50.2
SB	50.7	50.7	NB	50.7	50.7
SB	51		NB	51	
SB	51.3	51.3	NB	51.3	51.3
SB	51.7	51.7	NB	51.7	51.7
SB	52.1	52.1	NB	52.1	52.1
SB	52.5	52.5	NB	52.5	52.6
SB	52.7	52.7	NB	52.7	52.7

As discussed previously, the ATM reports only indicate when one of the gantry messages changed (e.g., when the Flex lane opened, when the advisory speed changed). No intermediate data are available between these timestamps. Therefore, additional data processing was required in order to integrate the travel speed data with the gantry messages. Basically, the gantry messages were filtered to identify the timestamp at which each unique message was displayed. This same messages were assumed to be displayed until the gantry message changed and the speed and volume profiles were integrated accordingly.

3.3.2.2 Analysis results

Consistent with the preceding discussion of annual trends, Figure 3-16 and Figure 3-177 show that the Flex route is generally operating under capacity, even during peak traffic periods. Congestion was generally only observed at the milemarkers immediately upstream of the lane drop in the northbound direction. This is the one section of the Flex route where additional insights may be drawn as to the operational capacity of the Flex route and each of the travel lanes. To this end, the sample week of speed and volume data were used to develop a series of similar speed-flow plots. The data were extracted from the fall season under good weather conditions and in the absence of any non-recurring congestion as noted previously.

In contrast the preceding curves, which assumed fixed hours of operation over the calendar year, this analysis considered the actual operation times for the Flex route, which tended to vary slightly from day to day based on an investigation of ATM reports. For instance, during certain days, the Flex route opened at 2:50 PM in the northbound direction rather 3:00 PM. The associated gantry messages displayed on DMS1 from the ATM reports were integrated with the corresponding speed and volume data to discern further details of traffic flow conditions as the Flex route opened. Rather than averaging the speed and volume data (as in the analyses of annual data), this analysis involved the development of higher fideltiy plots using raw data at one-minute intervals.

To that end, Figure 3-18 provides a series of overall speed-flow plots at this level of detail. The trends from these speed-flow curves are largely similar to what was shown in the average annual data presented previously. Southbound traffic consistently operated near free-flow conditions while performane in the northbound direction was similar, except for the speed drops that begin to occur after MM 49.5. As in Figure 3-16, green points are reflective of periods when the Flex route is in operation and red points are reflective of periods when the Flex lane is closed.

In the southbound direction, the maximum flow rates generally cover a range of up to 6,240 to 7,020 veh/hr (2,080 to 2,340 veh/hr/ln). There are a small number of points beyond this range; however, these flows are not sustained and it should be noted these are hourly volume estimates based upon one-minute intervals. The throughput generally tends to increase further downstream along US-23 and there is some oscillation from milemarker to milemarker, which is likely a reflection of segment-specific issues such as the presence of entrance ramps and horizontal curvature in these areas. It is important to note that virtually no congestion is observed in the southbound direction, except for a brief period from MM 51.7 to MM 52.1 when the Flex lane appears to have been opened after some congestion in the two normal travel lanes. When all three lanes were in operation, no significant reductions were observed southbound, which suggests the values above provide lower bounds for capacity.

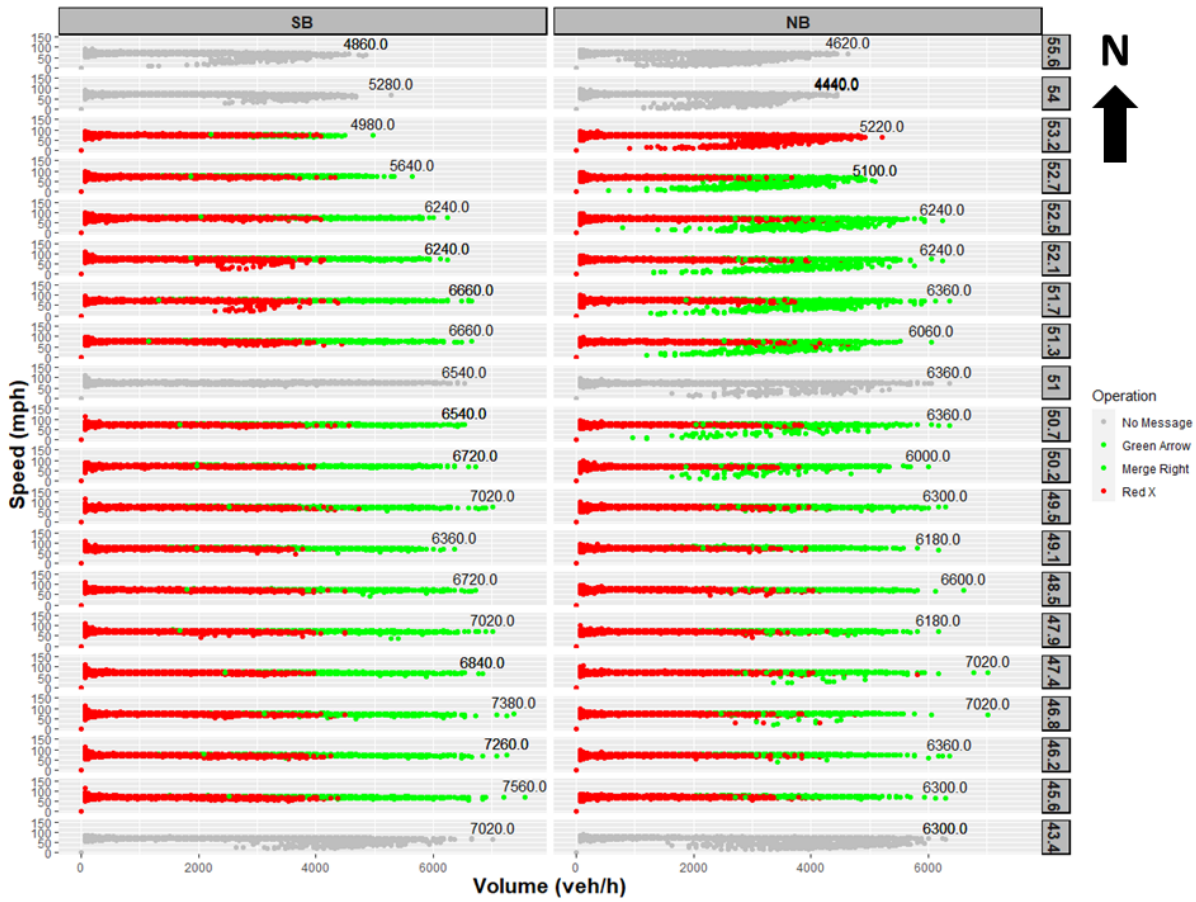


Figure 3-18 Speed - flow curve for US-23 Flex route (weekdays, one-week data)

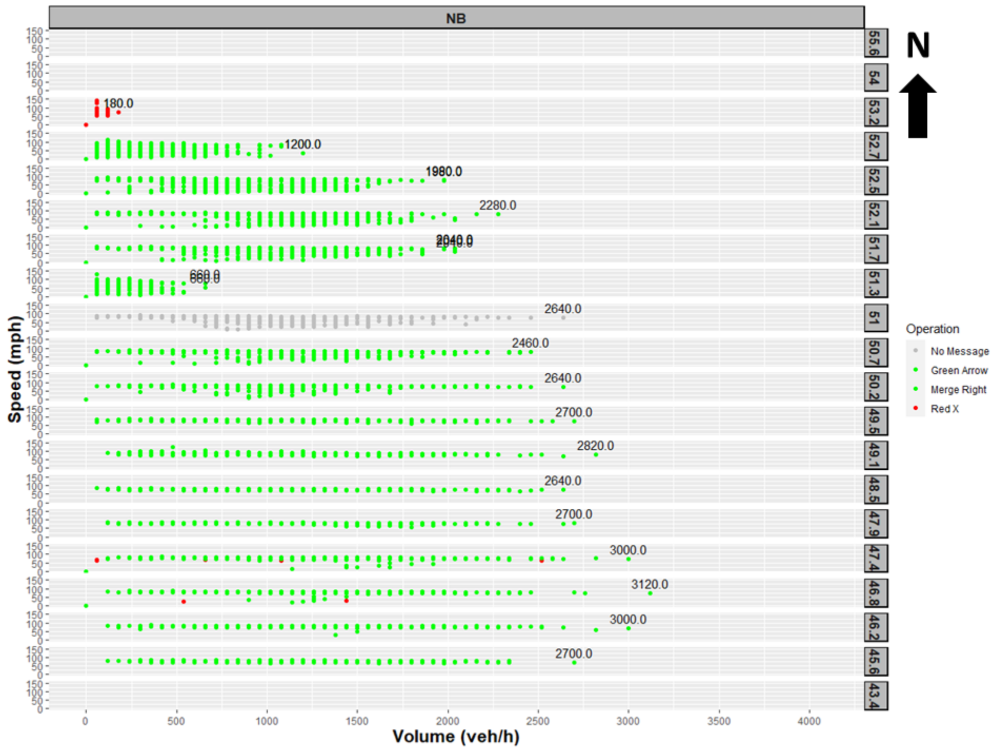
In contrast, northbound flow rates were consistently lower than in the southbound direction, with maximum volumes ranging from approximately 6,000 veh/hr to 6,300 veh/hr (2,000 to 2,100 veh/hr/ln), again with a limited number of one-minute flow rates beyond these values. There are also marked reductions in travel speeds due to recurring congestion, particularly downstream of MM 49.5.

In order to better understand the nature of the congestion in the northbound direction, lane-specific speed and flow curves were also generated as shown in Figure 3-19. Over the southern extents in the northbound direction (from MM 45.6 to 51.0), approximately 39% of the volume was observed in the Flex lane, 35% in the left lane, and 26% in the right lane. Nearer to the northern terminus, this distribution shifted as the corresponding percentages included 31%, 39%, and 30%

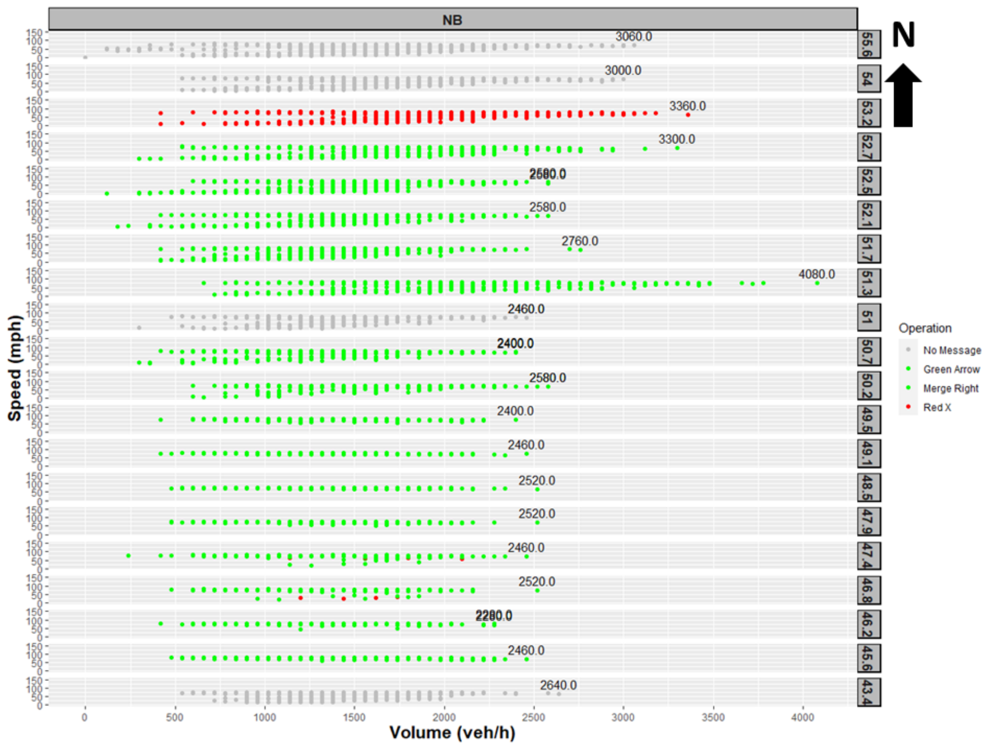
of traffic in the Flex, left, and right travel lanes, respectively. Traffic largely began shifting out of the Flex lane between MM 52.5 and 52.7 as these percentages changed to 18%, 50%, and 32% at the latter milemarker. Finally, at the final northbound gantry (MM 53.2), approximately 3% of traffic was in the left-shoulder as vehicles approached the merge point/lane drop.

Some caution should be exercised when trying to use the lane-by-lane speed-flow plots to estimate per-lane capacity values. There are some milemarkers where there are obvious discrepancies with respect to the lane-by-lane volume distrbutions, most notably at MM 51.3 where the roadside sensors are assigning much of the left shoulder (Flex lane) traffic to the left travel lane. Over the entire segment, there is considerable variability in the lane-specific volumes and, as such, the total throughout across all travel lanes are likely to provide a more reasonable floor for lane-by-lane capacity as compared to the per-lane volumes.

Overall, the plots show that flow rates were generally under capacity regardless of direction and mile marker, except for this northernmost portion in the northbound direction. Immediately beyond the lane drop, capacity values of 4,400 to 4,600 veh/hr (2,200 to 2,300 veh/ln) are consistently observed. As such, the lower throughout at the preceding northbound milemarkers (e.g., MM 52.5 to 53.2) are likely to be lower than what will be observed with the subsequent extension that is planned to I-96.



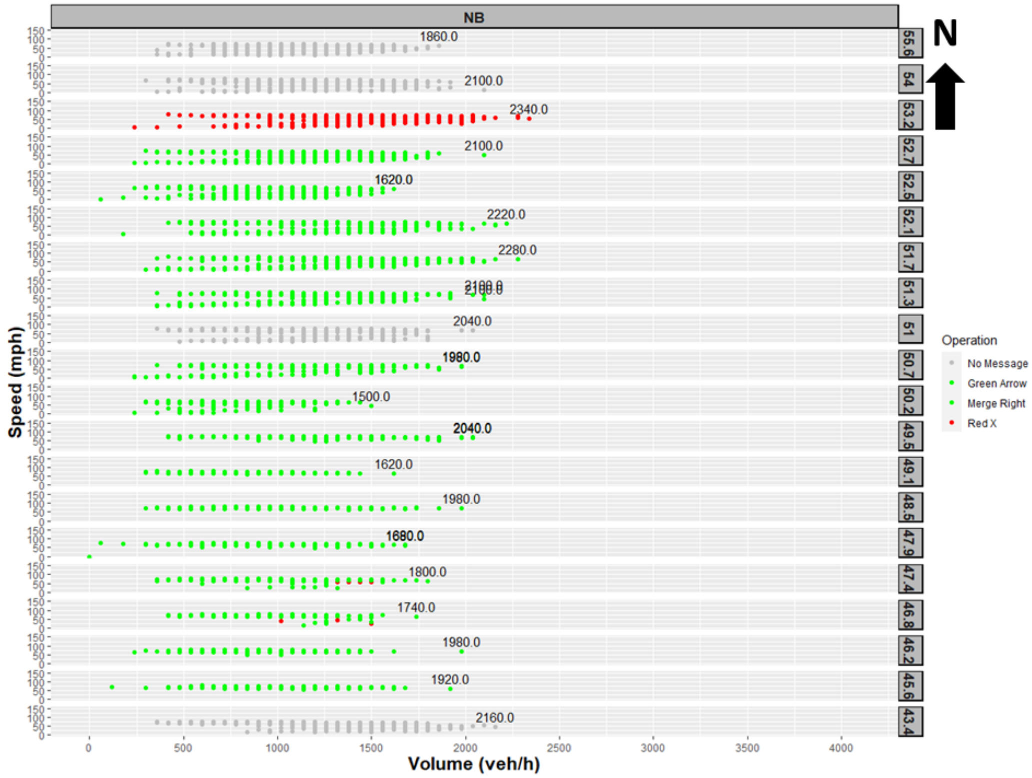
a. Left shoulder (Flex lane)



b. Left lane

Figure 3-19 Northbound speed - flow curves for US-23 Flex route during weekday peak period on lane-by-lane basis

Figure 3-19 cont'd



c. Right lane

3.4 Compliance

The compliance of drivers reflects the effectiveness of the operations of the Flex route and the gantry messages. In general, the compliance of drivers were measured by lane merging compliance and advisory speed compliance (Schaefer et al., 1998). In this study, the Flex lane compliance and variable advisory speed compliance were evaluated.

3.4.1 Flex Lane Compliance

The MVDS reports were utilized to determine the Flex lane compliance rate due to the fact that the data from MVDS reports was the only data that included the volume with the lane designation. The non-compliance rate with the vacate lane sign is defined as the percentage of drivers traveled on the blocked lane indicated by red "X". In other words, if a driver enters the Flex lane while the lane is closed for the motorists, the driver does not comply with the red "X" sign (Schaefer et al., 1998). Table 3-9 demonstrates results of Flex lane compliance rate. After one year of implementation of Flex route, the compliance rate increased. It might be caused by the drivers' familiarities of the Flex route. People tended to be less cautious once they were familiar with the operations of the Flex route.

Table 3-9 Flex lane compliance rate

Direction	Year	Number of Vehicles Using Flex Lane During Off-Peak Hours	Number of Vehicles During Off-Peak Hours	Non-Compliance Rate (%)
Southbound	2018	7976	1617935	0.49
	2019	13768	1648073	0.84
Northbound	2018	11517	1390271	0.83
	2019	15705	1427621	1.10

The monthly percentage of non-compliance rate was also calculated (Figure 3-20). As shown in the figure, the non-compliance rates of 2019 were higher than 2018 for most months, which is consistent with the finding in Table 3-9. More violations occurred in the northbound direction when compared to southbound. The peaks of non-compliance rate were observed during August and September for both SB and NB. One possible reason is that these two months are considered the start/end of the school as more intercity trips or trips between states were more likely to take place. In that instance, unfamiliarity of hard shoulder running rules would happen more frequently than in other months. Therefore, more enforcement on the Flex route could be considered during that time of year.

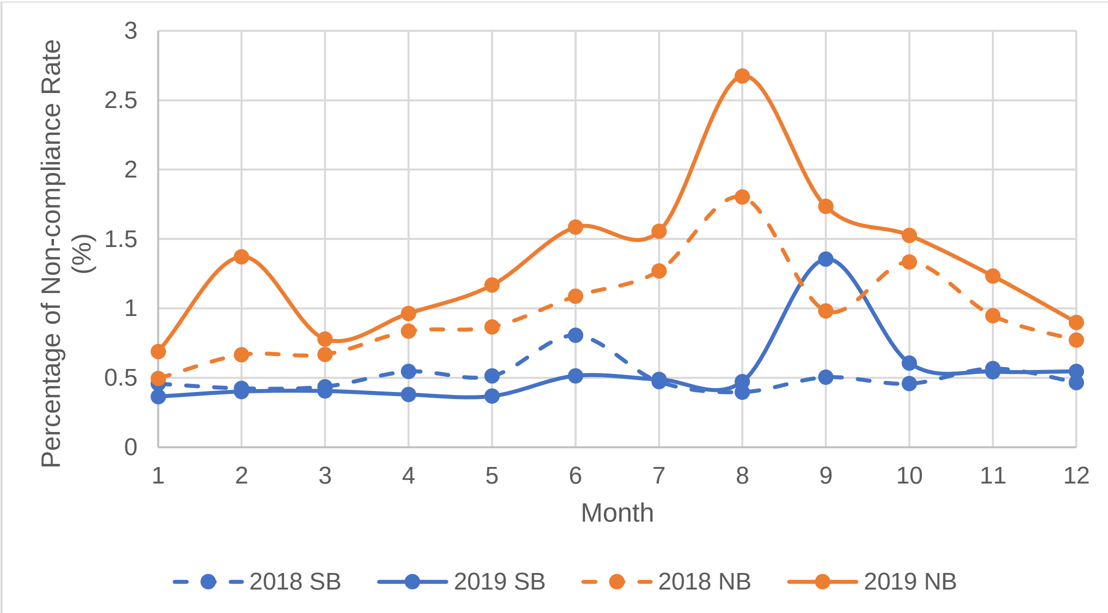
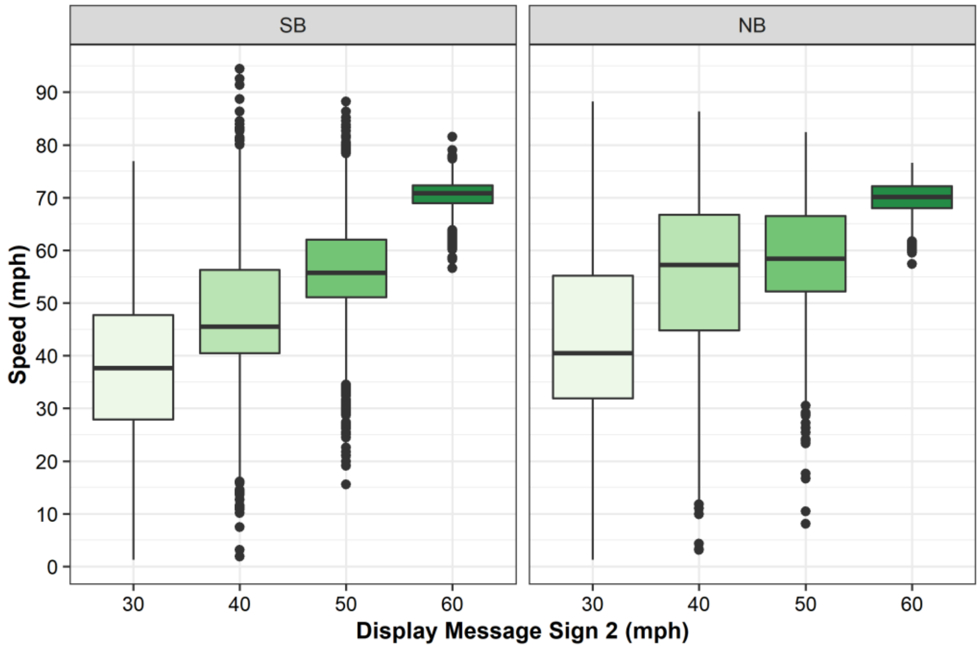


Figure 3-20 2018 and 2019 monthly percentage of non-compliance rate by direction

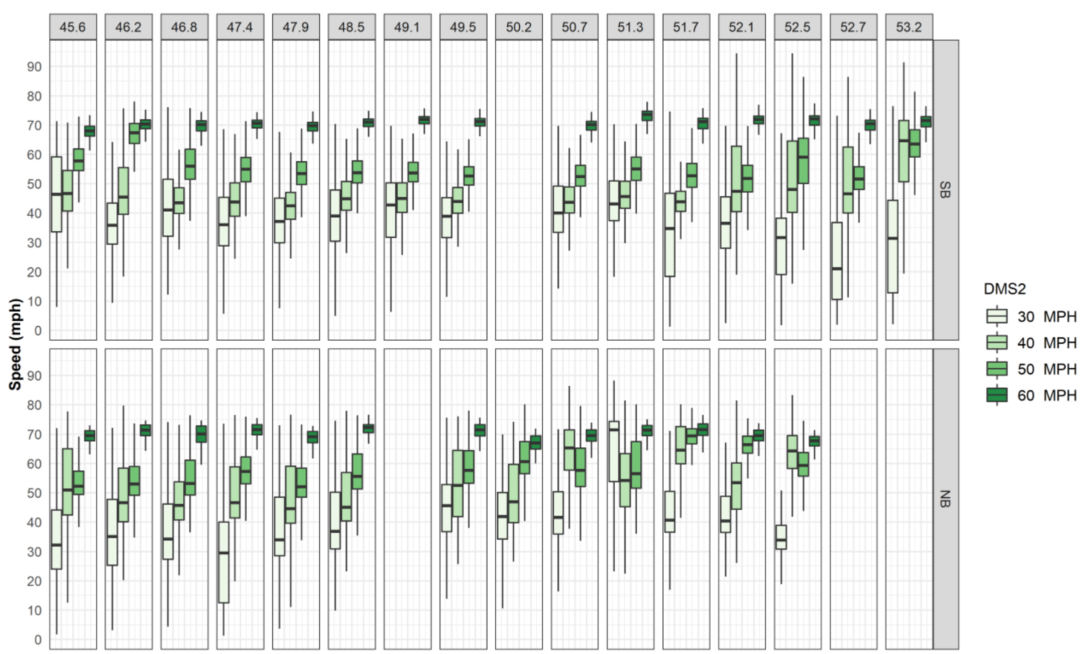
3.4.2 Advisory Speed Compliance

3.4.2.1 Frequency Analysis

The speed data from MVDS reports and the gantry messages from ATM reports were used to determine the advisory speed compliance rate. After joining the gantry messages to the speed, the drivers' compliance rate can be examined by understanding how drivers respond to different advisory speeds (i.e., 30 mph, 40 mph, 50 mph, and 60 mph). Box plots were used to study drivers' speed selection behaviors. The box plot summarized the minimum, first quantile, median, third quantile, and maximum values. Outliers were also can be found in the plots. Figure 3-21 includes the box plots for the entire Flex route and each mile marker. Based on the plots, the x-axis represents the message signs when displaying the advisory speeds of 30, 40, 60 mph. The y axis indicates the driver's speeds along the Flex route on the northbound and southbound.



a. Overall



b. Mile marker by mile marker basis

Figure 3-21 Driver's speed selection behaviors under various advisory speeds on US-23 Flex route

As the figures demonstrated, some drivers' speeds were consistent under the advisory speed of 60 mph. However, as the advisory speeds reduced toward 30 mph, greater variability in vehicle speed was observed, particularly at 30 mph.

Additionally, to assess drivers' behavior right after they notice the dynamic message, the advisory speed displayed on DMS2 was joined to the speed corresponding to the one-mile marker ahead for both directions (SB and NB). For example, if the advisory speed of 60 mph is displayed at MM45.6 on northbound, the speed at MM46.2 and beyond was area of interest. Figure 3-22 depicts an example of the data joining on northbound.

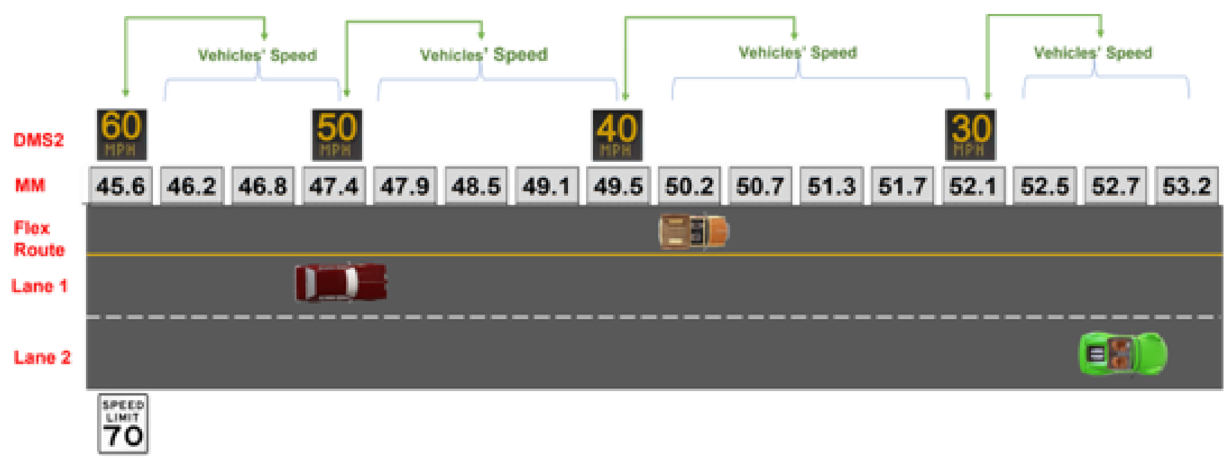
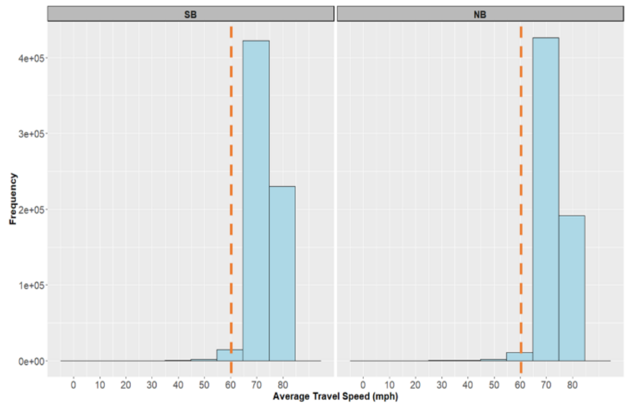


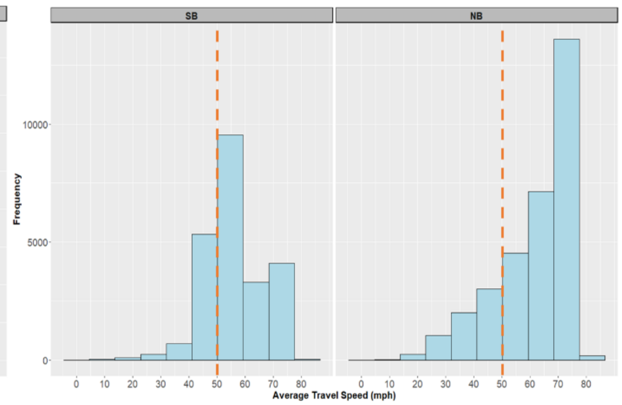
Figure 3-22 Example of travel speed and advisory speed data integration in northbound direction

After data integration, the data was divided into four categories based on four levels of advisory speeds (i.e., 60 mph, 50 mph, 40 mph, and 30 mph). As discussed in the previous sections, the advisory speeds were generally displayed while the Flex route was in operation. The regular operational time of Flex lane was from 6:00 AM to 9:30 AM in the southbound direction and 3:00 PM to 7:00 PM in the northbound direction, but it also opened under special events such as football games. To reduce the noise caused by irregular data and find consistent performance, the final data were subset to only include the regular operational time during weekdays across the entire calendar year.

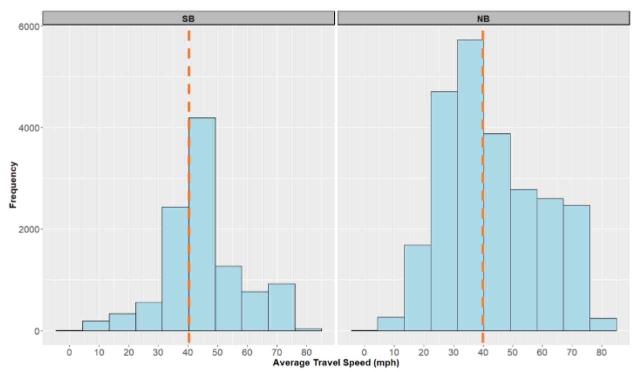
First, the frequency of average driving speed under various advisory speeds was observed. Figure 3-23 shows the histogram of average speed under four advisory speeds. As Figure 3-23a indicated, most drivers tended to travel at 65 to 75 mph or even higher under the advisory speed of 60 mph regardless of direction. Only a small portion of drivers had a travel speed of 60 mph after the advisory speed of 60 mph was displayed. Once the advisory speed decreased to 50 mph (Figure 3-23b), in the southbound direction, most driving speeds fell into the range of 50 to 60 mph, but drivers were more likely to travel with higher speed in the range of 68 to 78 mph in the northbound direction. Additionally, Figure 3-23c showed that most travel speeds fell into the range of 40 to 50 mph on southbound and 30 to 40 mph on northbound, respectively, under the advisory speed of 40 mph. It indicated that the drivers were more likely to comply with the advisory speed of 40 mph. Lastly, the driving speeds under the advisory speed of 30 mph were also evaluated (Figure 3-23d). The southbound had a relatively smaller sample size compared to the northbound direction. As introduced previously, the advisory speed of 30 mph was typically displayed at the merging point at the lane drop section in the northbound direction. Therefore, more samples were found northbound, and in this direction, most of the travel speed fell into the range of 22 to 32 mph. As a result of frequency analysis, drivers were more likely to comply with the lower advisory speed, especially northbound.



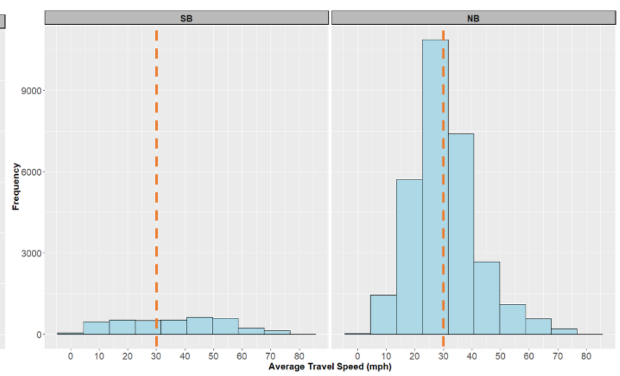
a. Advisory speed of 60 mph



b. Advisory speed of 50 mph



c. Advisory speed 40 mph

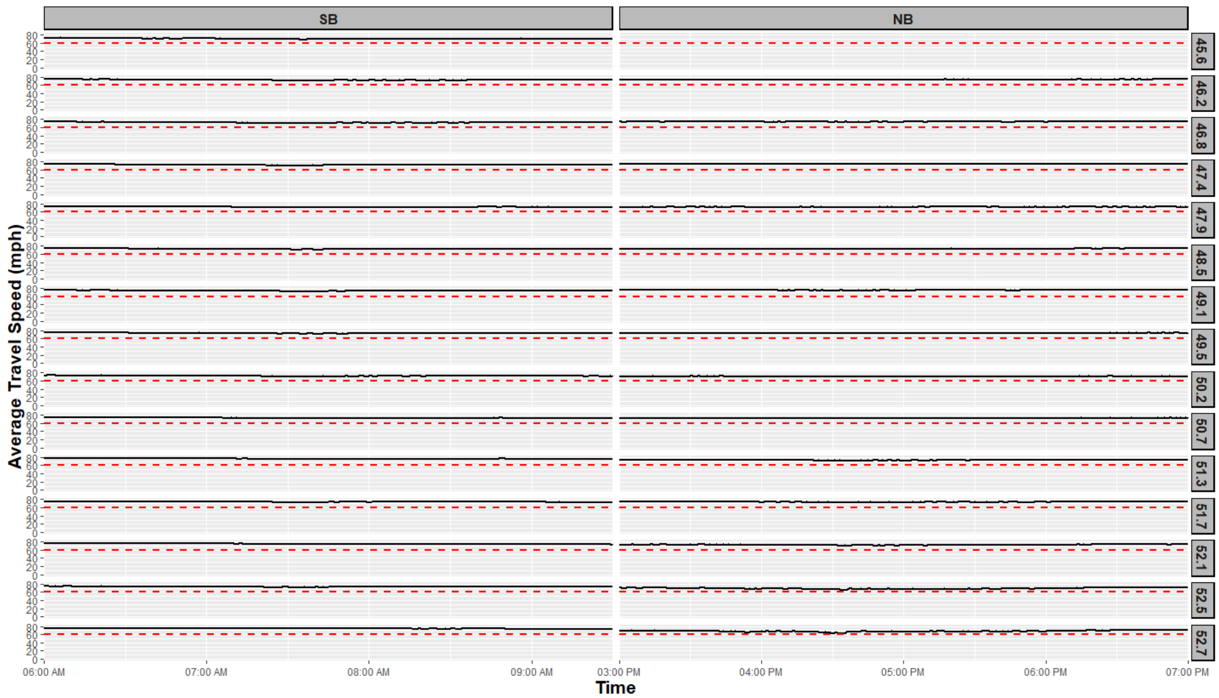


d. Advisory speed of 30 mph

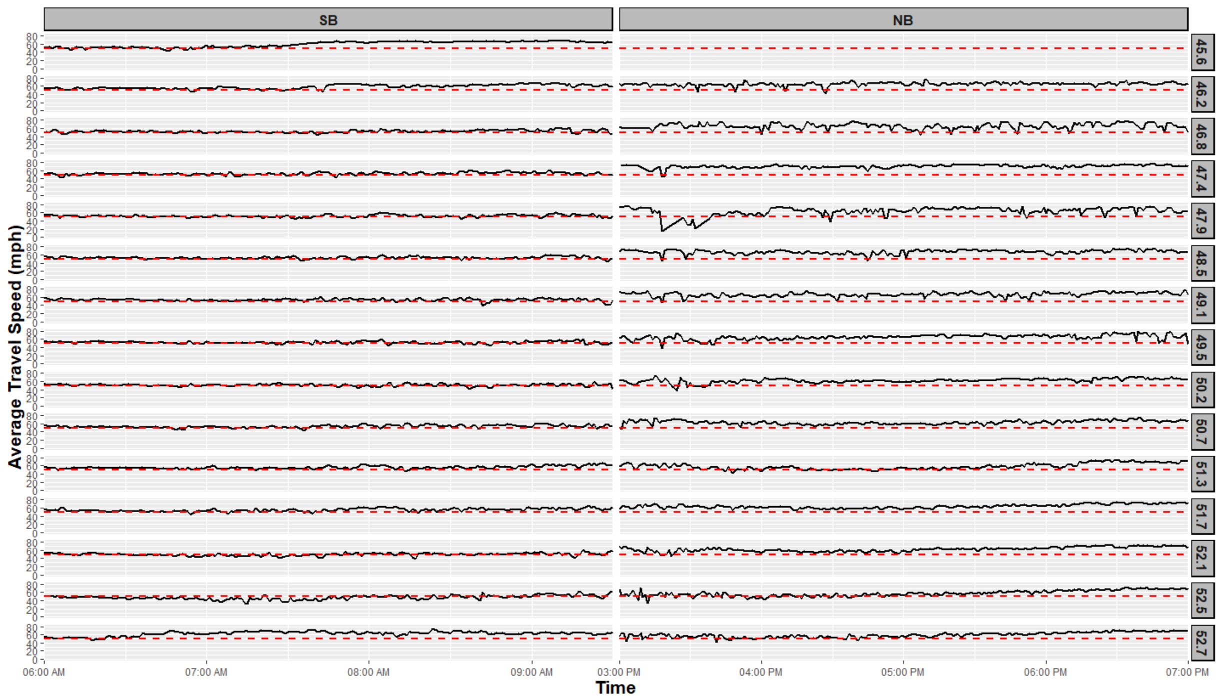
Figure 3-23 Number of observation of actual travel speed under various advisory speeds

Moreover, the speed profiles for each mile marker over peak period under various advisory speeds were also plotted to understand the driver behaviors (Figure 3-24). The red dash line represents the advisory speed in the plots, and the black line indicates the actual travel speed. The direction of travel in the southbound direction was from MM 53.2 to MM45.6 and vice versa in the northbound direction. As the plot of advisory speed of 60 mph showed (Figure 3-24a), the travel speed was higher than the advisory speed. The decrease of the actual speed was observed towards the end of the flex lane on northbound, but the overall travel speed was still higher than the advisory speed. The plot of advisory speed of 50 mph also presented a similar trend in the northbound direction (Figure 3-24b). The actual travel speed on northbound was higher than the advisory speed of 50 mph at the beginning section of northbound. At the end of northbound, the trend of actual speed was almost identical to the advisory speed, but it was only valid before 5 PM. Unlike the northbound direction, the actual speed in the southbound direction was close to the advisory speed of 50 mph.

A similar trend in southbound direction was observed under the advisory speed of 40 mph. Drivers tended to comply with the advisory speed of 40 mph in the southbound direction (Figure 3-24c). Fluctuations were observed in the northbound direction for the first few mile markers due to the relatively smaller sample size. The travel speeds were more uniform and better aligned with the advisory speed of 40 mph towards the merging section in northbound direction (i.e., MM 50.2 to MM 53.2). Finally, the actual travel speed was examined under the advisory speed of 30 mph (Figure 3-24d). More variability was observed in that direction due to the smaller sample size, but it fluctuated around the advisory speed of 30 mph. In the northbound direction, the difference between actual travel speed and advisory was almost neglectable, especially towards the terminus of the flex route. The advisory speeds of 40 and 30 mph were generally displayed at the merging section on northbound. Therefore, the alignments between actual speed and advisory speed were observed at the merging section. As the findings indicated, the drivers tended to comply with the lower advisory speeds, such as advisory speeds of 40 and 30 mph. Once the advisory speed increased to 50 and 60 mph, drivers were more likely to travel higher than the advisory speed. The findings were more pronounced in the northbound direction.



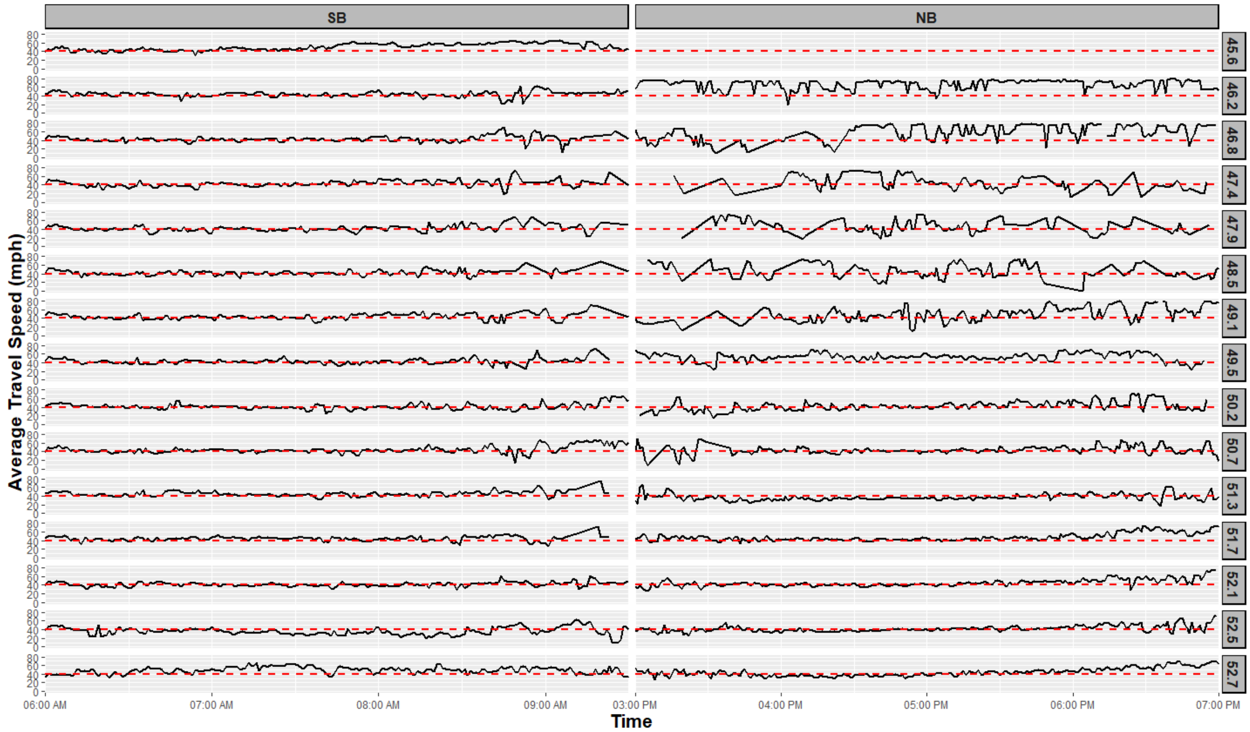
a. Advisory speed of 60 mph



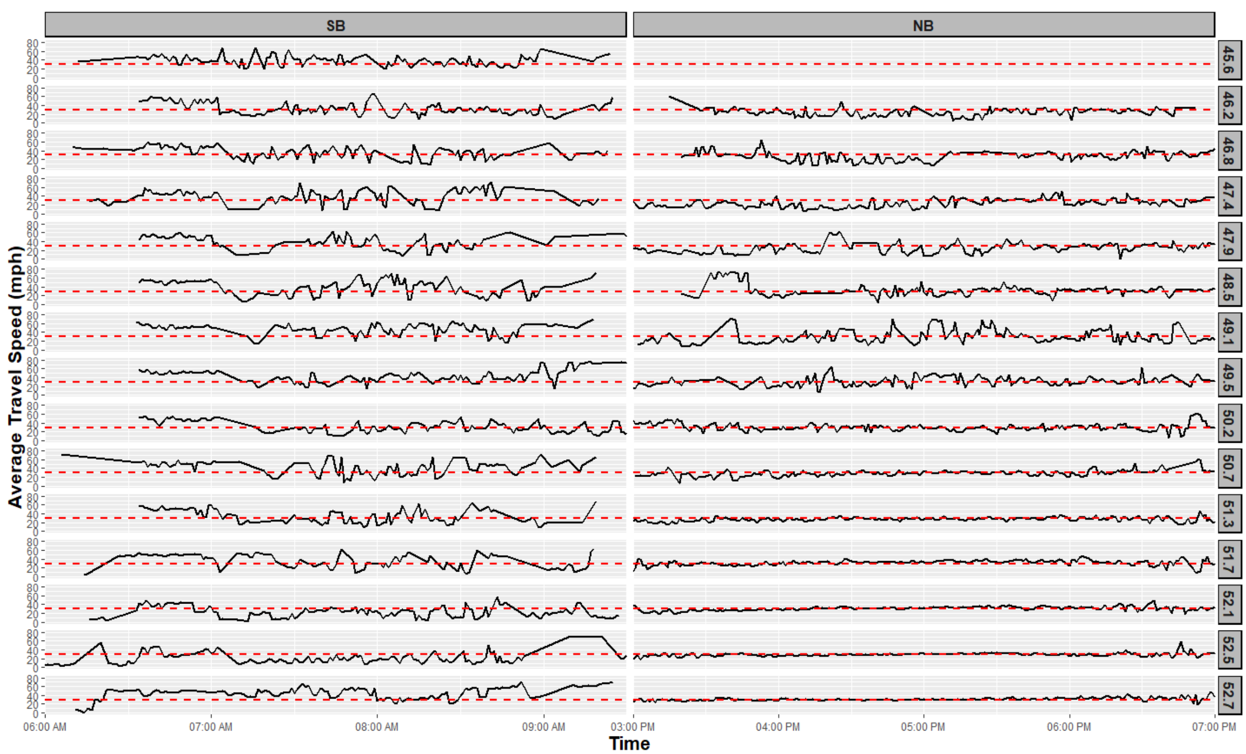
b. Advisory speed of 50 mph

Figure 3-24 Speed profiles under various advisory speeds

Figure 3-24 cont'd



c. Advisory speed of 40 mph



d. Advisory speed of 30 mph

3.4.2.2 Regression Analysis

Other than the plots, a linear regressions model was utilized to analyze the driver's performance under different advisory speeds. Each of the dependent variables noted above is essentially continuous in nature. To investigate the relationships between continuous variables and a series of independent variables of interest, ordinary least square (OLS) linear regression presents an appropriate modeling framework. The functional form (Equation 5) of the OLS linear regression model is (Washington, Karlaftis, & Mannering, 2011):

$$\mathbf{Yi = \beta 0 + \beta 1X1 + \beta 2X2 + \cdots + \beta kXk + \varepsilon} \qquad \textbf{Equation 5}$$

Where Yi is dependent variable (actual travel speed) for mile marker i; β0 refers to constant term (i.e., y-intercept); β1 , β2 ,…, βk represents estimated regression coefficients for each independent variable; X1 to Xk indicate independent variables (e.g., advisory speed or seasons, etc.); lastly, ε means normally distributed error term with mean of zero and variance of σ2. The error term is assumed to be independently and identically distributed across mile markers.

The results of linear regression models for vehicle speeds at each direction of travel are shown in Table 3-10, and are reflected graphically in Figure 3-25. Each model presents the estimated coefficient, along with the standard error and p-value. When interpreting the results, a positive value of the estimated coefficient indicates that vehicle speed increases with the increase in the independent variable and vice versa for negative parameter estimates.

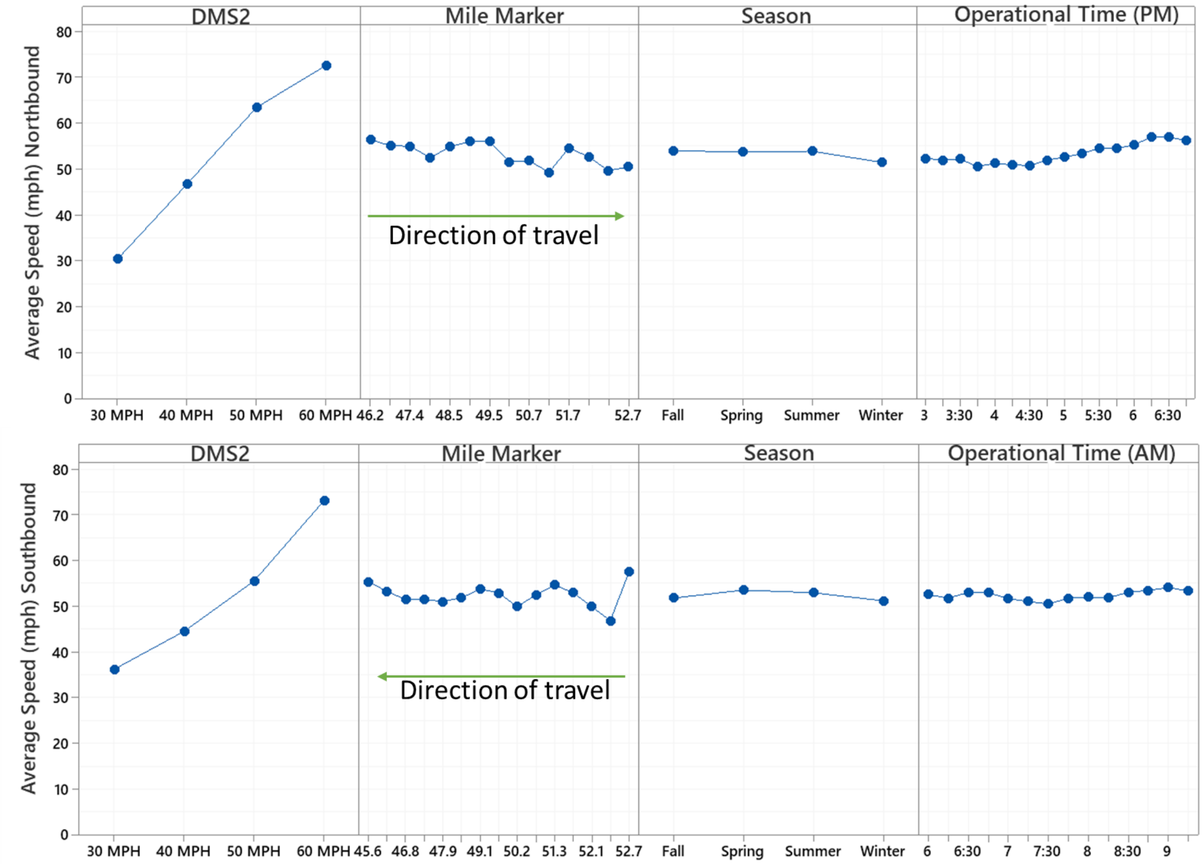


Figure 3-25 Mean speed versus DMS2, mile marker, season, and operational time for both northbound and southbound

Table 3-10 Variable speed models for Flex route by direction

Parameter	**Direction**					
	Northbound			**Southbound**		
	Estimate	SE	P-value	Estimate	SE	P-value
Intercept	67.065	0.268	<0.001	77.354	0.279	<0.001
DMS2						
60 mph	*Baseline*					
50 mph	-9.171	0.117	<0.001	-17.613	0.126	<0.001
40 mph	-25.908	0.132	<0.001	-28.646	0.141	<0.001
30 mph	-42.243	0.131	<0.001	-36.973	0.177	<0.001
Mile Marker						
45.6	*NA*			-2.166	0.247	<0.001
46.2	5.942	0.240	<0.001	-4.311	0.252	<0.001
46.8	4.601	0.251	<0.001	-6.059	0.257	<0.001
47.4	4.509	0.241	<0.001	-6.039	0.261	<0.001
47.9	1.962	0.257	<0.001	-6.516	0.262	<0.001

Table 3-10 (cont'd)

48.5	4.439	0.251	<0.001	-5.671		0.263	<0.001
49.1	5.498	0.240	<0.001	-3.776		0.261	<0.001
49.5	5.540	0.229	<0.001	-4.630		0.261	<0.001
50.2	1.081	0.218	<0.001	-7.638		0.260	<0.001
50.7	1.339	0.217	<0.001	-5.017		0.261	<0.001
51.3	-1.183	0.214	<0.001	-2.895		0.261	<0.001
51.7	4.140	0.211	<0.001	-4.563		0.263	<0.001
52.1	2.200	0.209	<0.001	-7.642		0.261	<0.001
52.5	-0.803	0.209	<0.001	-10.694		0.256	<0.001
52.7	*Baseline*						
Seasons							
Winter	*Baseline*						
Fall	2.481	0.130	<0.001	0.610		0.123	<0.001
Spring	2.316	0.131	<0.001	2.348		0.150	<0.001
Summer	2.411	0.130	<0.001	1.770		0.153	<0.001
PM				**AM**			
Operational Time				**Operational Time**			
3:00-3:15	*Baseline*			6:00-6:15	*Baseline*		
3:16-3:30	-0.402	0.288	0.163	6:16-6:30	-0.771	0.292	0.008
3:31-3:45	-0.164	0.278	0.554	6:31-6:45	0.491	0.282	0.082
3:46-4:00	-1.779	0.277	<0.001	6:46 -7:00	0.393	0.281	0.162
4:01-4:15	-1.101	0.267	<0.001	7:01-7:15	-0.879	0.273	0.001
4:16-4:30	-1.427	0.268	<0.001	7:16-7:30	-1.514	0.274	<0.001
4:31-4:45	-1.575	0.266	<0.001	7:31-7:45	-2.061	0.269	<0.001
4:46-5:00	-0.407	0.269	0.131	7:46 -8:00	-0.806	0.272	0.003
5:01-5:15	0.225	0.262	0.392	8:01-8:15	-0.572	0.266	0.031
5:16-5:30	0.997	0.267	<0.001	8:16-8:30	-0.729	0.270	0.007
5:31-5:45	2.233	0.268	<0.001	8:31-8:45	0.541	0.272	0.047
5:46-6:00	2.160	0.273	<0.001	8:46 -9:00	0.895	0.284	0.002
6:01-6:15	2.900	0.266	<0.001	9:01-9:15	1.559	0.282	<0.001
6:16-6:30	4.615	0.276	<0.001	9:16-9:30	0.793	0.293	0.007
6:31-6:45	4.661	0.283	<0.001	-	-	-	-
6:46-7:00	3.878	0.286	<0.001	-	-	-	-
R-sq	**78%**			**74%**			

Based on this table, when 30 mph was displayed on the DMS2, both travel directions (NB and SB) recorded a decrease in speeds by 42 mph and 37 mph, respectively, compared to when 60 mph was displayed. Vehicle speeds at northbound and southbound were decreased by 26 mph and 29 mph, respectively, when 40 mph was displayed. A lower reduction in speeds was found when the 50 mph advisory speed was displayed for both directions (9 mph at NB and 18 at SB), compared to the 60 mph sign.

Mile markers were also included in the model; for northbound, the direction of travel starts from MM 46.2 to 52.7. Upon entering the Flex route, average speeds decreased as vehicles traveled toward MM 52.7, with speed reductions ranging from 6 to 1 mph, on average, compared to MM 52.7. This is expected as vehicles are moving toward the bottleneck. While for southbound, the direction of travel starts from MM 52.7 to MM 45.6. As vehicles were traveling toward 45.6-mile marker, on average, speeds were increased.

Since the data is collected year-round, the effects of seasonal variations were also accounted for in the model for speed distributions. As expected, the speeds were higher (range from 1 mph to 2.5 mph) during the spring, summer, and fall seasons as compared to the winter season for both directions.

The speeds were also found to be affected by the time of operations. Note that the northbound operates the advisory speed from 3:00 pm to 7:00 pm, and for southbound direction, it was from 6:00 am to 9:30 am. The linear regression results showed that the speeds on northbound were lower from 3:16 pm to 5:00 pm, compared to 3:00 to 3:15 pm. In contrast, the speeds picked up and increased (ranging from 1 mph to 7 mph) as the time went from 5:15 pm to 7 pm, compared to 3:00 pm to 3:15 pm. Similarly, for the southbound, the speeds were lower from 6:16 am to 8:30 am, while higher from 8:31 am to 9:30 am as compared to 6:00 am to 6:15 am.

Moreover, to better assess the data and provide some recommendations, the speed profiles for each mile marker at each direction were visualized 15 minutes before the operational time, during, and 15 minutes after the operational time, as shown in Figure 3-26 and Figure 3-27 . The y-axis shows drivers speed, the x-axis shows time, panels represent the mile markers, and colors reflect the dynamic messages (i.e., 30 mph, 40, mph, 50 mph, 60 mph, and no message displayed). In these plots, one week worth of data (Monday to Friday) during the fall season was used. These days were selected in a normal condition (i.e., no holiday or crash events). For the northbound direction and as shown in Figure 3-26, the dynamic message sign started to display the 60 mph ten minutes before the operational time (3:00 PM) until 5:00 PM for the MM 46.2 (start of Flex route) to MM 49.5. This is also true for MM 50.2 to MM 51.3 except for between 4 to 5 PM, when travel speeds started to drop and different messages (50, 40, and 30 mph) started to be displayed. While for MM 51.7 to 52.7, the 60-mph sign was only displayed until 3:30 pm and then from 5:30 to 7:00 pm, when the travel speeds were back to normal. From 3:30 pm to 5:30 pm, travel speeds dropped drastically and more of 30 mph and 40 mph signs were displayed. On the other hand, the southbound direction, as shown in Figure 3-27, had the consistent speed across the peak period regardless of the advisory speed and mile marker. The speed during weekends also showed consistent trend. The speed in northbound direction during weekends was plotted in Figure 3-28 as an example.

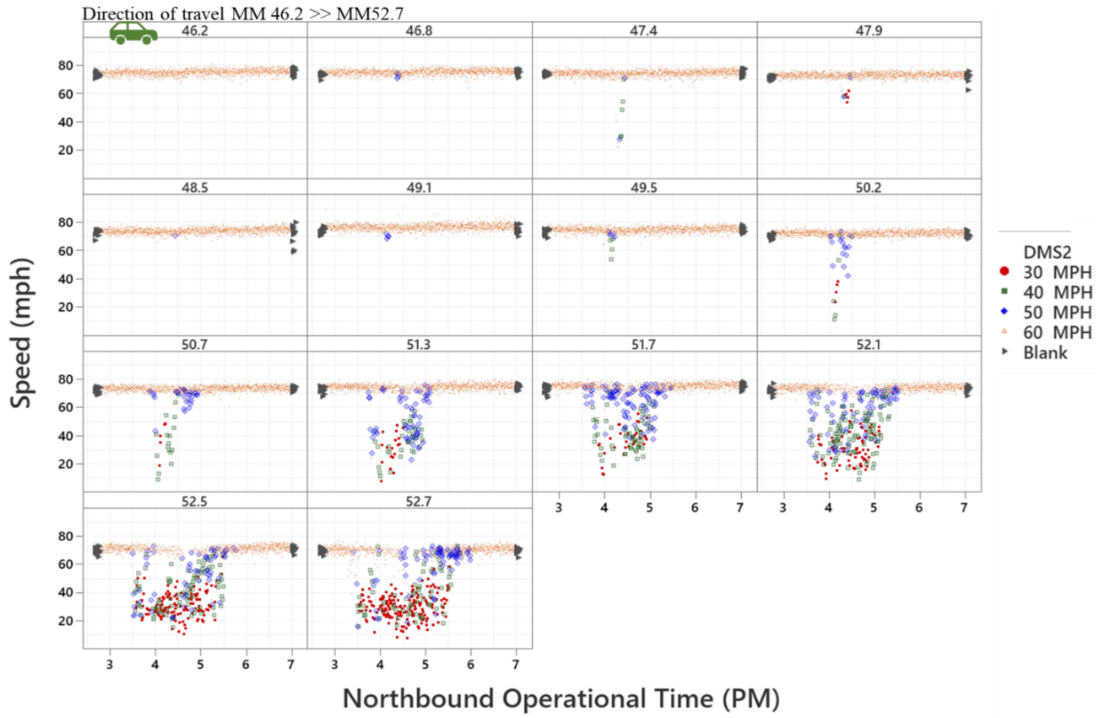


Figure 3-26 Northbound drivers' speed profile during only weekdays, 15 minutes before the operational time, during, and after

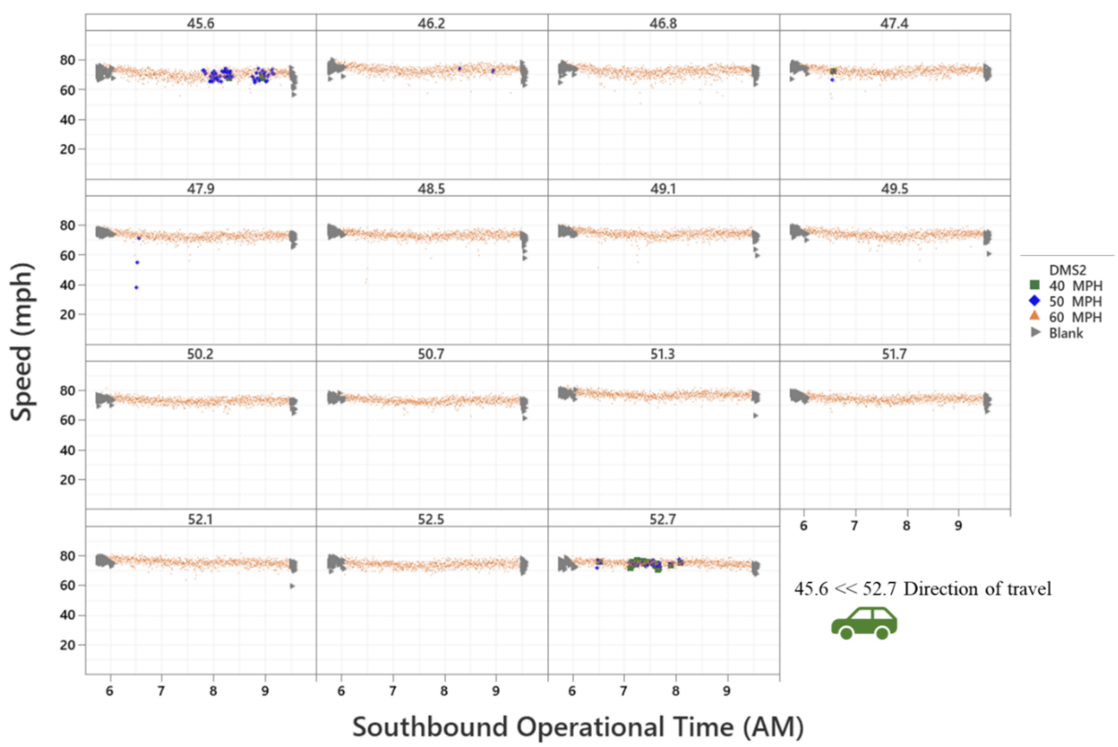


Figure 3-27 Southbound drivers' speed profile during only weekdays, 15 minutes before the operational time, during, and after

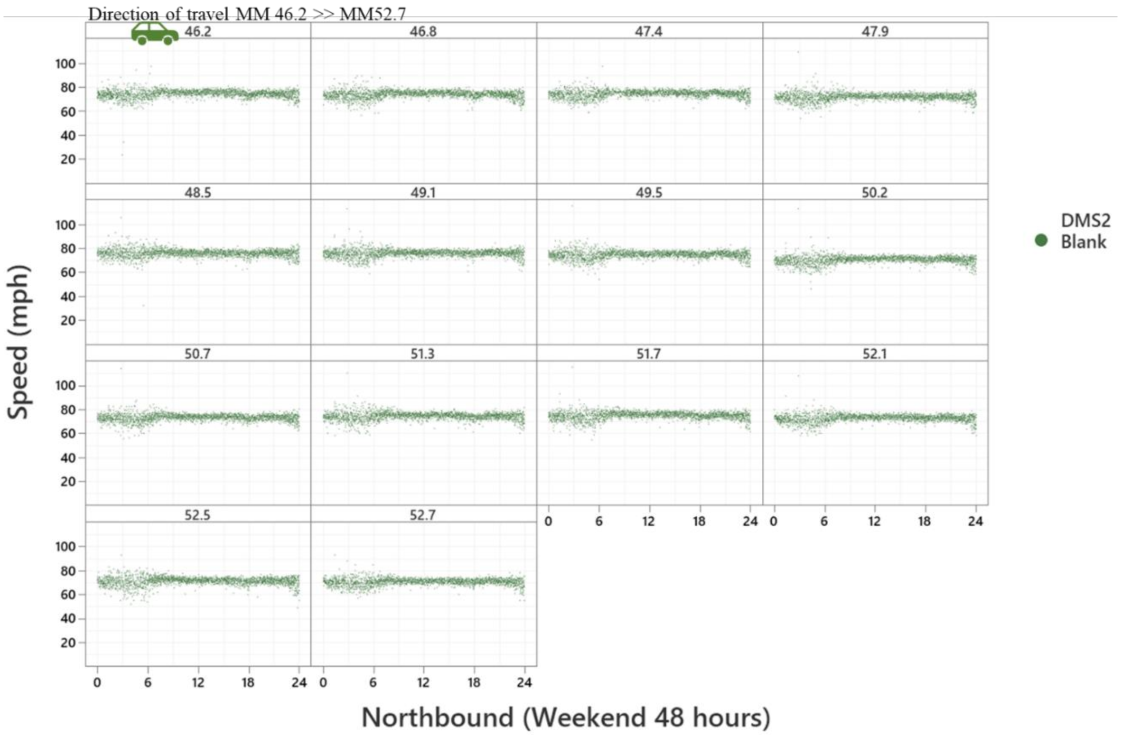


Figure 3-28 Northbound drivers' speed profile during weekend

Finally, based on Figure 3-26 and Figure 3-27output, the data was aggregated from MM 46.2 to 49.5 as one chunk (i.e., upstream the Flex route for NB and downstream for SB) and from 50.2 to 52.7 as a second set. Then, two-way interaction plots between these two sets of MMs and DMS2 were schemed for both directions separately, as shown in Figure 3-29. For the northbound direction, when the 30-mph message is displayed anywhere on the Flex route, the travel speeds match the displayed message. For the 60-mph message, as noted previously, generally, average travel speeds are higher than the 60-mph message by 10 mph, i.e., 70 mph. Interestingly, for 40-mph and 50-mph messages, a difference between the upstream and downstream was observed. The figure shows that the average travel speed from MM 50.2 to 52.7 closely matches the displayed messages while they are higher on MM 46.2 to 49.5. This suggests that most drivers were dropping their speed because the overall speeds dropped, not because of the dynamic message sign. One possible solution could be dropping the display message sign 5-mph for the 60, 50, and 40 mph (i.e., display 55-mph, 45-mph, and 35-mph) while keeping the 30 mph the same or dropping it to 25 mph. This will also help with the southbound trend since the average travel speeds were always above what is displayed on the DMS2 by about 5 mph.

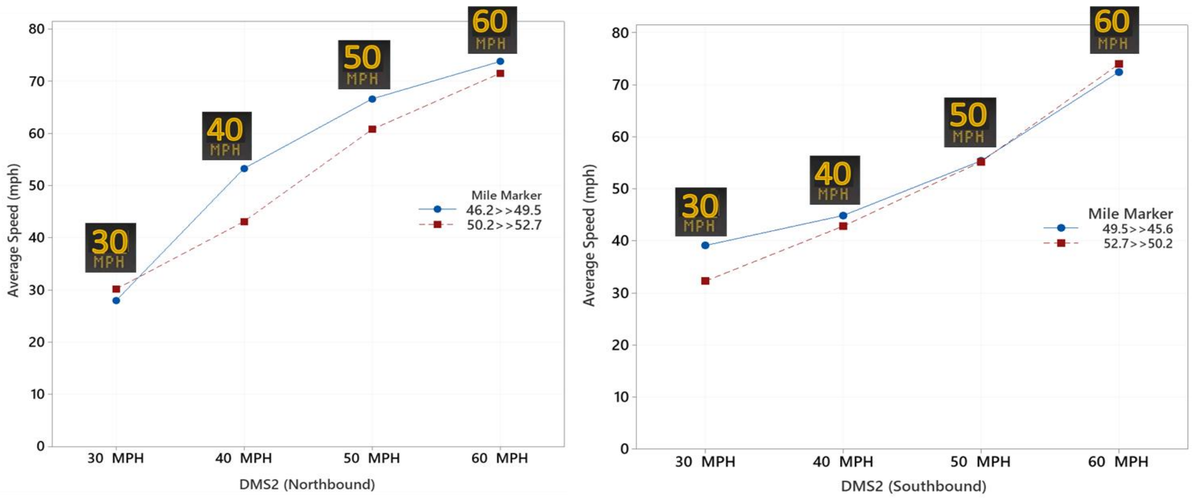


Figure 3-29 Two-way interaction between DMS2 and the aggregated mile markers for both directions on mean speed

3.5 Performance during Special Days

The US-23 Flex route is one of the major routes people typically use to travel to Ann Arbor during peak hours or for University of Michigan home football games. In addition to the regular operational time during the weekdays, the Flex lane also opened to the motorists under critical situations such as occurrences of crashes, football games, or other heavy congestion. It is important to assess the effectiveness of the Flex route during these special days and provide better recommendations in the future. The following section introduces the performance of Flex route during game days, holidays, and Fridays. The data utilized in this section include travel speed data from MVDS reports and gantry messages from ATM reports.

3.5.1 *Game Day Performance*

The game day data such as the football schedule, weather, and instances of crashes were determined from three websites, respectively: University of Michigan Athletics (University of

Michigan, 2021b), Weather Underground (Weather Underground, 2021), and Michigan Traffic Crash Facts (MTCF) (University of Michigan, 2021a). This data for football games in 2018 and 2019 is summarized in Table 3-11. The corresponding travel speeds with one-minute interval along the Flex route were obtained from the MVDS reports. Additionally, the gantry messages, especially the messages of Flex lane closure during the game days, were obtained from the ATM reports.

In order to determine the effectiveness of the Flex route on game days, the game day data was collected and the gantry messages were integrated with the travel time over game days. The data integration procedures were similar to the procedures introduced in section 3.4.

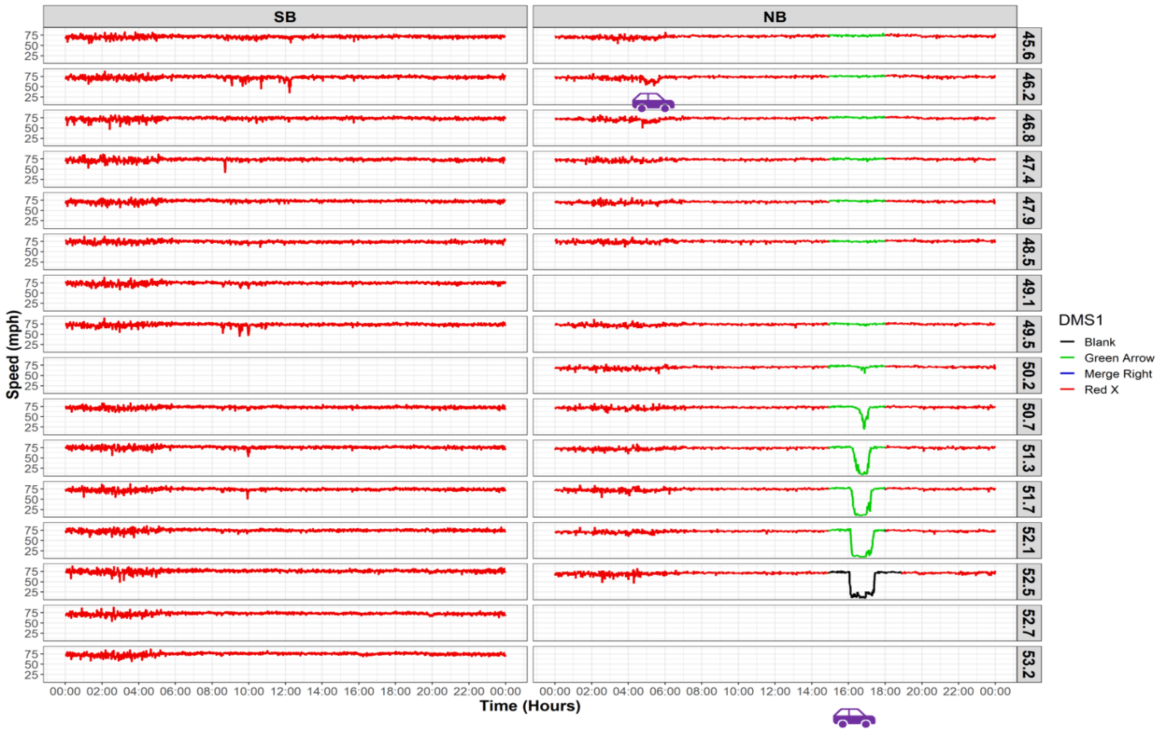
Table 3-11 University of Michigan home football games (2018-2019)

Team	Date	Start Time	Duration	End Time	Attendance	Scores
Western Michigan	9/8/2018	12:00 PM	3:12	3:12 PM	110814	49-3
Southern Methodist University	9/15/2018	3:30 PM	3:24	6:54 PM	110549	45-20
Nebraska	9/22/2018	12:00 PM	3:30	3:30 PM	111037	56-10
Maryland (HC)	10/6/2018	12:00 PM	3:18	3:18 PM	109531	42-21
Wisconsin	10/13/2018	7:30 PM	3:07	10:37 PM	111360	38-13
Penn State	11/3/2018	3:45 PM	3:17	7:02 PM	111747	42-7
Indiana	11/17/2018	4:00 PM	3:38	7:38 PM	110118	31-20
Middle Tennessee State	8/31/2019	7:30 PM	3:26	10:56 PM	110811	40-21
Army	9/7/2019	12:00 PM	3:34	3:34 PM	111747	24-21
Rutgers	9/28/2019	12:00 PM	3:09	3:09 PM	110662	52-0
Iowa	10/5/2019	12:00 PM	3:26	3:26 PM	111519	3-10
Notre Dame	10/26/2019	7:30 PM	3:31	11:01 PM	111909	45-14
Michigan State	11/16/2019	12:00 PM	3:34	3:34 PM	111496	44-10
Ohio State	11/30/2019	12:00 PM	3:41	3:41 PM	112071	27-56

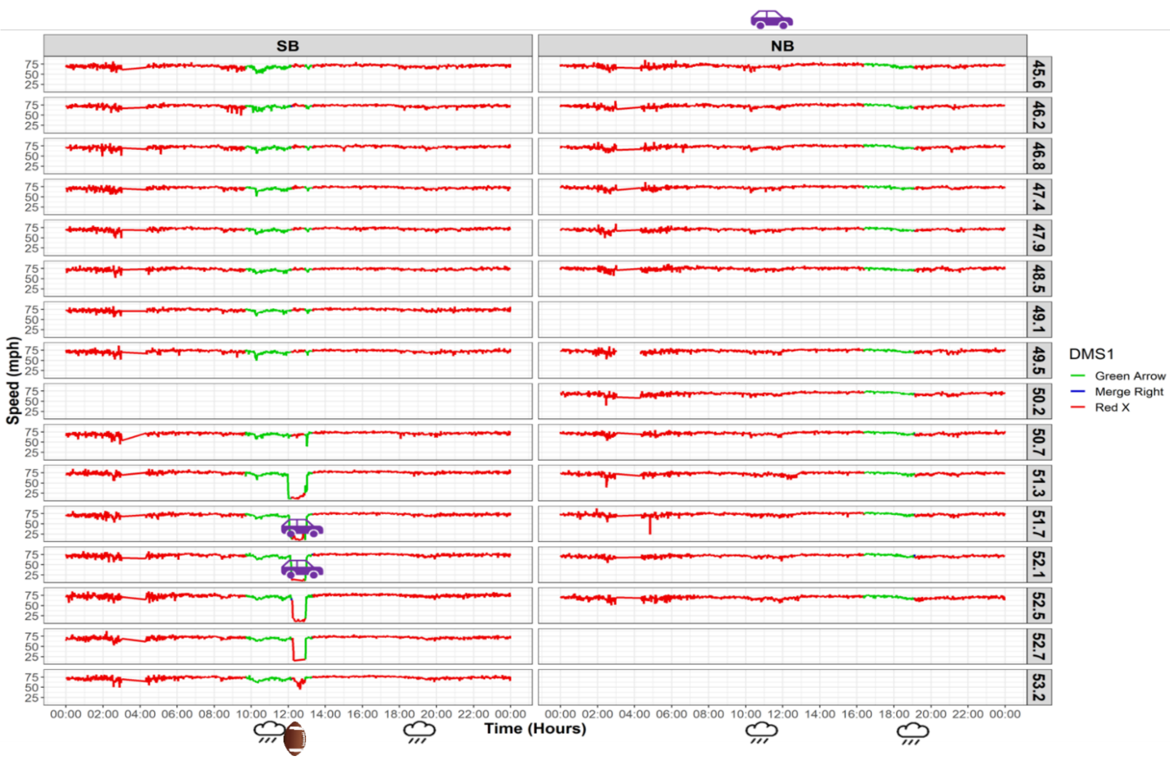
In general, the Flex route operated efficiently during most football games that happened between 2018 and 2019 in Ann Arbor. However, there were several games that deserved additional attention, such as, the home games against Nebraska, Maryland, Army, Rutgers, and Iowa. The following paragraphs will discuss the specifics of each game individually. On the graphs, the blue car icon, raining icon, and the football icon indicate the location and time of crashes, the time of precipitation, and football games, respectively.

Figure 3-30a shows that the Flex lane was not in operation during the Nebraska game. The Flex route operated in the northbound direction during the afternoon. Several moderate fluctuations of speed were observed at multiple locations without showing any particular trend, which can be indicative of congestion or other factors such as the occurrence of a crash. One necessary note is that two crashes happened on northbound US-23 on that day, which could impact the downstream traffic traveling northbound.

Additionally, the southbound Flex lane opened around 10 AM for the Maryland game (Figure 3-30b). Some fluctuations were still observed on southbound US-23, particularly as traffic neared Ann Arbor. If the Flex lane opened earlier, it might have been able to accommodate these issues occurring in the southbound direction. Similarly, the Flex route started to operate around 10 AM for games against Army and Rutgers (Figure 3-30c and Figure 3-30d). Speed drops were found in the southbound direction. Conversely, the Iowa game (Figure 3-30e) had similar kickoff time (12 PM), but the operation of the Flex route started around 8 AM in the southbound direction. There were no significant fluctuations of travel speed observed. Therefore, it is suggested that the Flex lane should operate three or four hours earlier than kickoff time when football games occur.



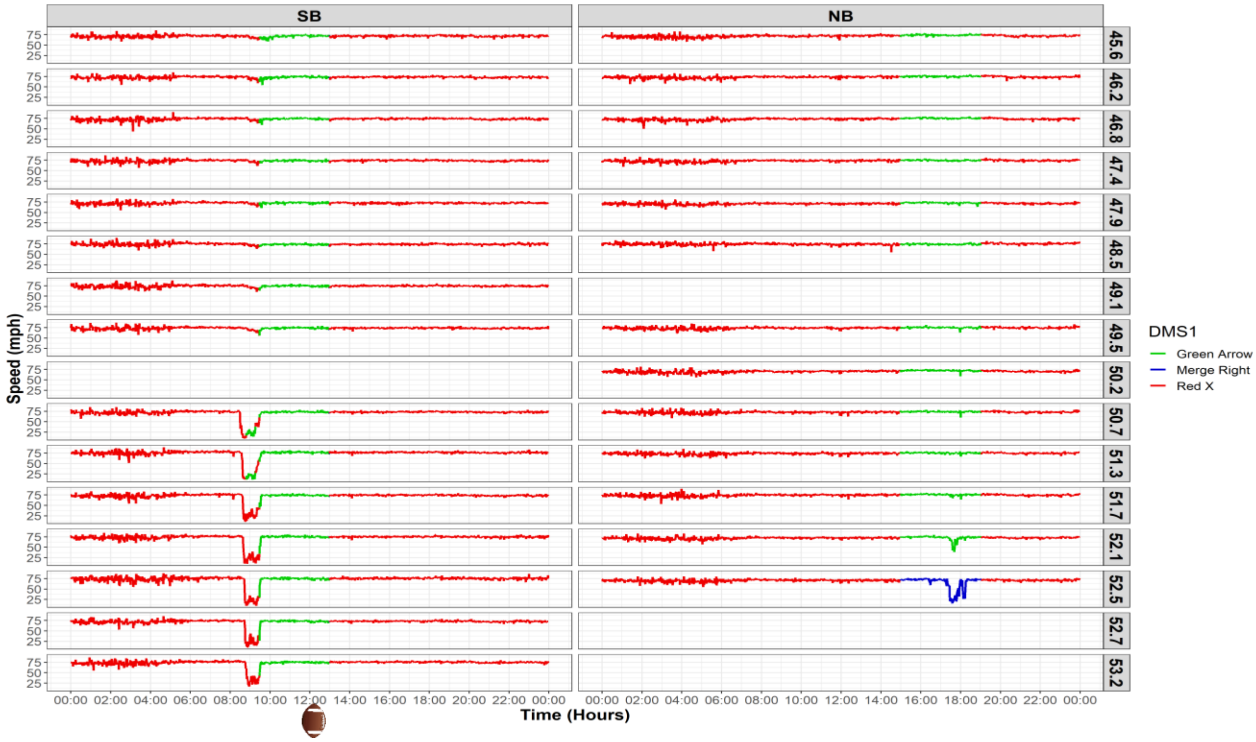
a. September 22, 2018 – Nebraska, 12:00 PM – 3:30 PM



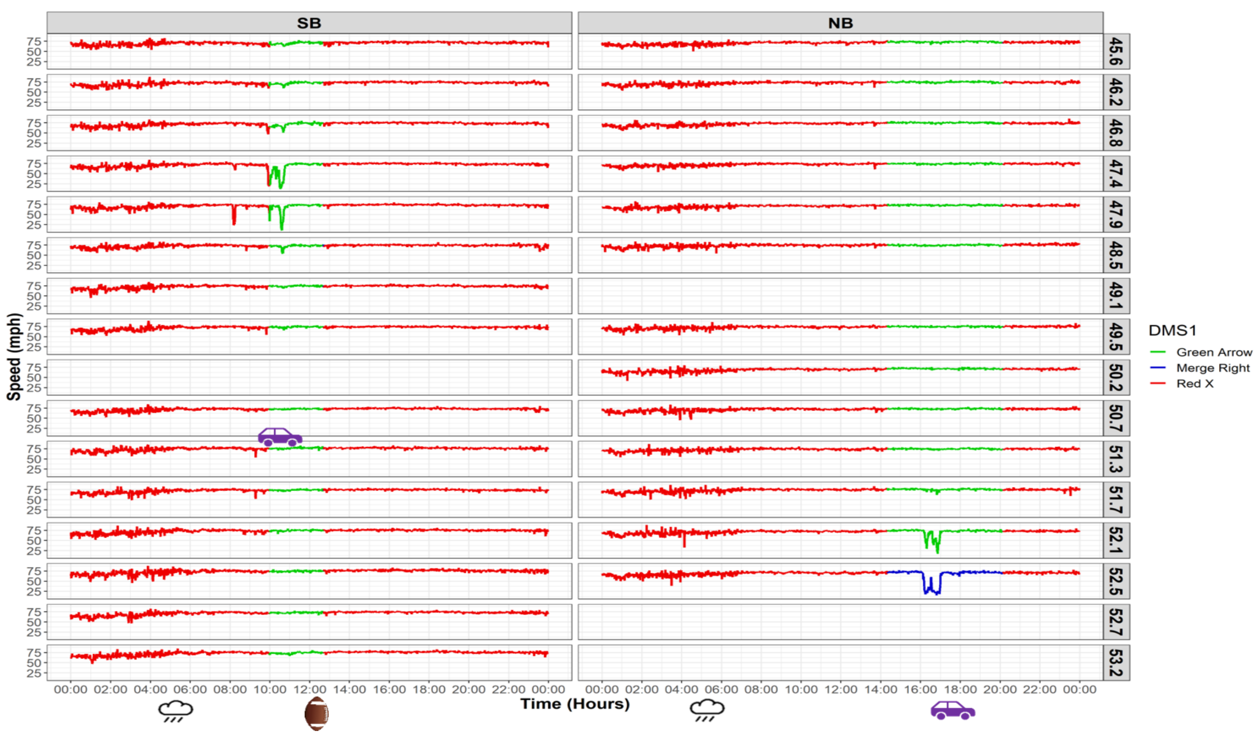
b. October 6, 2018 – Maryland, 12:00 PM – 3:18 PM

Figure 3-30 Drivers' speed selection behavior on US-23 Flex route on football game days

Figure 3-30 cont’d

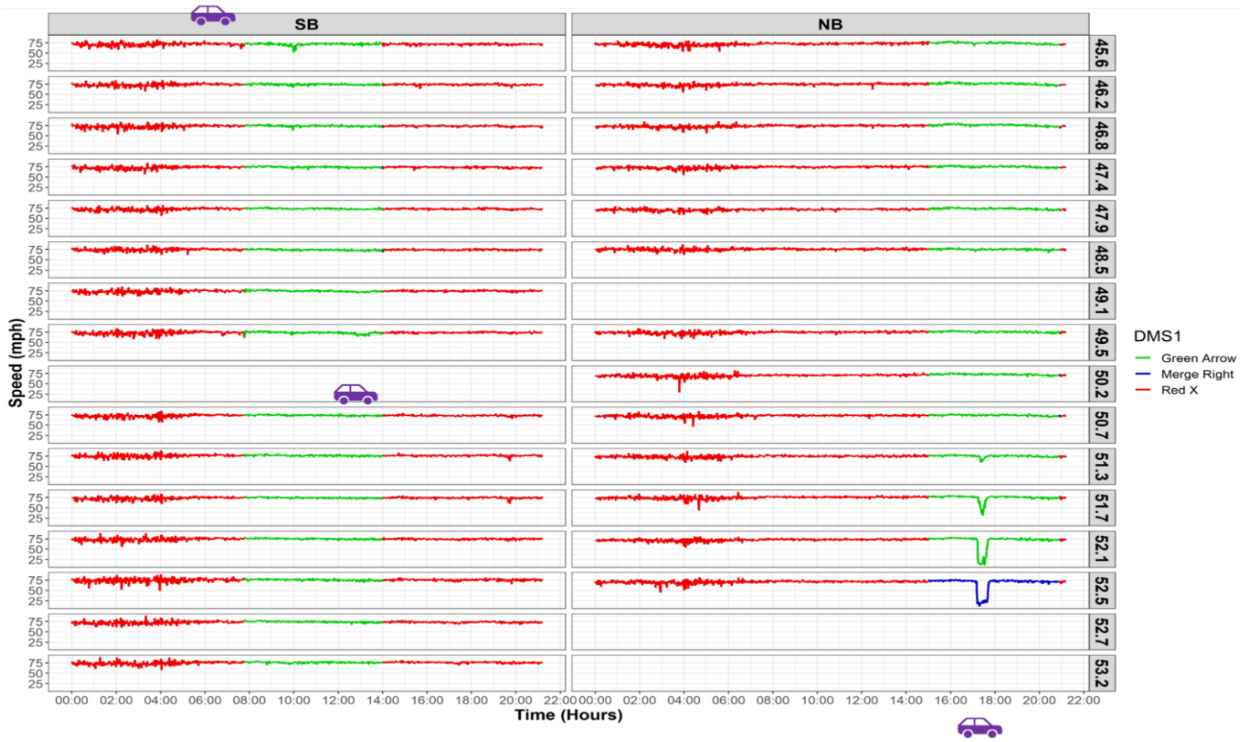


c. September 7, 2019 – Army, 12:00 PM – 3:34 PM



d. September 28, 2019 – Rutgers, 12:00 PM – 3:09 PM

Figure 3-30 cont'd

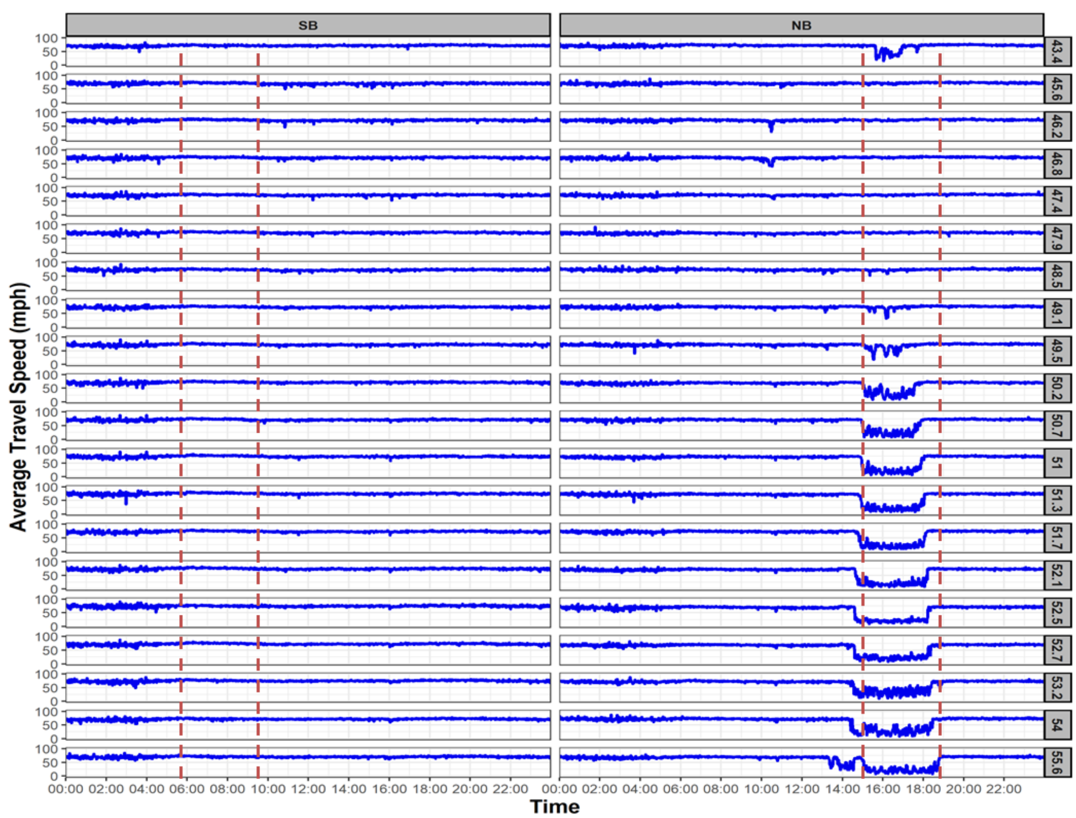


e. October 5, 2019 – Iowa, 12:00 PM – 3:26 PM

3.5.2 Holiday and Friday Performance

The travel pattern typically changes before, after, or during the holidays such as Independence Day, Thanksgiving, Christmas, or New Year. Thus, the performance of the Flex lane during holidays was also evaluated. The holidays in 2018 and 2019 were identified, as well as several days before and after the holidays. The corresponding travel speed over those days was obtained from MVDS reports. The speed profiles were plotted for each selected date. After inspecting all the speed profiles, the traffic during holiday seasons was found to be well-accommodated by the Flex lane under most circumstances and holidays. However, a few days before five holidays required additional attentions. These days include the Friday before Memorial Day, July 3rd before Independence Day, Friday before Labor Day, Wednesday before Thanksgiving, and Friday before Christmas. Figure 3-31 exhibits the speed profiles during these special days (Figure 3-31a-e) and an example of holiday performance (Figure 3-31f). The red dash lines on the graphs indicate the range of typical operational time of the Flex lane.

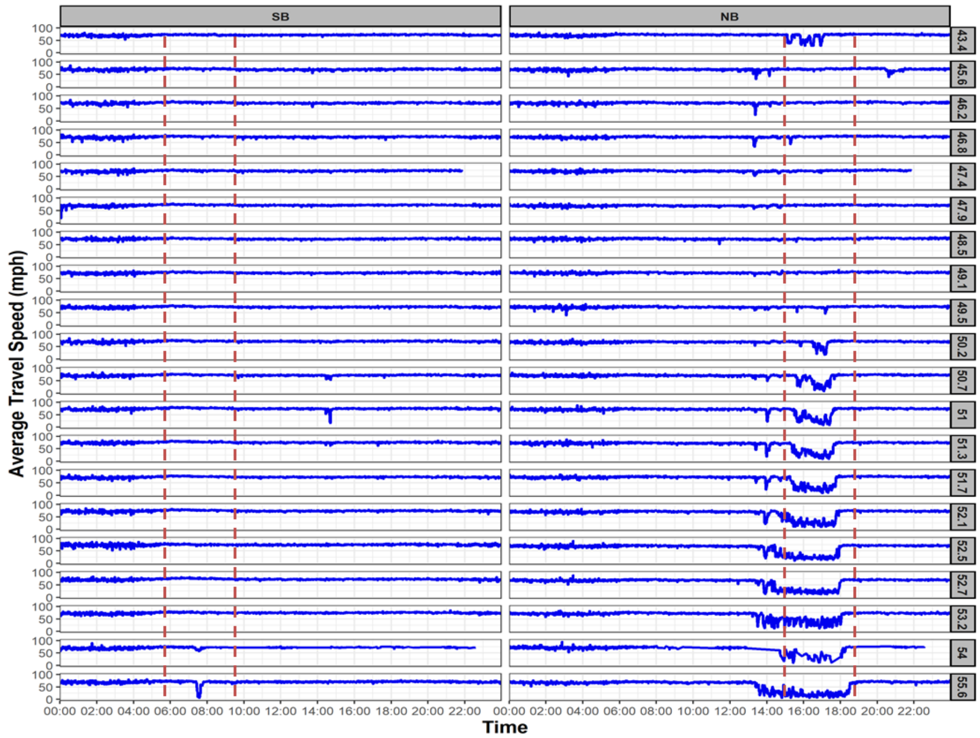
As the figures demonstrated, there were no concerns for the southbound traffic. Most speed drops were found in northbound direction due to the bottleneck discussed earlier. Fortunately, the issues could be resolved by the future extension of the Flex route to I-96. However, to address most of the issues currently, the Flex lane was recommended to operate one or two hours earlier than the regular time in northbound direction (3:00 PM). The action could mitigate the problems that occurred on most days. Only on Friday before Labor Day (Figure 3-31c), the Flex lane was suggested operating three hours earlier to accommodate the northbound traffic.



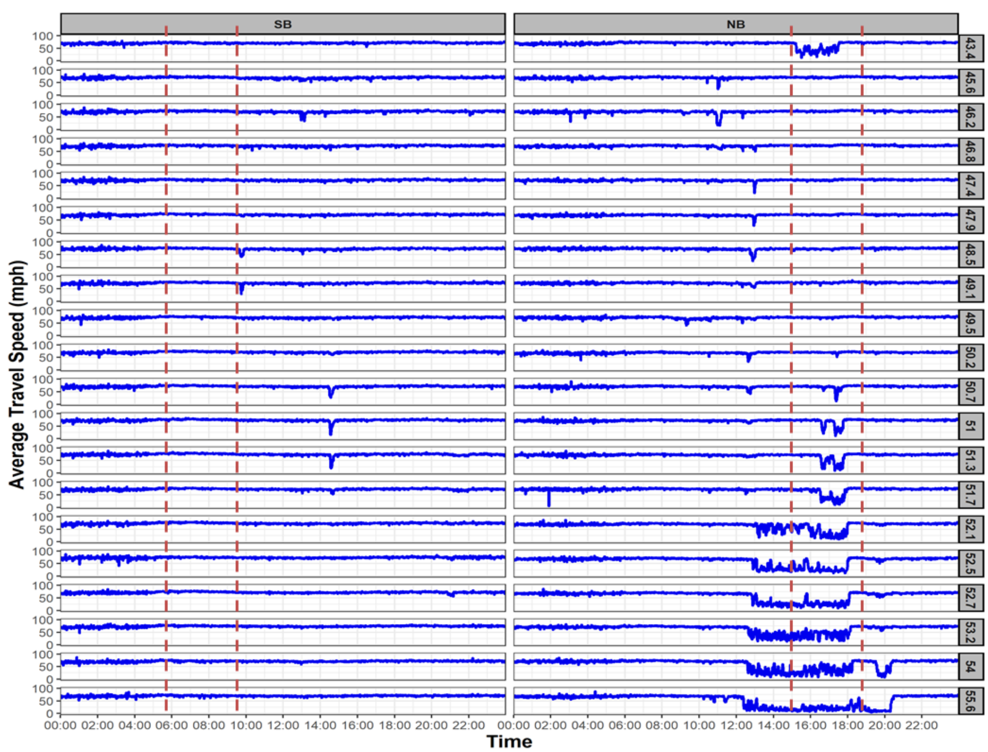
a. Friday before Memorial Day

Figure 3-31 Drivers' speed selection behavior on US-23 Flex route on holidays

Figure 3-31 cont'd

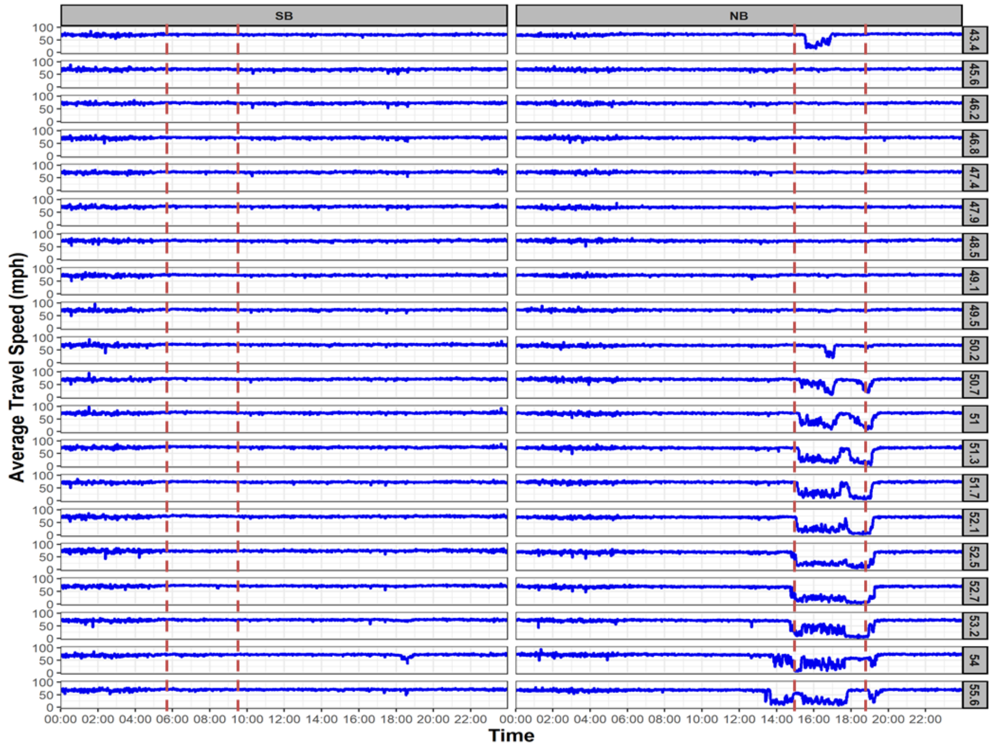


b. July 3rd before Independence Day

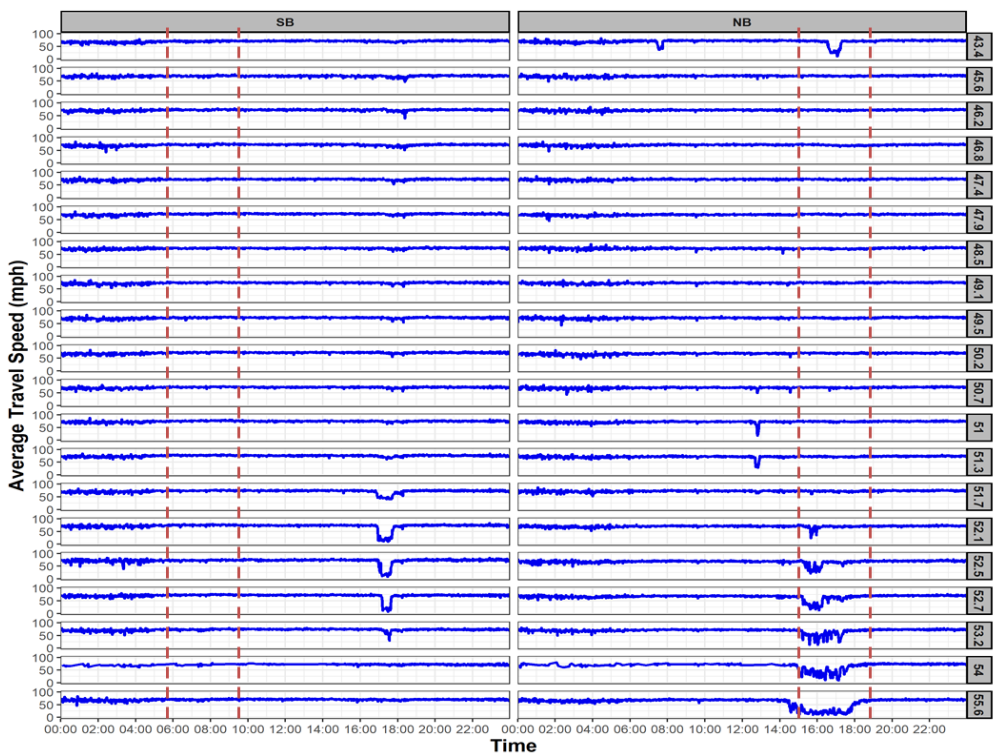


c. Friday before Labor Day

Figure 3-31 cont'd

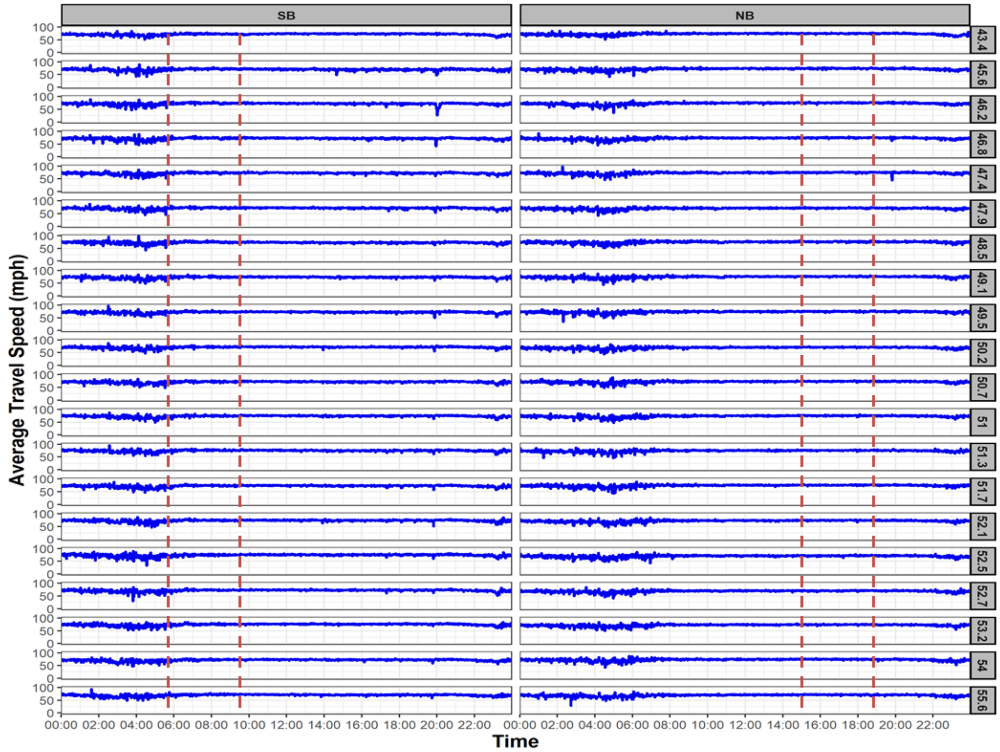


d. Wednesday before Thanksgiving



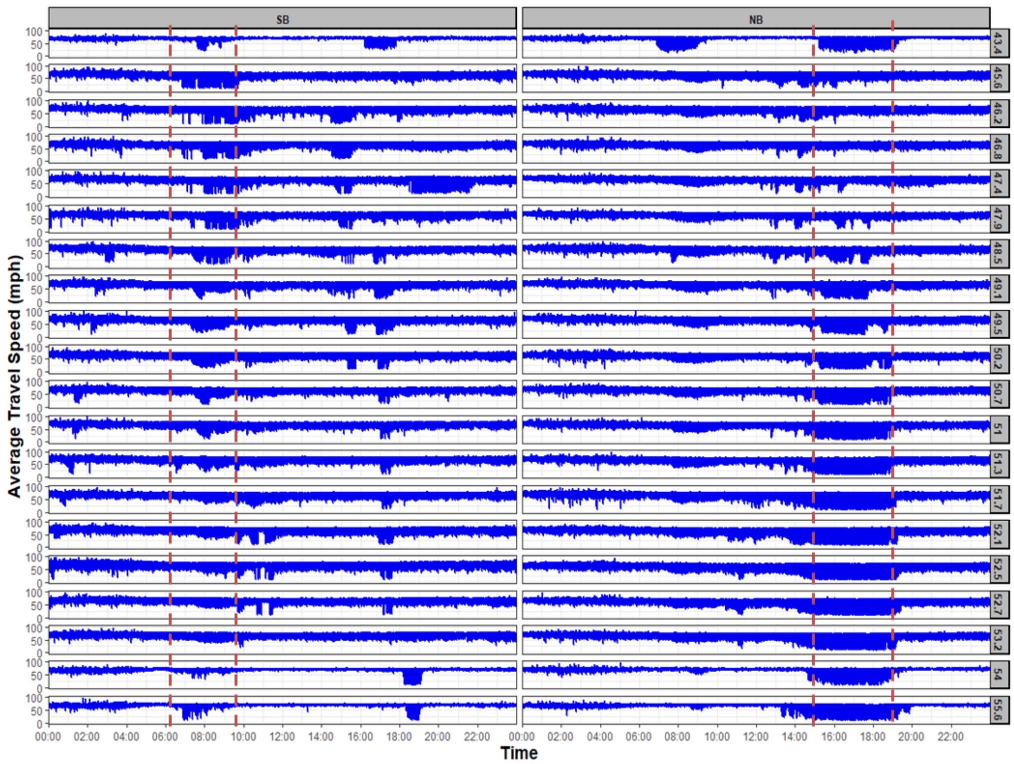
e. Friday before Christmas

Figure 3-31 cont'd

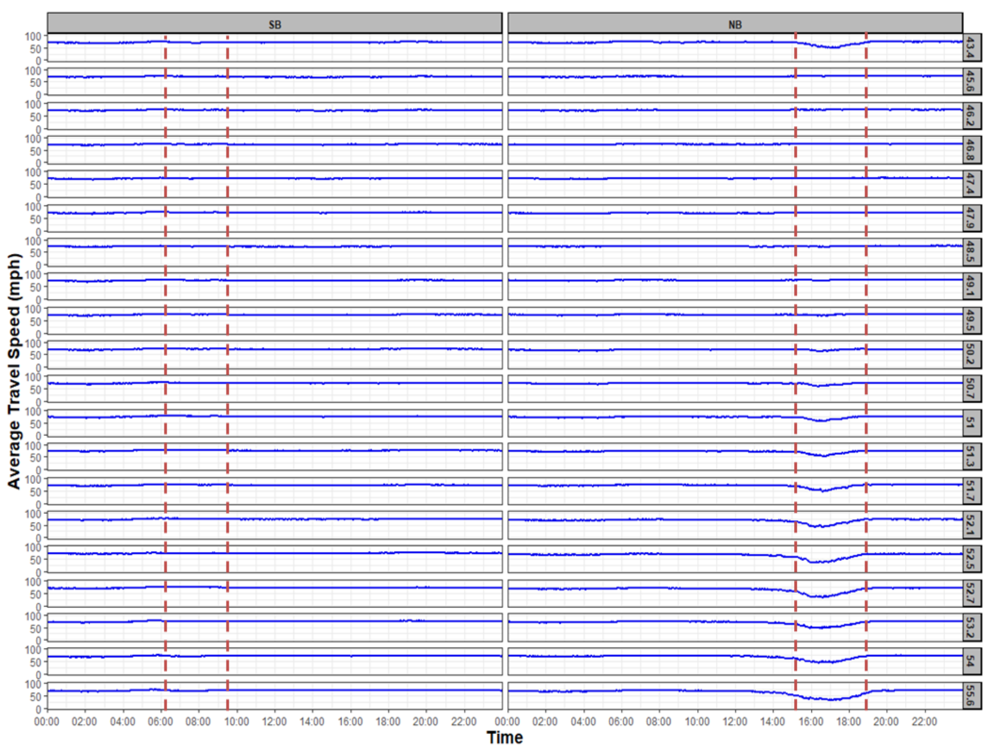


f. Memorial Day

Additionally, the performance of Fridays was also evaluated (Figure 3-32). Every individual Friday over the analysis period (2019) was plotted as a part of the demonstration in Figure 3-32a. Figure 3-32b displayed the average travel speed over all Fridays during the analysis period. Similar to the general trend during the holiday season, the southbound had no critical issues. Towards the end of northbound, the speed gradually decreased. It is suggested that, again, the Flex lane could potentially be open one or two hours earlier than the regular time. The future project of extending US-23 could alleviate the issues.



a. Speed of every individual Fridays for one calendar year



b. Average speed of all Fridays for one calendar year

Figure 3-32 Drivers' speed selection behavior on US-23 Flex route on Fridays

3.6 Incident Clearance Data

The effectiveness of the Flex route under various incidents was evaluated by using the incident clear data. The data was available before and after implementing the Flex route. The following sections provide the procedures used to integrate data and discuss the findings.

3.6.1 Data Integration

As introduced previously, the incident clearance data was obtained from two different vendors (i.e., MDOT Freeway Courtesy Patrol (FCP) and Incident Clear Data (ICD)). In order to join two datasets together, the shapefile from MDOT was utilized. Aside from the general event information, the data from MDOT FCP also included the location information such as PR numbers and mile points of each event. In each case, the events from FCP can be easily located by using the Michigan sufficiency file. However, unlike the FCP data, the data from ICD provided the coordinates of each event. After using ArcMap to locate the events from ICD, the locations of some events were found to not match with the descriptions from the original dataset. For instance, an event occurred on the US-23 Flex route near the M-14 interchange based on the description from the dataset. However, the corresponding coordinates for this event show that it occurred on the US-23 Flex route near Territorial Road. In such cases, the locations of events were manually modified following the descriptions in the original dataset. Additionally, if no detailed descriptions were provided, it was assumed the location based on the coordinates was correct.

3.6.2 Results

One straight forward method to quantify the effectiveness of the Flex route was to compare the differences of incident cleared time before and after the operation of the Flex route. The incident cleared time was defined as the difference between the timestamps when FCP or emergency services arrived and the timestamp when the incident were cleared. In this study, the incidents were classified into seven categories: Abandoned vehicle, crash, debris, flat tire, mechanical, no gas, and others. The changes of cleared time during before and after period for each event were presented in Table 3-12. After operating the Flex route, the incident cleared time decreased significantly for most types of events, especially for those that related to crashes, debris, and mechanical issues. However, an increase in cleared time was found for the events on northbound US-23 which involved an abandoned vehicle or a vehicle that ran out of gas.

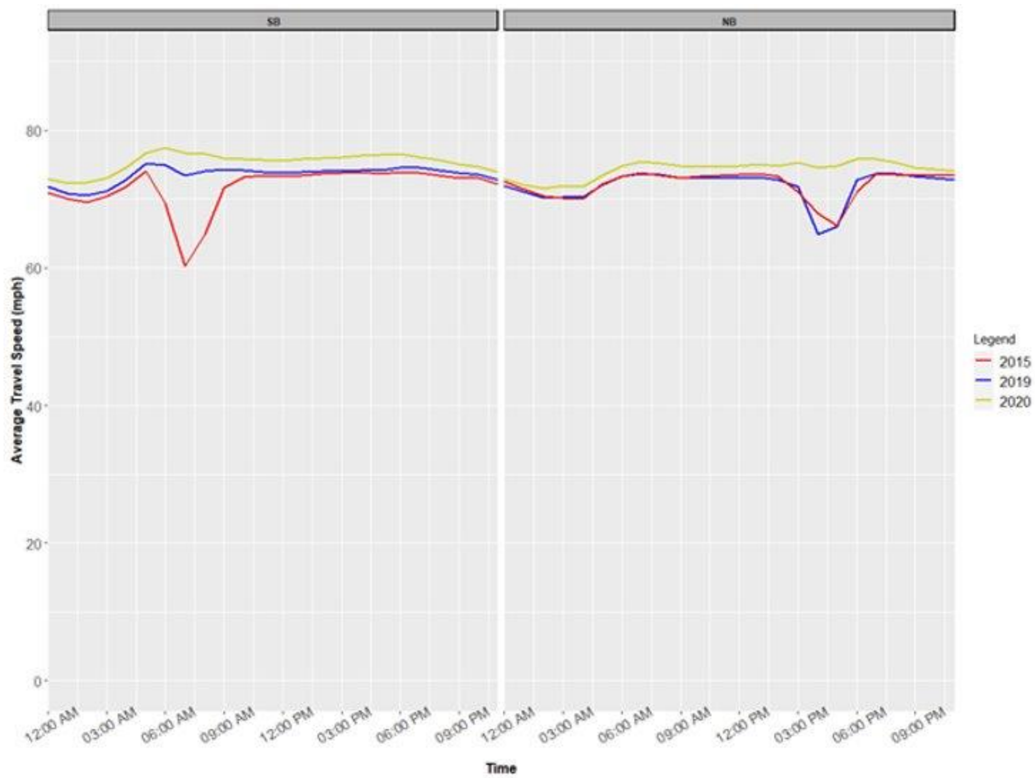
Table 3-12 Comparisons of incident cleared time before and after the implementation of US-23 Flex route

Year	Direction	Abandoned Vehicle (mins)	Crash (mins)	Debris (mins)	Flat Tire (mins)	Mechanical (mins)	No Gas (mins)	Other (mins)
Before (2015 – 2016)	SB	3.2	51.2	6.9	17.0	13.4	7.8	13.7
	NB	2.8	39.0	8.3	17.1	14.9	5.8	8.7
After (2018-2019)	SB	2.8	39.6	4.4	14.0	9.7	5.5	4.9
	NB	3.7	28.7	4.5	14.4	11.9	7.7	6.6
Difference (%)	SB	-12.7	-22.7	-36.2	-17.6	-27.6	-29.6	-64.2
	NB	31.2	-26.5	-45.6	-16.0	-20.4	34.6	-24.4

3.7 Impacts of Pandemic

In March 2020, the World Health Organization (WHO) announced a pandemic that happened worldwide named Corovarise Disease (COVID -19) (WHO, 2020). In response to this pandemic, many countries implemented several social distancing measures (e.g., keep social distance, wear face-covering, stay-home order, and travel restrictions etc.) to prevent the transmission of the disease, including the United States. Several studies from the U.S. found a significant reduction in personal trips and public transportations throughout the country as a result of those measures (Shannon et al., 2020; Newburger, 2020; Lazo et al., 2020; Tomer et al., 2020; Davis, 2020). Considering the impacts of pandemics all over the country, the performance of Flex route under the pandemic is also interested to investigate. The speed and volume data of 2019 and

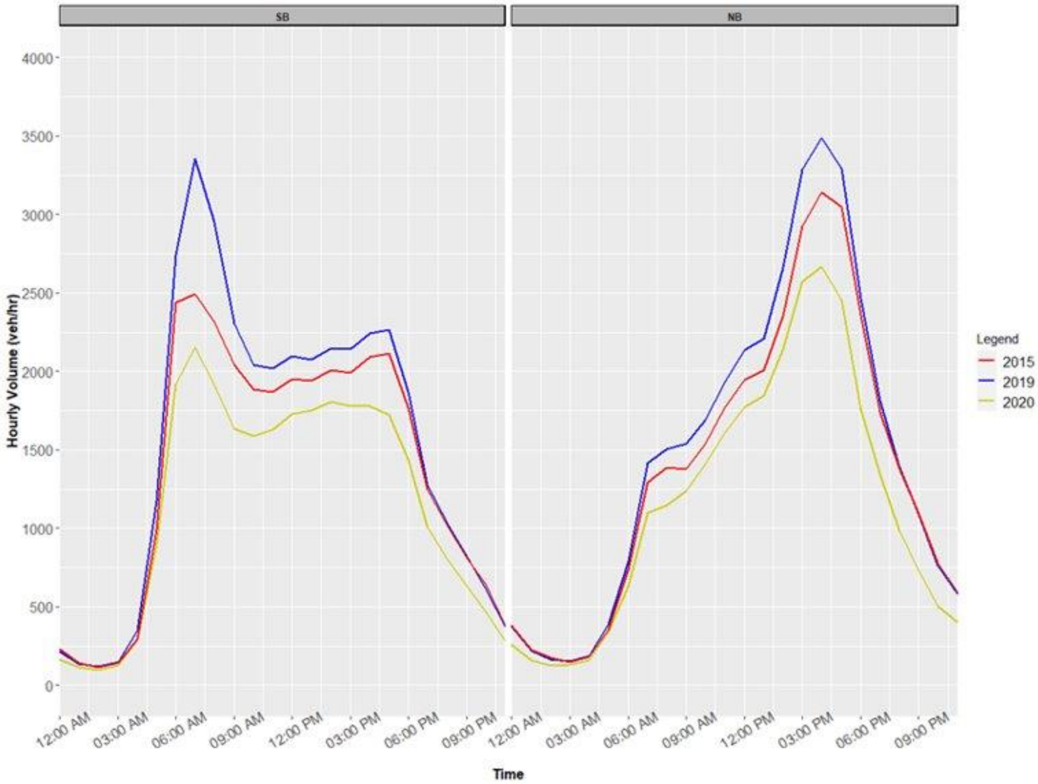
2020 were also obtained from the same PTR station introduced earlier. The speed and volume trends are shown in Figure 3-33. In 2020, the highest speed and lowest volume were observed. Compared to the year 2019, the speed improved, but there were fewer vehicles on the road. Moreover, the operational performance (i.e., travel speed) was estimated by utilizing the probe vehicle data of 2019, 2020 and the data between January 2021 to August 2021 from RITIS. One point needs to be noted that only the probe vehicle data after June 2019 was included in the analysis due to the modifications of vendor. A specific description of the probe vehicle data can be found in the previous section



a. Average travel speed

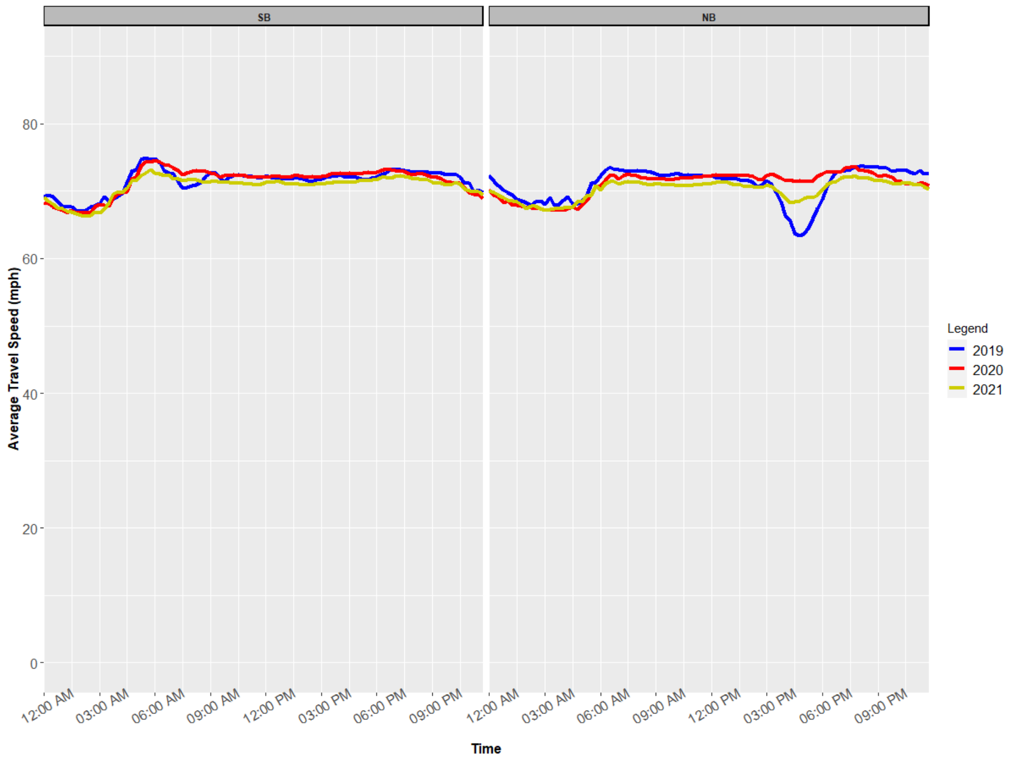
Figure 3-33 Yearly US-23 Flex route average travel speed and volume over time

Figure 3-33 cont'd

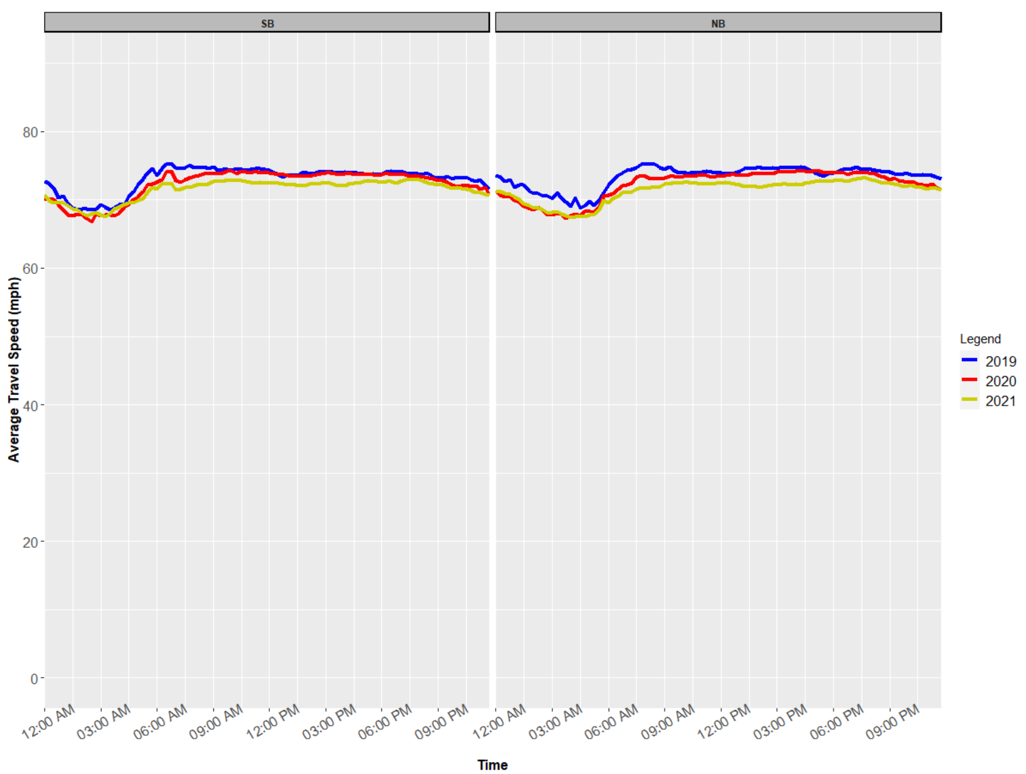


b. Hourly volume

Similar to the travel time reliability, the trend of average travel speed was developed for the entire Flex route. Figure 3-34 displays the average travel speed during weekdays and weekends individually. A decreased trend was observed during the early morning. The sensor errors might occur during that time after a detailed data inspection. In addition to that, the year 2019 had the lowest speed during the peak period compared to the other two years. The speed of 2020 was higher than 2019 and 2021, which was consistent with the fact that the personal trips and public transportation reduced after the restraining orders. Drivers could travel with less volume and higher speed. After lifting the orders and the invention of vaccines, the traffic in 2021 was gradually back to normal. Therefore, the speed decreased again in 2021. The speed of 2021 during weekends was slightly lower than the other two years.



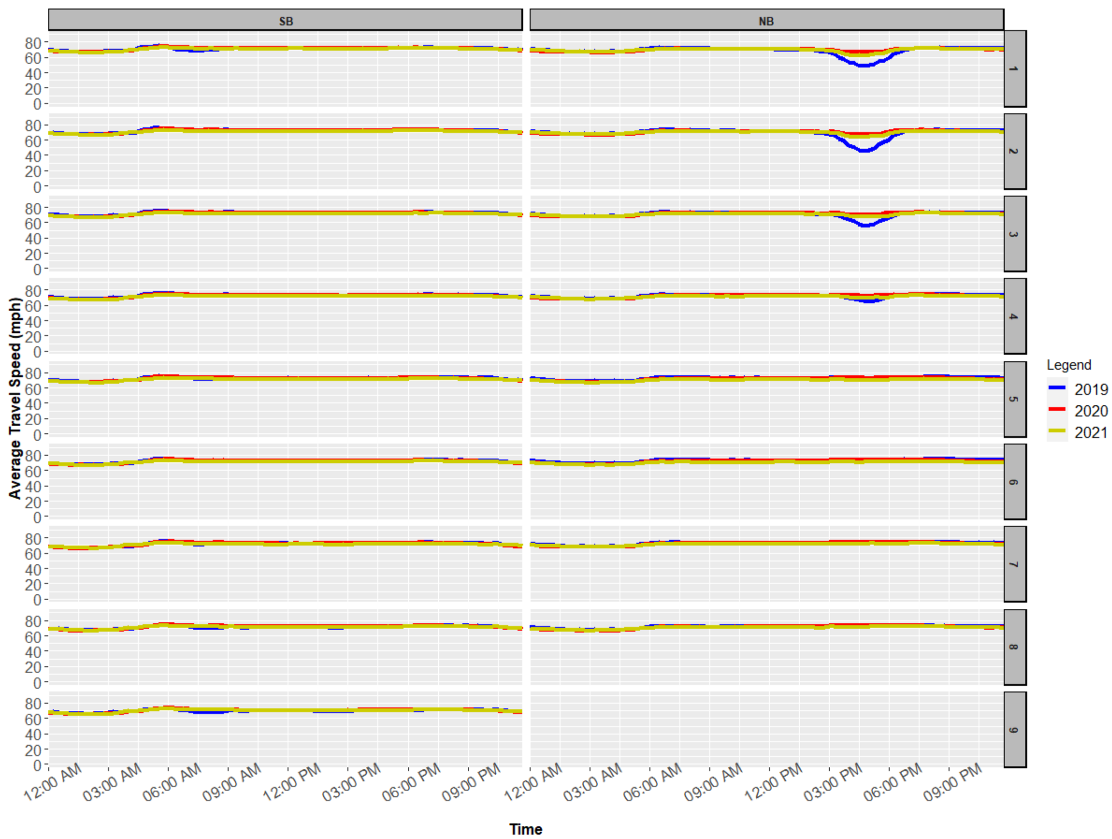
a. Weekdays



b. Weekends

Figure 3-34 Yearly US-23 Flex route average travel speed

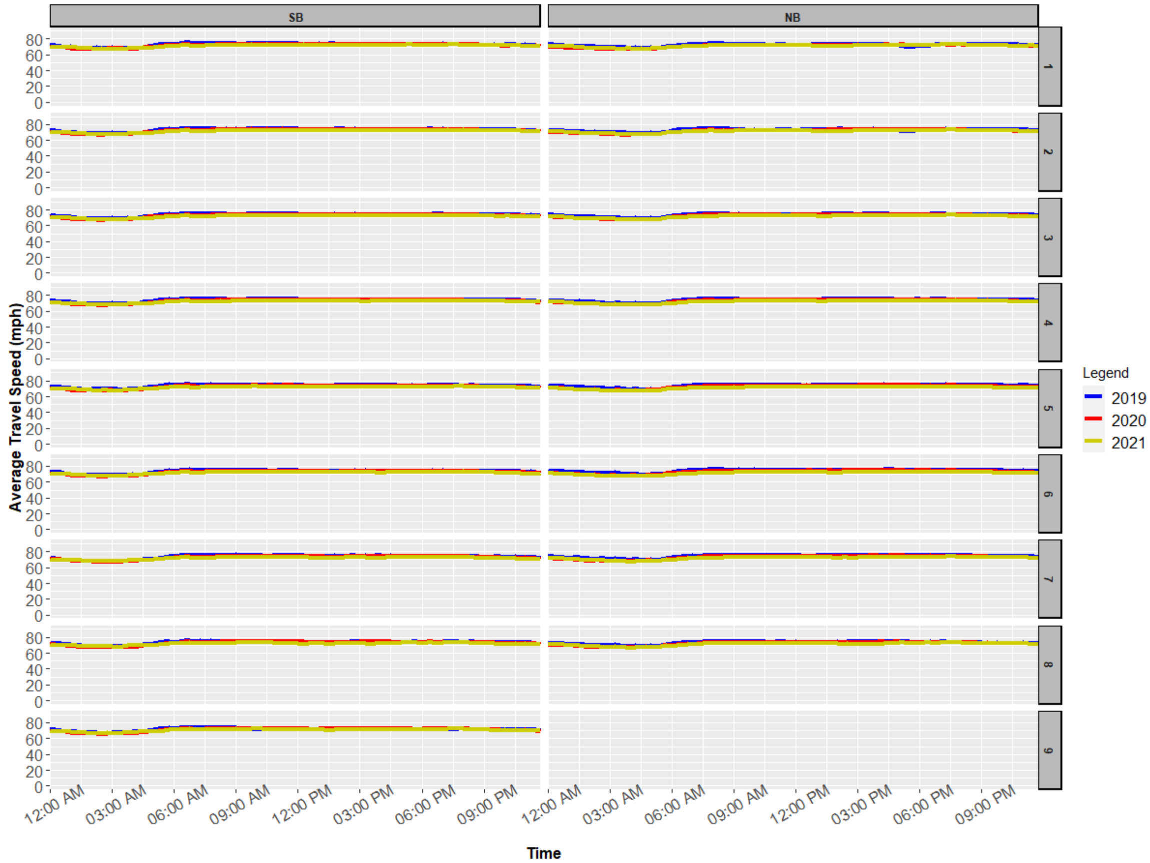
The speed profiles were also generated at the segment level. Figure 3-35 includes the segment-specific speed profiles for each direction during weekdays and weekends. The trends during weekends were consistent between 2019, 2020, and 2021. The speed drops that occurred toward the end of northbound during weekdays were almost gone under the pandemic period.



a. Weekdays

Figure 3-35 Yearly US-23 Flex route average travel speed at segment-level

Figure 3-35 cont'd



b. Weekends

3.8 Summary

In general, the operational performance of US-23 Flex route, in terms of travel time, speed, and flow rate, improved after constructing the Flex route, particularly in the southbound direction. The introduction of the Flex lane created a bottleneck downstream of the end of the Flex lane in the northbound direction, which has led to persistent queuing in that section during peak traffic periods. However, this congestion is likely to be mitigated by the subsequent extension of the Flex route to I-96.

CHAPTER 4 SAFETY IMPACTS

Beyond the impacts on traffic operations detailed in the preceding chapter, the changes in travel times and speeds introduced related impacts on safety performance in terms of the frequency and severity of crashes. This chapter details a before-and-after evaluation of the Flex route to examine changes in these metrics.

4.1 Data

Several data sources were used to perform this evaluation, including historical information detailing traffic crashes, traffic volumes, and roadway characteristics. Detailed information regarding each database and the data integration process is discussed in the following subsections.

4.1.1 Crash Data

All crashes from the Michigan State Police (MSP) crash database were obtained for a period of five years (i.e., 2012 to 2016) before the construction of the Flex route, and two years (i.e., 2018 and 2019) after its completion. As in the case of the operational analysis, 2020 data were not included given significant variations in travel patterns resulting from the COVID-19 pandemic. The MSP database includes details of crash-, vehicle-, and person-level information corresponding to each police-reported crash that occurred in Michigan over this time period. Information such as the worst level of injury sustained in the crash based on the KABCO scale (K-fatal injury, A-incapacitating injury, B-non-incapacitating evident injury, C-possible injury, O-no injury) and the time-of-day when the crash occurred were among the primary factors of interest.

For the purposes of this study, there was particular interest in distinguishing differences in safety performance not just between the before and after periods, but also over different times of day in consideration of when the Flex route is generally in operation. To this end, the crash data were aggregated in three-hour intervals to observe changes in the frequency and rate of crashes between the pre- and post-implementation periods and the times when the Flex route was (not) in operation. Note that the Flex route operates between 6:00 AM and 9:30 AM for southbound direction, and 3:00 PM and 7:00 PM for northbound direction.

4.1.2 Traffic Volume

The real-time traffic volume data were obtained from the MVDS reports between 2018 and 2019. The reports provide disaggregate level information of traffic volumes at every minute interval for the Flex route and the segments upstream and downstream. The reports also provide volume data at one-mile intervals. For the purpose of this research, the volume data was aggregated into one-hour intervals.

However, hourly volume data from the MVDS reports are only available from January 1, 2018 onward. Consequently, in order to estimate hourly traffic volumes at one-hour intervals for the before period, permanent traffic recorder (PTR) data were used to estimate the average increase in traffic between the periods before and after the Flex route went into operation. Based upon these increases, the traffic volumes were assumed to follow the same general time-of-day patterns during both periods as determined from the MVDS data.

Given relatively limited sample sizes of crashes in one-hour intervals, the crash data were subsequently aggregated into three-hour intervals for the purposes of the safety analysis. Consequently, the volume data were also aggregated at the same three-hour intervals. The crash and volume data were used to estimate crash rates per million vehicle miles traveled (VMT).

4.1.3 Data Integration

The Flex route segments and the upstream and downstream segments of it were aggregated into approximately one-mile length based on the Michigan DOT sufficiency file. This file follows the Michigan Geographic Framework, which serves as the base map for the Michigan government.

The file contains physical road (PR) number and the beginning and ending mile points, enabling the joining of crash data to the target segments. In order to join the volume data at the segment level, PR number and the mile point were first obtained for the traffic volume data. Consequently, the traffic volume data were joined to the segment level using this information. The process of joining these databases utilizes three different software for specific tasks; ArcGIS to obtain the PR number, and beginning and ending mile post for the volume data, RStudio to aggregate the volume data in one-hour interval, and Excel to join all databases together. As noted above, the number of crashes were calculated for each segment in three-hour intervals and crash rates per million VMT were calculated for the periods both before and after construction of the Flex route.

4.2 Results

4.2.1 Crash rate and frequency analyses

Table 4-1 shows a high-level summary that compares the total number of crashes per year between the periods before and after construction of the Flex route. The pre-Flex route data is based upon five years of data (2012-2016) while the post-Flex route data is based upon two years of data (2018-2019). The table shows a comparison of the annual averages of fatal, injury, and property damage only crashes based on the entire analysis period (irrespective of time-of-day).

Overall, crashes were reduced by 4.5 percent in both directions. The reductions in PDO and injury crashes were 4.2 and 5.4 percent, respectively. While fatal crashes were reduced, it is important to note that only 5 such crashes were observed in total across the seven-year analysis period.

Turning to the individual directions of travel, safety improvements were significantly more pronounced in the southbound direction, where total crashes were reduced by 22.8 percent. Reductions in fatal, injury, and PDO crashes averaged 16.7 percent, 13.3 percent, and 24.8 percent, respectively. In contrast, crashes in the northbound direction increased by 13.2 percent. Increases were also observed for injury crashes (1.3 percent) and PDO crashes (16.3 percent). No fatal crashes were experienced during the after period, compared to one crash during the before period (with this crash occurring outside of the peak congestion periods).

Table 4-1 Comparison of annual numbers of crashes by direction before and after Flex route implementation

Crash Severity	Southbound		Northbound		Both Directions (Total)	
	Before	After	Before	After	Before	After
Fatal Crashes (K)	0.6	0.5	0.2	0.0	0.8	0.5
Injury Crashes (A, B, C)	19.6	17.0	23.2	23.5	42.8	40.5
PDO (O)	96.4	72.5	97.2	113.0	193.6	185.5
Total	116.6	90.0	120.6	136.5	237.2	226.5

When considering only the peak period during which the Flex route is in operation (i.e., from 6:00-9:30 am southbound and 3:00-7:00 pm northbound), these differences are more pronounced. Table 4-2 shows a similar summary of changes in the annual number of crashes on the Flex route focusing on the periods when the Flex lane was in operation. Total crashes and injury crashes were reduced by 1.7 percent and 14.1 percent, respectively, while PDO crashes increased by 1.2 percent. No fatal crashes were recorded during this operational period (before or after Flex route construction).

In the southbound direction, total, PDO, and injury crashes were reduced by 45.2 percent, 43.2 percent, and 53.5 percent, respectively. Meanwhile, in the northbound direction, injury and PDO crashes increased by 17.9 and 33.9 percent, respectively, between the before and after periods. The majority of the increase in crashes experienced in the northbound direction occurred at the lane drop/merge point.

Table 4-2 Comparison of annual numbers of crashes by direction before and after Flex route implementation during peak traffic periods

Crash Severity	Southbound (6:00-9:30 am)		Northbound (3:00-7:00 pm)		Both Directions (Peak Periods by Direction)	
	Before	After	Before	After	Before	After
Fatal Crashes (K)	0.0	0.0	0.0	0.0	0.0	0.0
Injury Crashes (A, B, C)	8.6	4.0	10.6	12.5	19.2	16.5
PDO (O)	35.2	20.0	47.8	64.0	83.0	84.0
Total	43.8	24.0	58.4	76.5	102.2	100.5

Table 4-3 provides a detailed summary of the annual number of crashes experienced along the entire Flex route corridor in three-hour intervals, as well as similar data for the adjacent upstream and downstream segments. For segments adjacent to the Flex route, crashes were shown to increase slightly in both directions, as well as both upstream and downstream of the Flex route. The upstream segments in the northbound and southbound directions showed 18.1 and 4.5 percent increases in crashes during the after period, respectively. The downstream segments recorded 12.2 and 11.5 percent increases in crashes in the northbound and southbound directions.

Table 4-3 Comparison of annual before-and-after crashes by direction on Flex route and upstream/downstream segments by time-of-day

Road	Crash Type	Northbound		Southbound	
		Before	After	Before	After
Flex Route	12:00 AM to 3:00 AM	8.2	2.5	5.8	7.5
	3:00 AM to 6:00 AM	6.0	6.5	6.0	5.5
	6:00 AM to 9:00 AM	7.0	8.5	37.6	22.0
	9:00 AM to 12:00 PM	11.2	7.0	19.4	14.0
	12:00 PM to 3:00 PM	16.6	21.0	14.4	15.0
	3:00 PM to 6:00 PM	46.0	66.5	16.4	10.5
	6:00 PM to 9:00 PM	19.4	15.0	10.4	11.0
	9:00 PM to 12:00 AM	6.2	9.5	6.6	4.5
	Total Crashes	120.6	136.5	116.6	90.0
Upstream	12:00 AM to 3:00 AM	3.6	4.5	1.6	0.0
	3:00 AM to 6:00 AM	4.6	7.0	2.6	0.5
	6:00 AM to 9:00 AM	16.8	22.0	14.8	21.5
	9:00 AM to 12:00 PM	14.4	18.0	4	3.5
	12:00 PM to 3:00 PM	10.4	18.5	3.6	3.5
	3:00 PM to 6:00 PM	29.8	34.0	4.2	2.0
	6:00 PM to 9:00 PM	18.6	13.0	2.8	3.0
	9:00 PM to 12:00 AM	7.6	8.0	1.8	3.0
	Total Crashes	105.8	125.0	35.4	37.0

Table 4-3 cont'd

Downstream	12:00 AM to 3:00 AM	0.8	0.5	1.2	2.5
	3:00 AM to 6:00 AM	1.8	1.0	4.4	1.0
	6:00 AM to 9:00 AM	4.6	9.0	20.0	27.0
	9:00 AM to 12:00 PM	4.6	4.5	13.4	13.0
	12:00 PM to 3:00 PM	10.0	8.5	8.8	10.0
	3:00 PM to 6:00 PM	32.4	35.5	12.6	12.5
	6:00 PM to 9:00 PM	11.0	13.0	10.2	12.5
	9:00 PM to 12:00 AM	3.0	4.5	5.2	6.0
	Total Crashes	68.2	76.5	75.8	84.5

It is important to note that these raw crash counts do not account for the increases in traffic volume that occurred between the before and after periods. Consequently, the raw numbers tend to under- or over-estimate the magnitude of the changes in crashes. To this end, the data from Table 4-3 were used to calculate crash modification factors (CMF) to discern which of these changes in crashes were statistically significant at a 95 percent confidence level. These CMFs are multipliers that represent the average change in crashes that occurred between the before and after periods after accounting for the increases in traffic volumes.

The expected crash frequency was calculated by multiplying the average annual number of before period crashes by the change in volume between the before and after periods. This results in an estimate of the number of crashes that would have occurred during the after period, at similar traffic volume levels, if the Flex route had not been constructed. The actual annual numbers of crashes experienced after the Flex route went into operation are then divided by these expected frequencies in order to arrive at the CMFs shown in Table 4-4. A 95-percent confidence interval was constructed for each crash modification factor. If these intervals included 1.00, it means there is no significant difference in crashes between the before and after periods.

Table 4-4 Crash modification factor (CMF) for the Flex route by direction and time-of-day

Scenario	**Crash Modification Factor**	**Lower Confidence Limit**	**Upper Confidence Limit**
Entire Day			
Total Crashes	0.83*	0.68	0.97
NB – Total Crashes	0.98	0.75	1.22
SB – Total Crashes	0.66*	0.49	0.84
Peak Period (6:00 AM to 9:00 AM and 3:00 PM to 6:00 PM)			
NB – Total Crashes	1.24	0.80	1.69
SB – Total Crashes	0.49*	0.25	0.74

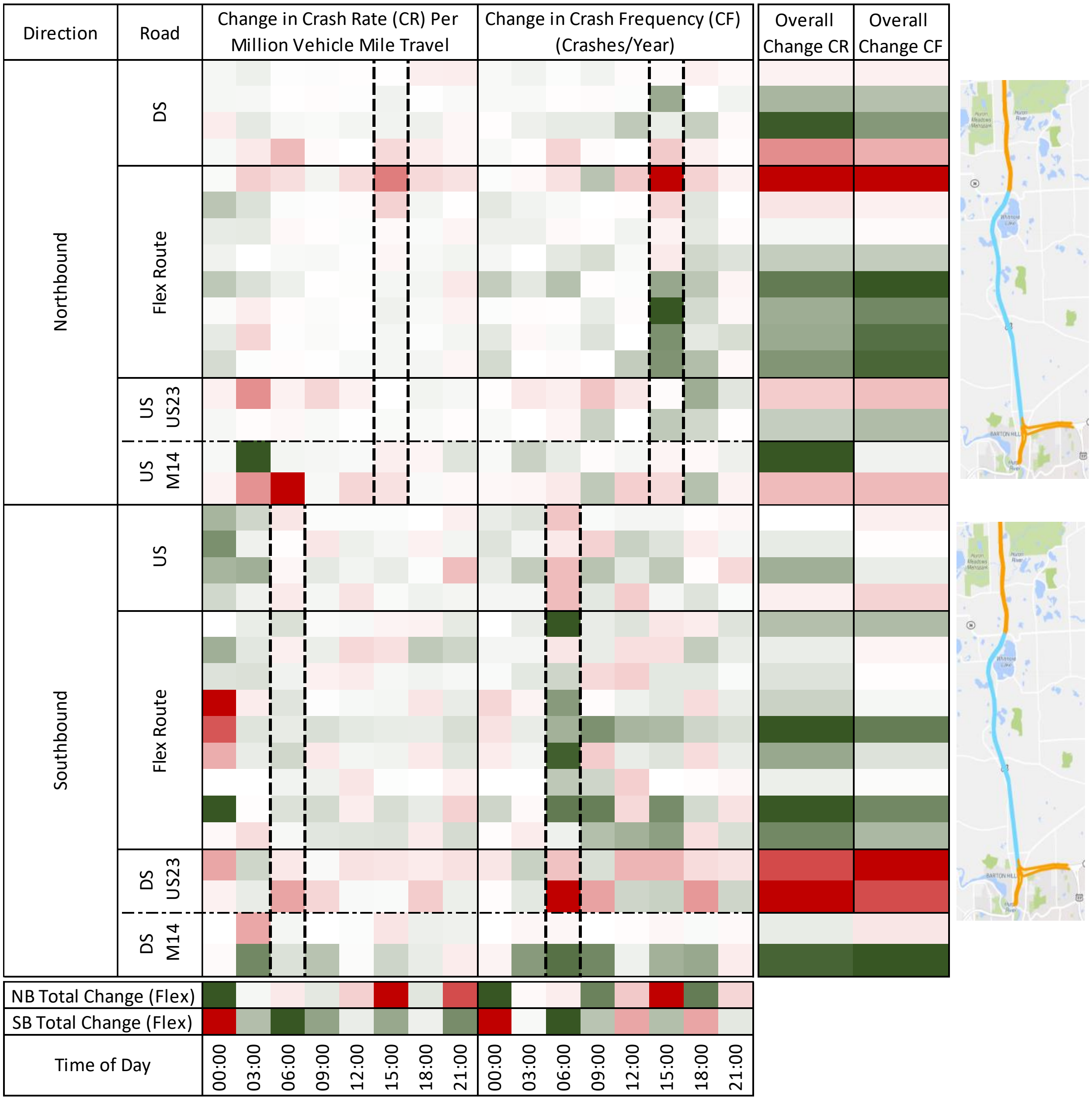
Note: * CMF is significant at 95% confidence level

These results show decreases of 17 percent in total crashes (both directions) and 34 percent for crashes in the southbound direction. Both reductions are found to be statistically significant. Turning to the three-hour time periods detailed previously, crashes were reduced by 51 percent in the southbound direction (from 6:00-9:00 am). While this result was also found to be statistically significant, the 24 percent increase during the PM peak period (3:00-6:00 pm) in the northbound direction was not.

Further details of this disaggregate-level investigation is illustrated in Figure 4-1, which includes a heat map that illustrates changes in both the rate (crashes per million VMT) and frequency of crashes. This includes comparisons of how the safety performance varies both over the physical limits of the Flex route, including the upstream and downstream segments, as well as by time-of-day.

In the figure, green-colored cells are indicative of segments and time periods that experienced fewer crashes or lower crash rates after construction of the Flex route. In contrast, the red cells are reflective of segments and time periods where crash frequencies and/or rates were found to increase as compared to the pre-Flex route time period. The intensity of the color depicts the magnitude of change in crash rates and frequencies as the darker the color, the larger the magnitude of the change. The cells bordered by the dashed line indicate the periods where the Flex route is generally in operation.

These figures reinforce the results discussed previously. In general, crash rates decreased across the Flex route corridor beginning in 2018. Since traffic volumes increases, this resulted in significant reductions in crash frequency as compared to the expected number of crashes if the Flex route had not been constructed. Performance in the southbound direction is consistently positive. In the northbound direction, crashes actually decreased along the southern portions of the route prior to a sharp increase at the lane drop. Figure 4-1 also shows that crashes tended to increase both upstream and downstream. This is particularly true on the downstream section of US-23 immediately south of the US-23/M-14 interchange. The improvements along the Flex route appear to have some carryover effects that may warrant consideration in future projects. In contrast, crashes declined downstream of M-14. Collectively, these results suggest that planning for future Flex routes should carefully consider potentially upstream and downstream effects.



Note: **1. Before period crash data is from 2012 to 2016**
2. Three-hour interval

Figure 4-1 Changes in crash rate and crash frequency along the US-23 Flex route

4.2.2 Regression Analysis

To better understand the impact of Flex route on traffic safety, several safety performance functions (SPF) were developed. Generally, two types of regression models are commonly used to analyze this type of data: 1) Poisson; and 2) negative binomial models. For the Poisson model to be true, the mean number of crashes must be equal to the variance. However, often time the variance is greater than the mean, which is also known as overdispersion. The overdispersion in the data is addressed by changing the distribution assumption to the negative binomial. In this research, the probability of Flex route segment *i* experiencing y_i crashes based on a given year can be calculated using Equation 6:

$$\boldsymbol{P(y_i) = \frac{\Gamma((1/\alpha)+y_i)}{\Gamma(1/\alpha)y_i!}\left(\frac{1/\alpha}{(1/\alpha)+\lambda_i}\right)^{1/\alpha}\left(\frac{\lambda_i}{(1/\alpha)+\lambda_i}\right)^{y_i}} \qquad \textbf{Equation 6}$$

where the term Γ(.) is a gamma function and α represents the overdispersion parameter. The expected number of crashes on segment *i*, λ_i can be calculated using Equation 7:

$$\boldsymbol{\lambda_i = EXP(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k + \varepsilon_i)} \qquad \textbf{Equation 7}$$

where β_1 to β_k are a series estimate coefficients that are obtained from the regression model, X_1 to X_k are a series of explanatory variables (e.g., AADT, segment length, Flex route present, etc.), and $EXP(\varepsilon_i)$ is a gamma-distributed error term with mean equal to one and variance of α.

In this research, a random effect framework is used to account for unobserved heterogeneity. The repetition of segments (eight times; one segment for every three-hour interval) may introduce correlation in the crash frequency within each segment across the time periods; individual segments may experience a high (or low) number of crashes compared to other similar segments due to factors that may not be captured in the model. Failure to account for this issue may result in biased, inefficient, or inconsistent parameter estimates. Employing the random effect framework to the negative binomial regression model allows the constant term to vary across segments but remain the same within the eight time periods, as shown in Equation 8:

$$\boldsymbol{\beta_i = \beta + \varphi_i} \qquad \textbf{Equation 8}$$

where φ_i is an error term that follows a normal distribution with mean zero and variance σ^2. The Equation 4-2 is then conditional on the distribution of φ_i and the estimation is conducted using simulation-based maximum likelihood.

Since the number of years for crash data between before and after the construction of Flex route was different (i.e., five years for before and two years for after the placement of Flex route), an offset variable for the number of years was introduced in the analysis to normalize the model based on annual crashes. In addition, segment length was also treated as an offset variable, where the expected number of crashes would be for one mile of road segment.

Table 4-5 shows the descriptive statistics of analysis segments based on the direction of travel. Based on this table, both directions had approximately similar three-hour traffic volume that ranged from 404 to approximately 10,000 vehicles in three hours. The segment length in this analysis had an average value of one mile with a minimum of 0.45 (i.e., segments toward the end/beginning of Flex route). The same proportion of data was used in the analysis comparing before and after the construction of the Flex route. The northbound direction had an average of two crashes per year for each segment, while southbound recorded only one crash per year. Although the difference between the average number of crashes between the two directions of traffic was small, the maximum number of crashes per year recorded for northbound direction is significantly higher than the southbound direction (Table 4-4 shows details of crash information based on direction and time of day).

Table 4-5 Descriptive statistics for Flex route by direction

Variable	Northbound				Southbound			
	Min.	Max.	Mean	Std. Dev.	Min.	Max.	Mean	Std. Dev.
Traffic volume (3 hours interval)	625	9870	4058	2718	404	9381	4224	2637
Segment length (miles)	0.48	1.25	1.06	0.24	0.45	1.16	0.97	0.19
Before period	0	1	0.50	0.50	0	1	0.50	0.50
After period	0	1	0.50	0.50	0	1	0.50	0.50
Total crashes per year	0	47	2	4	0	8	1	1

Note: Min. is minimum; Max. is maximum; Std. Dev. is standard deviation

A random effect negative binomial model was developed separately for each direction of travel, as shown in Table 4-6. Each model presents the estimate coefficient, along with the standard error, and *p*-value. When interpreting the results, a positive value of estimate coefficient indicates that crashes increase with the increase in the independent variable, and vice versa for negative parameter estimates.

Based on this table, both travel directions recorded an increase in crashes when traffic volume increased. A one percent increase in traffic volume (three hours volume) would result in 0.40 percent and 0.47 percent increase in the number of crashes for northbound and southbound directions, respectively. After the Flex route was constructed, both models showed a reduction in the number of crashes. This reduction was found to be more pronounced in the southbound direction as opposed to the northbound. The findings showed that crashes decreased by 17.8 percent and 25.3 percent for northbound and southbound directions, respectively. However, the effect for northbound direction was not statistically significant at a 95 percent confidence level.

Table 4-6 Crash prediction models for Flex route by direction

Variable	Northbound			Southbound		
	Estimate	Std. Error	P-Value	Estimate	Std. Error	P-Value
Intercept	-3.057	0.724	<0.001	-3.530	0.557	<0.001
LN (traffic volume for 3 hours)	0.406	0.088	<0.001	0.471	0.067	<0.001
After period (Flex route present)	-0.196	0.138	0.157	-0.292	0.101	0.004
Peak hour (NB: 3pm-6pm; SB: 6am-9am)	1.074	0.196	<0.001	0.616	0.124	<0.001
Overdispersion	0.293			0.073		

Note: NB is northbound; SB is southbound; Std. Error is standard error

Since the data was structured such that each segment was repeated eight times based on the three-hour interval (i.e., segments for 3am-6am, 6am-9am, 9am-12pm, etc.), the analysis allows the time of day to be included in the models. Based on Table 4-6, an indicator variable for peak hour segments was tested. Note that the peak hour for northbound direction was from 3:00 pm to 6:00 pm, and for southbound direction, it was from 6:00 am to 9:00 am. The findings from this research revealed that peak hour periods experienced a higher number of crashes than off-peak hours for both directions of traffic. The increase in the number of crashes during this period was pronounced in the northbound direction (increased by 193 percent) as compared to southbound direction (increased by 85 percent). This also can be seen from the summary of crash data from Table 4-3.

Figure 4-2and Figure 4-3illustrate how the number of crashes per mile per year varies for different traffic volume ranges, study periods, and time of day. These plots were estimated using the models from Table 4-6. For the northbound direction (Figure 4-2), the changes in the number of crashes between the before and after period for peak hour become more pronounced as the traffic volume increases. However, these changes remained approximately the same during off-peak hour across all traffic volume. In the southbound direction (Figure 4-3), changes in crashes increase as the traffic volume increases for both peak and off-peak hour.

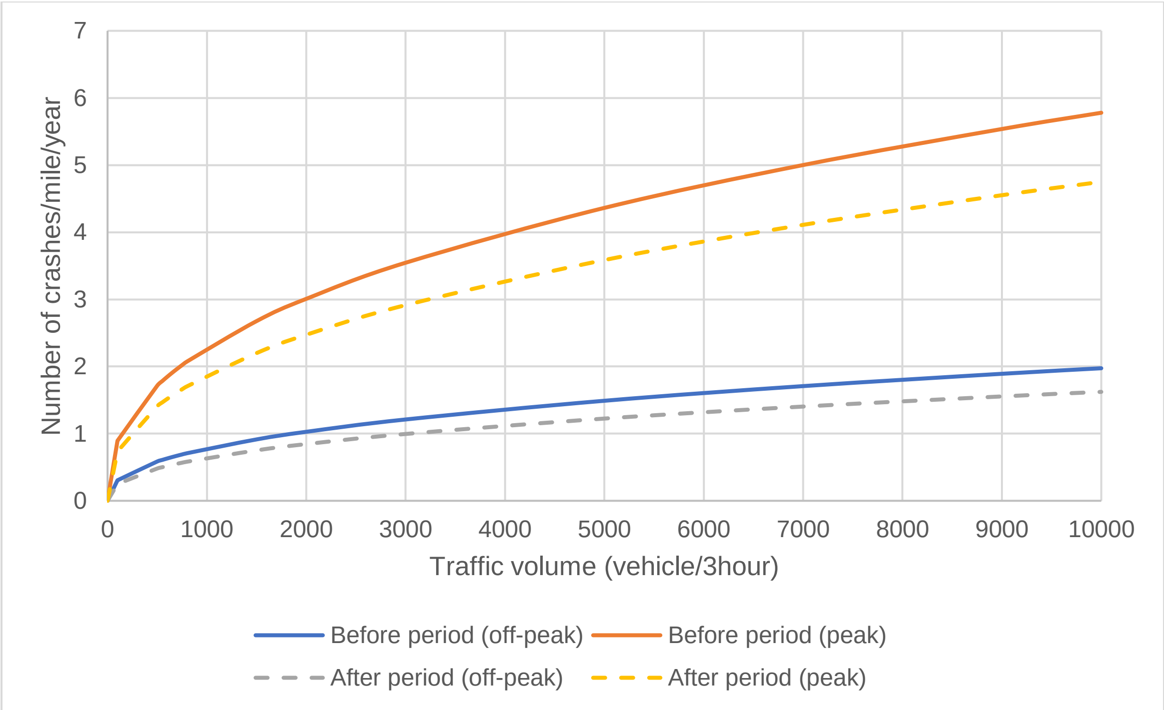


Figure 4-2 Crashes per mile per year by traffic volume on northbound direction

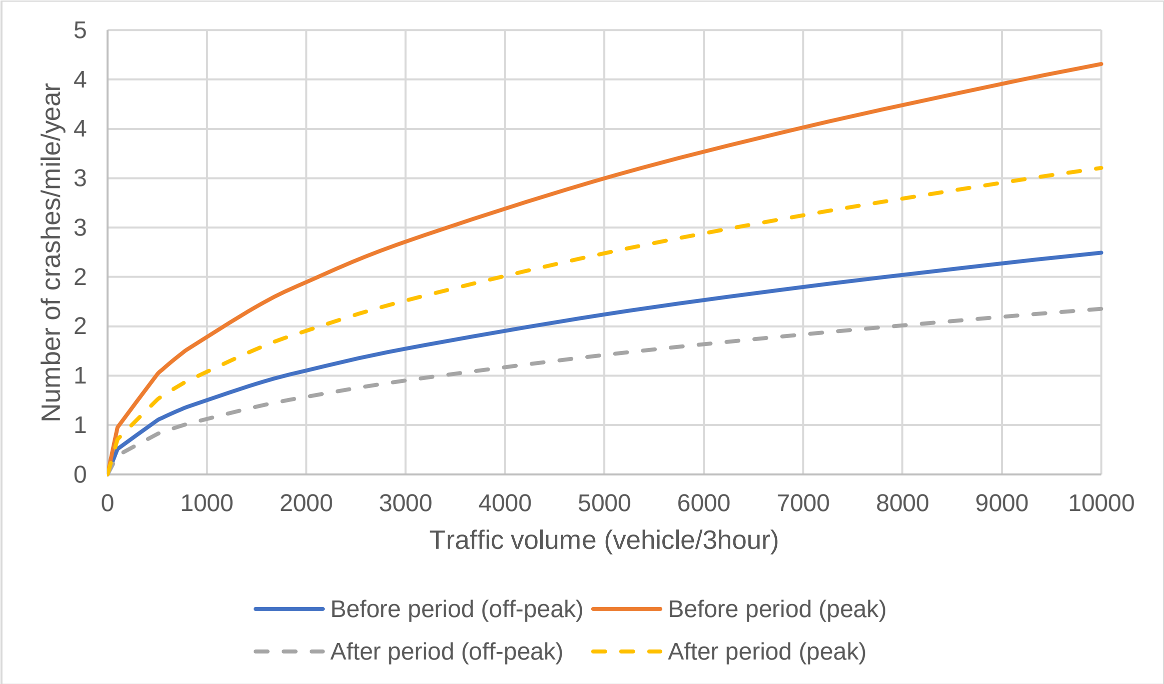


Figure 4-3 Crashes per mile per year by traffic volume on southbound direction

4.3 Impacts of Pandemics

In addition to the operational performance, safety performance was also important to understand. To do so, the crash data of 2020 was obtained from the Michigan Police department. The corresponding volume with 15 minutes intervals was available from PTR data introduced earlier.

Table 4-7shows a comparison of the annual averages of fatal, injury, and property damage only crashes between two years before pandemic (2018-2019) and pandemic year (2020). (irrespective of the time of day). As the table indicated, crashes were reduced by almost 50 percent regardless of the type of crashes and direction.

Table 4-7 Annual numbers of crashes by direction under pandemic

Crash Severity	Southbound		Northbound		Both Directions (Total)	
	2018-2019	2020	2018-2019	2020	2018-2019	2020
Fatal Crashes (K)	0.5	0	0	0	0.5	0
Injury Crashes (A, B, C)	17	8	23.5	8	40.5	16
PDO (O)	72.5	30	113	54	185.5	84
Total	90	38	136.5	62	226.5	100

When considering only the peak period during which the Flex route is in operation (i.e., from 6:00-9:30 am southbound and 3:00-7:00 pm northbound), the trend was consistent with the general trend (Table 4-8). The overall crashes decreased by 60 percent in both directions. Injury crashes reduced by 50 and 68 percent in southbound and northbound directions, respectively.

Table 4-8 Annual numbers of crashes by direction under pandemic during peak traffic periods

Crash Severity	Southbound (6:00-9:30 am)		Northbound (3:00-7:00 pm)		Both Directions (Peak Periods by Direction)	
	2018-2019	2020	2018-2019	2020	2018-2019	2020
Fatal Crashes (K)	0	0	0	0	0	0
Injury Crashes (A, B, C)	4	2	12.5	4	16.5	6
PDO (O)	20	8	64	26	84	34
Total	24	10	76.5	30	100.5	40

In addition to that, Table 4-9 provides a detailed summary of the annual number of crashes experienced along the entire Flex route corridor in three-hour intervals. As table x showed, the greatest reduction in crashes (76 percent) occurred during morning and afternoon peak period (6:00 AM to 9:00 AM and 3:00 PM to 6:00 PM) in the northbound direction, but the greatest reduction in crashes (87 percent) were observed during the early morning (12:00 AM to 3:00 AM) in the southbound direction. Besides that, crashes increased 11 and 26 percent in the northbound and southbound direction, respectively, during the night (9:00 PM to 12:00 PM).

Table 4-9 Annual crashes on Flex route under pandemic by time-of-day

Time	Southbound		Northbound	
	2018-2019	2020	2018-2019	2020
12:00 AM to 3:00 AM	7.5	1.0	2.5	2.0
3:00 AM to 6:00 AM	5.5	2.0	6.5	5.0
6:00 AM to 9:00 AM	22.0	8.0	8.5	2.0
9:00 AM to 12:00 PM	14.0	6.0	7.0	3.0
12:00 PM to 3:00 PM	15.0	5.0	21.0	5.0
3:00 PM to 6:00 PM	10.5	2.0	66.5	25.0
6:00 PM to 9:00 PM	11.0	9.0	15.0	8.0
9:00 PM to 12:00 AM	4.5	5.0	9.5	12.0
Total Crashes	90.0	38.0	136.5	62.0

The corresponding crash rate in three-hour intervals was also calculated with the consideration of volume. The summary is included in Table 4-10. There is no specific trend found between each direction. In the northbound direction, the crash rate increased under most time periods except for morning peak (6:00 AM to 9:00 AM) and afternoon (12:00 PM to 6:00 PM).

During the morning peak and noon period (12:00 PM to 3:00 PM), the crash rate was reduced by 40 percent. However, during the early morning (12:00 AM to 3:00 AM) and late-night (9:00 PM to 12:00), the crash rate increased more than 100 percent. A similar trend was also observed southbound during late night. However, unlike the northbound, a reduction in the crash rate was found in the early morning (12:00 AM to 3:00 AM).

Table 4-10 Crash rate of Flex route under pandemic by time-of-day

Time	Southbound		Northbound	
	2018-2019	2020	2018-2019	2020
12:00 AM to 3:00 AM	2.46	0.83	0.52	1.20
3:00 AM to 6:00 AM	0.53	0.48	1.45	2.58
6:00 AM to 9:00 AM	0.39	0.42	0.37	0.23
9:00 AM to 12:00 PM	0.35	0.39	0.23	0.23
12:00 PM to 3:00 PM	0.38	0.30	0.50	0.28
3:00 PM to 6:00 PM	0.25	0.12	1.11	1.05
6:00 PM to 9:00 PM	0.42	0.87	0.43	0.63
9:00 PM to 12:00 AM	0.39	1.14	0.63	2.37
Overall	0.39	0.43	0.64	0.73

4.4 Summary

Overall, the improvements in traffic operations along the Flex route have corresponded with related improvements in traffic safety through reductions in the frequency and rate of crashes, as well. This is particularly true in the southbound direction. In the northbound direction, crashes did not change significantly overall. However, significant increases were experienced at the northbound lane drop. Many of these crashes occur due to merging traffic and, as such, any efforts to encourage early merging by drivers may help to mitigate this issue. This could include sinusoidal rumble strips or earlier notification of the impending lane drop.

CHAPTER 5 CONCLUSIONS

5.1 Operational Impacts

Performance of US-23 has improved across several metrics including maximum throughput, travel time during peak periods, and level of travel time reliability. In general, the southbound direction outperformed the northbound direction with respect to most metrics as congestion was very limited in this direction once the Flex route went into operation. While the northbound direction also showed better performance after the Flex lane opened in general, a downstream bottleneck was introduced at the northbound lane drop and this section has experienced significant congestion. Fortunately, this problem is expected to be alleviated by the planned extension of the Flex lane to I-96 in 2024. The operational analyses also showed improved operations when special events occurred. Incident clearance times largely decreased after the Flex route was opened. Part-time shoulder running also provided an additional travel lane during peak periods, such as University of Michigan home football games, reducing such non-recurrent congestion.

Drivers tended to comply with the rules of the Flex route. Only a small percentage of drivers traveled on the Flex lane while the gantry displayed the red X. In addition, the travel speed was consistent under the advisory speed of 60 mph, and more variability was found while the advisory speed reduced to 30 mph. After a detailed inspection, the drivers tended to travel at a speed 10 mph higher than the advisory speed of 60 mph in both directions. This is also true when the advisory speed of 50 mph was displayed in the northbound direction. The drivers complied with that advisory speed in the southbound direction. The travel speeds were also similar to the advisory speeds, while the advisory speeds of 40 and 30 mph were displayed regardless of the directions. This finding is more pronounced at the terminus of the Flex route in the northbound direction where the merging point occurred. The results of the linear regression model also had similar findings. It is suggested that most drivers reduce their speed because of the reduction in overall speed, not because of the displayed advisory speed.

The impacts of COVID-19 on the operational performance of the US-23 Flex route were also preliminarily investigated. Fewer vehicles were found on the roadway, and the travel speed increased compared to before. There was no reduction in speed observed during the peak period.

5.2 Safety Impacts

In general, the reduced levels of congestion that occurred after Flex route implementation were also associated with reductions in traffic crashes. Overall, crashes were reduced by roughly 17 percent across the entire corridor in both directions. The improvements were significantly more pronounced in the southbound direction, where crashes were reduced by 34 percent overall and more than 50 percent during the peak traffic periods. In contrast, crashes increased in the northbound direction, though these increases were not statistically significant.

As with the operational issues, the crashes tended to increase predominantly in the bottleneck area where the lane drop is present. While crashes were generally reduced along the Flex route, some increases and decreases occurred on the adjacent upstream/downstream segments. Given shifts in traffic volumes and latent demand, this is a challenging area to forecast for future Flex route projects.

The safety performance of US-23 Flex route during COVID-19 was also evaluated. The total number of crashes decreased after the COVID-19 (i.e., 2020) except for the late-night (i.e., 9 PM-12 PM). After considering the volume, the results indicated that the crash rates were higher during 6 PM and 12 AM regardless of the direction. It is also true for the time period of early morning in northbound direction (12 AM - 6 AM). Further investigation can be conducted once more data is available.

5.3 Limitations and Recommendations

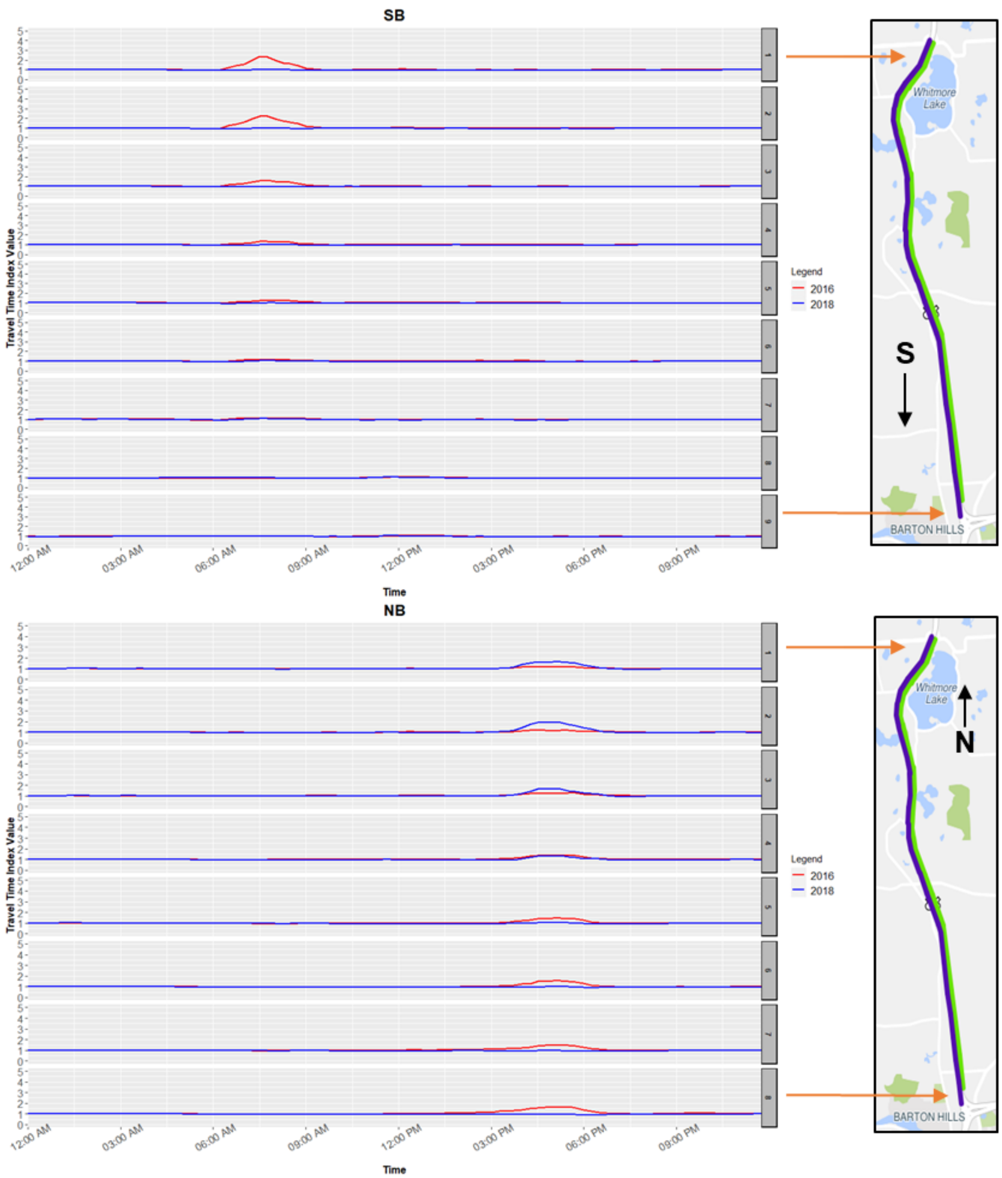
This study provides valuable insight on several topics; however, some limitations are associated with the research methods (e.g., data availability, data analysis). Due to the influences of the COVID-19 pandemic, 2020 data and beyond could not be utilized in the detailed analyses. Additionally, the missing data were also observed in each dataset. The details and consequences of missing data portions were explicitly introduced in the previous sections. Fortunately, the existing data provided sufficient information to evaluate the performance of the Flex route over the years. Furthermore, the MVDS reports included the speed and volume data for each lane after the construction of the Flex route. However, the speed information before the operation of the Flex route was obtained from the INRIX probe vehicle data and PTR data platform without lane designation. So, drivers' speed selection behavior on each lane could not be evaluated before opening the Flex route. Another important caveat, the PTR data was the only dataset containing the traffic volume from the before-period. Hence, PTR data could not capture the volume changes caused by exits or lane discrepancy along the route because there was only one PTR station on the Flex route located at Barker Road.

Moreover, the capacity of the Flex route could not be determined based on the available data. As the speed-flow curves presented in the previous sections indicate, the capacity of the Flex route had not yet been achieved. Finally, the impacts of additional novel constructions on the Flex route (e.g., extensions of ramps and new interchanges) were hard to predict with the available data. According to the speed profiles developed from probe vehicle data, there were no significant changes observed. Therefore, there was not sufficient information to estimate the changes due to other constructions.

Even though there were some limitations, this study can be used as future guidance and reference for D-PTSU installation. For example, based on the findings from the study, the part-time shoulder use was suggested to operate three to four hours earlier than the football kickoff time to avoid unnecessary congestion. Any efforts (e.g., earlier notification or rumble strips) to encourage early merging by drivers should be considered to mitigate the problems that occur due to bottlenecks. In addition, the upstream and downstream of the part-time shoulder use should also be considered while planning future projects.

APPENDICES

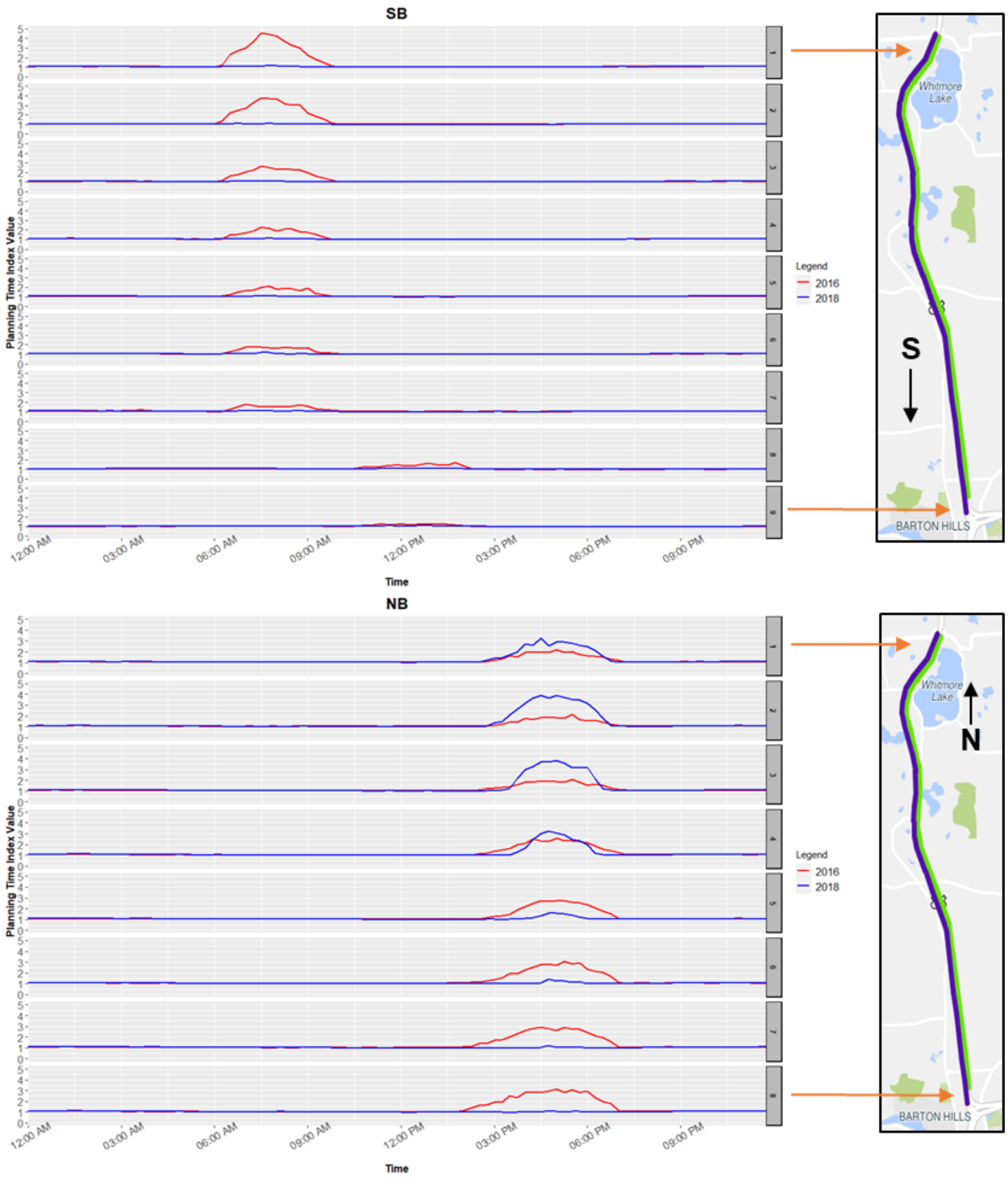
Appendix A Travel Time Reliability Results



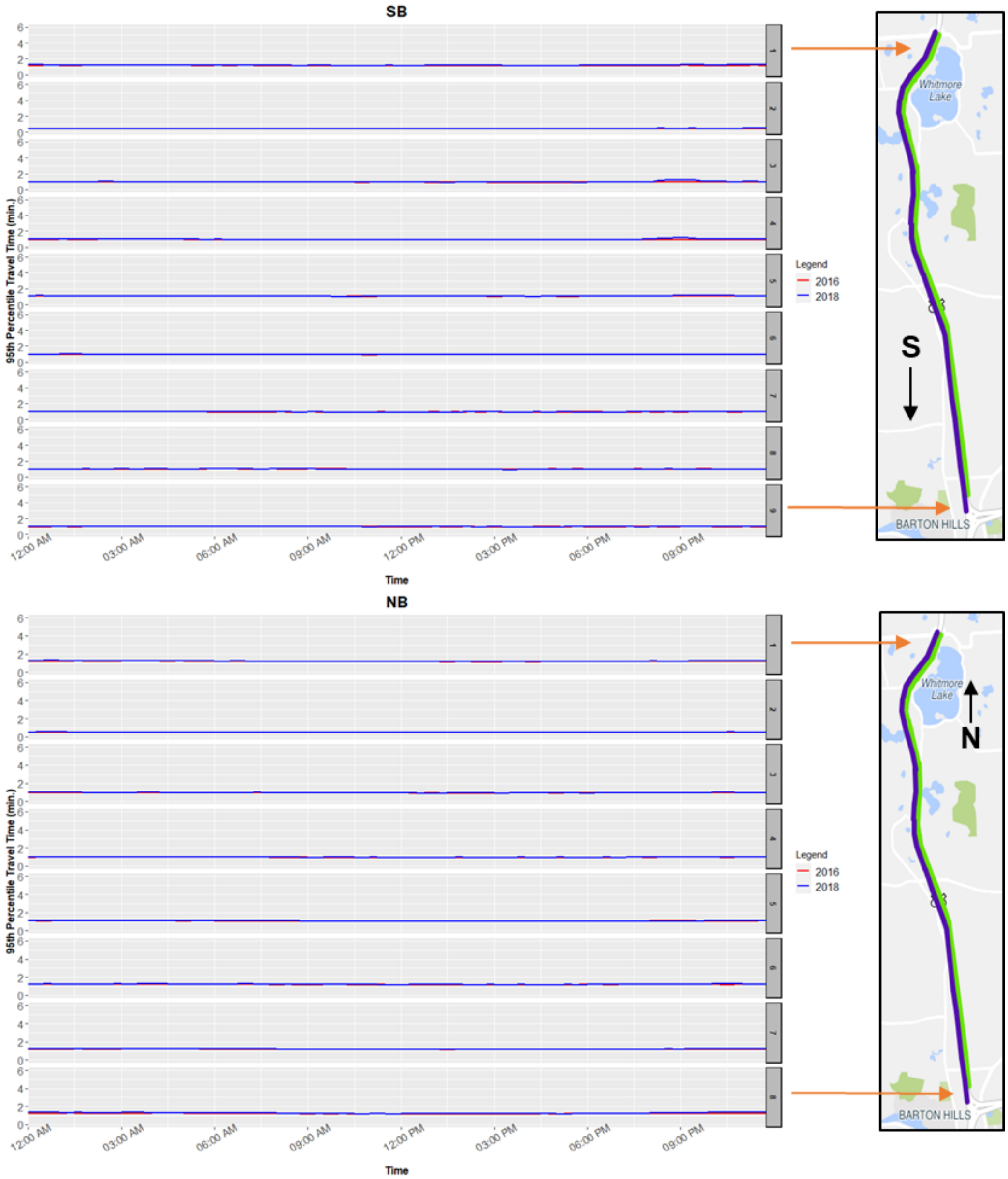
a. Plot of travel time index during weekdays

Figure A-1 Additional plots of travel time reliability over time at segment-level during weekdays

Figure A-1 cont'd



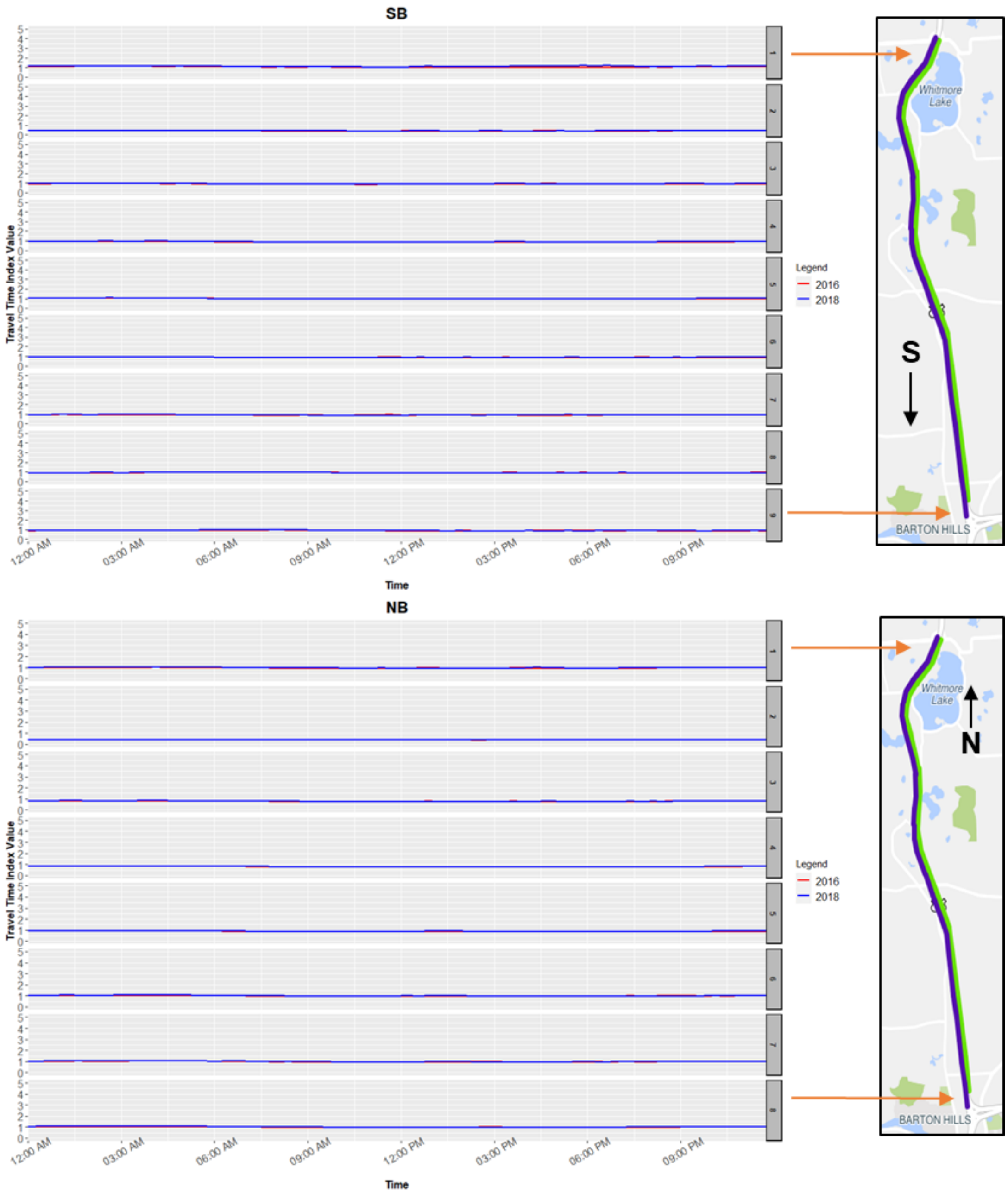
b. Plot of planning time index during weekdays



a. Plot of 95th percentile travel time during weekends

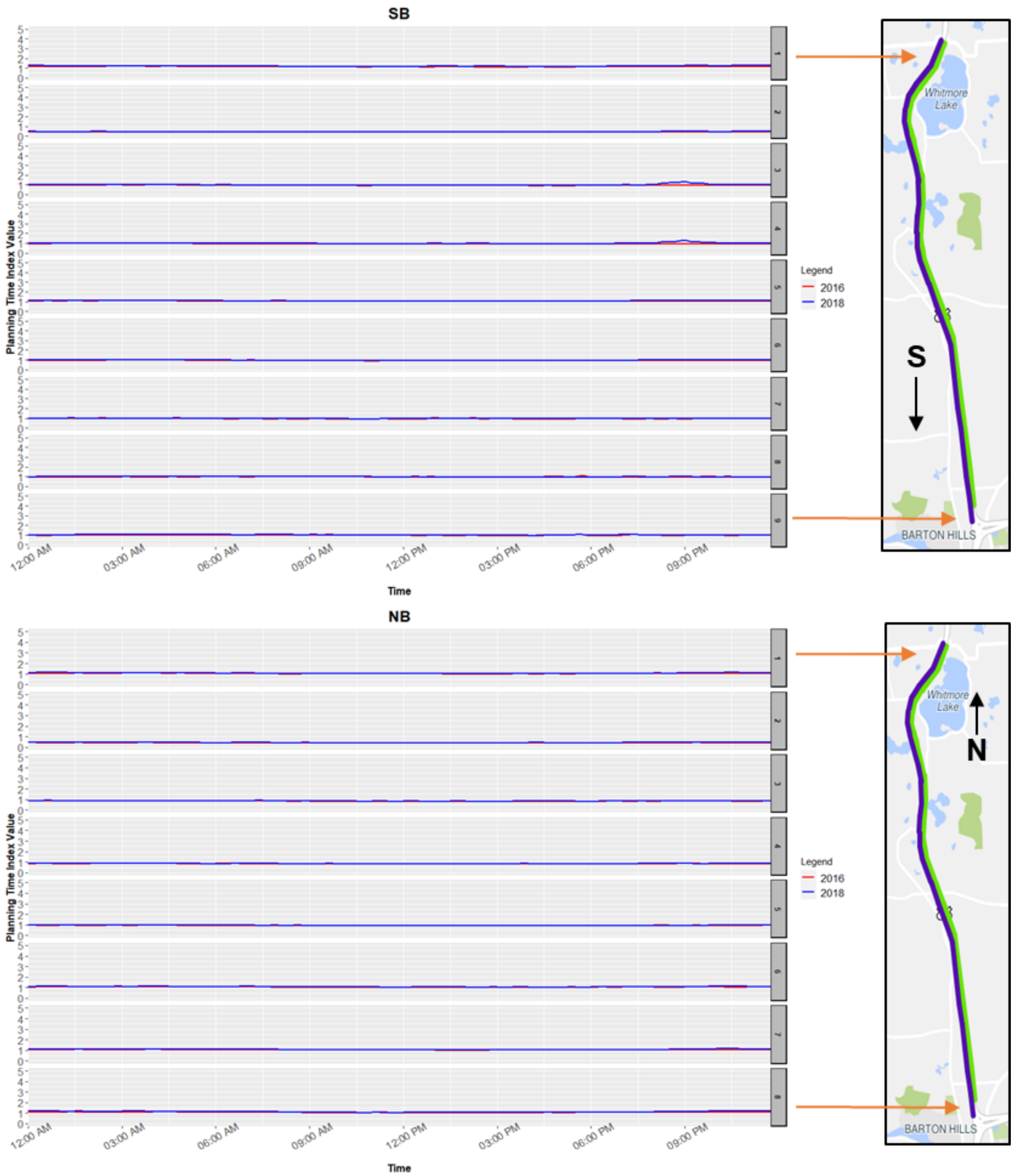
Figure A-2 Additional plots of travel time reliability over time at segment-level during weekends

Figure A-2 cont'd



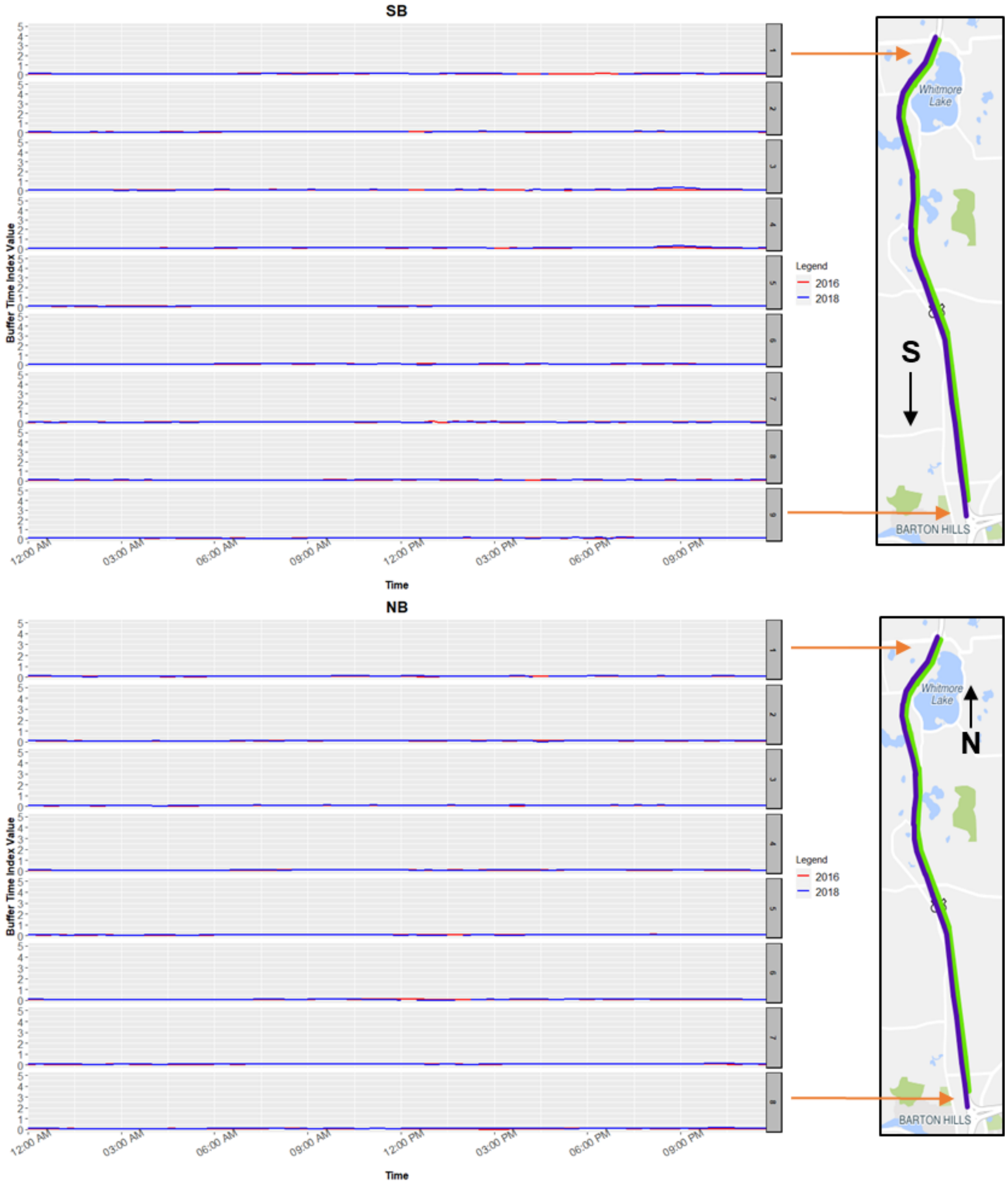
b. Plot of travel time index during weekends

Figure A-2 cont'd



c. Plot of planning time index during weekends

Figure A-2 cont'd



d. Plot of buffer time index during weekends

Appendix B Speed and Flow Relationship for Us-23 Flex Route

Table A-1 Descriptive statistics of 2018 MVDS reports

2018						
	Direction	**Variable**	**Min**	**Max**	**Mean**	**Std. Dev.**
Peak Hour	Southbound (6:00 AM - 9:30 AM)	Volume-Weight Speed (mph)	53.69	76.75	71.50	2.98
		Flow Rate (veh/h)	1370.00	3627.00	2713.00	457.08
	Northbound (3:00 PM - 7:00 PM)	Volume-Weight Speed (mph)	46.70	75.31	68.55	6.01
		Flow Rate (veh/h)	1642.00	4007.00	2887.00	459.03
Off-Peak Hour	Southbound (0:00 AM - 5: 59 AM; 9:31 AM - 11:59 PM)	Volume-Weight Speed (mph)	48.60	76.75	69.71	4.66
		Flow Rate (veh/h)	86.02	3627.37	1479.37	982.30
	Northbound (0:00 AM - 2:59 PM; 7:01 PM - 11:59 PM)	Volume-Weight Speed (mph)	46.70	75.37	69.99	3.96
		Flow Rate (veh/h)	109.80	4007.50	1270.80	877.15
Overall	Southbound	Volume-Weight Speed (mph)	48.60	76.75	70.16	4.35
		Flow Rate (veh/h)	86.02	3627.37	1463.38	938.64
	Northbound	Volume-Weight Speed (mph)	46.70	75.37	69.87	4.19
		Flow Rate (veh/h)	109.80	4007.50	1406.00	960.74

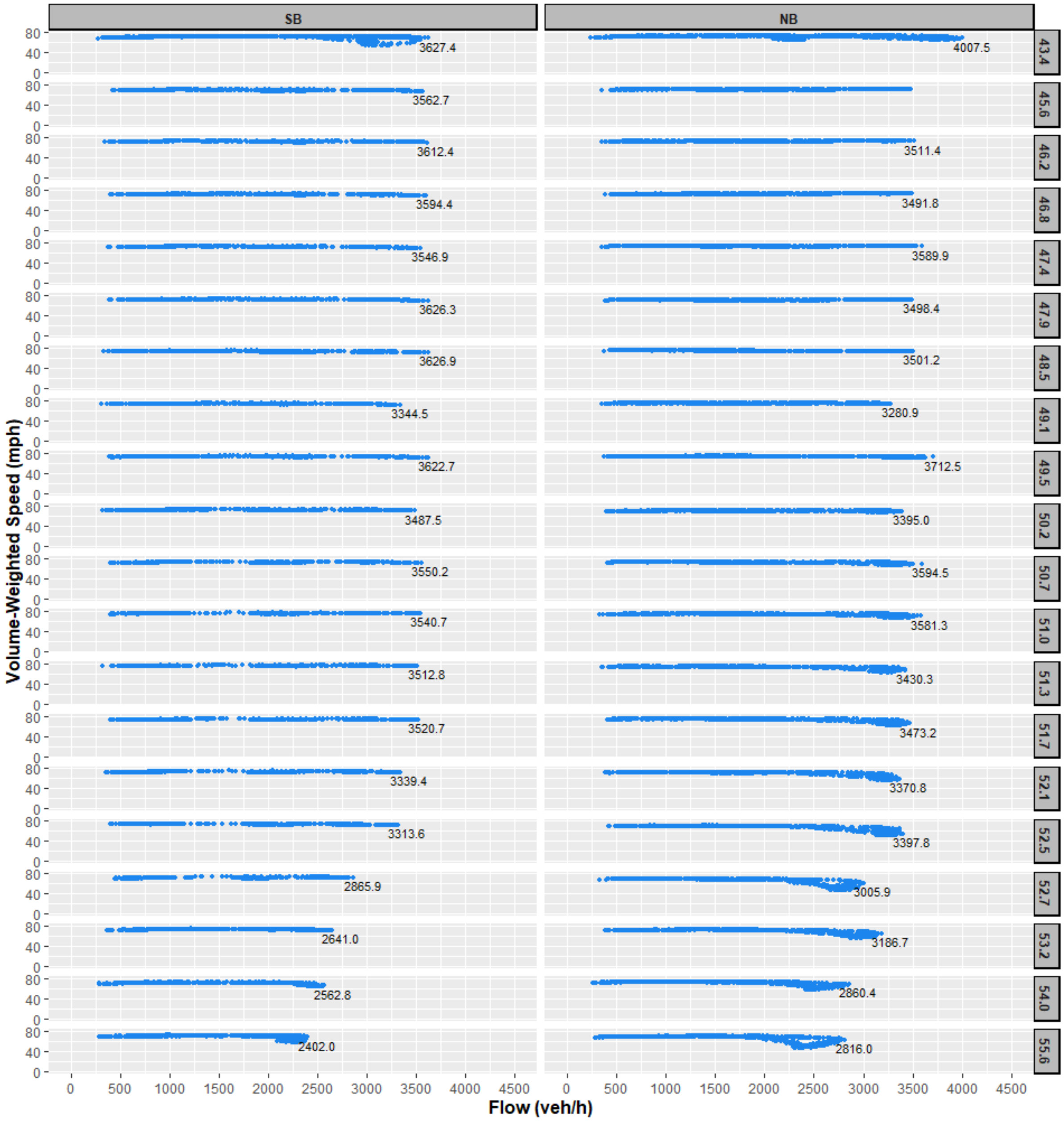
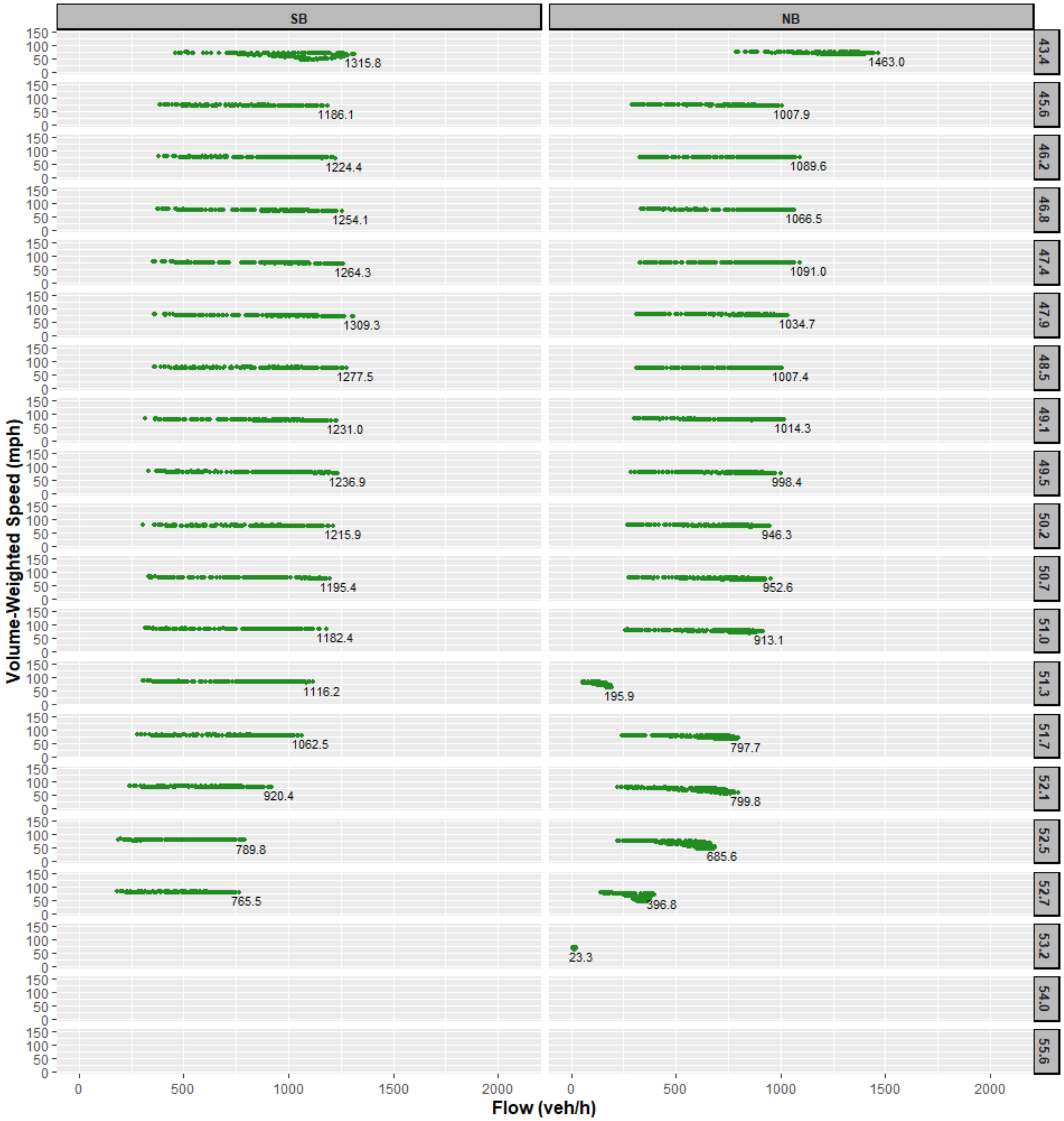


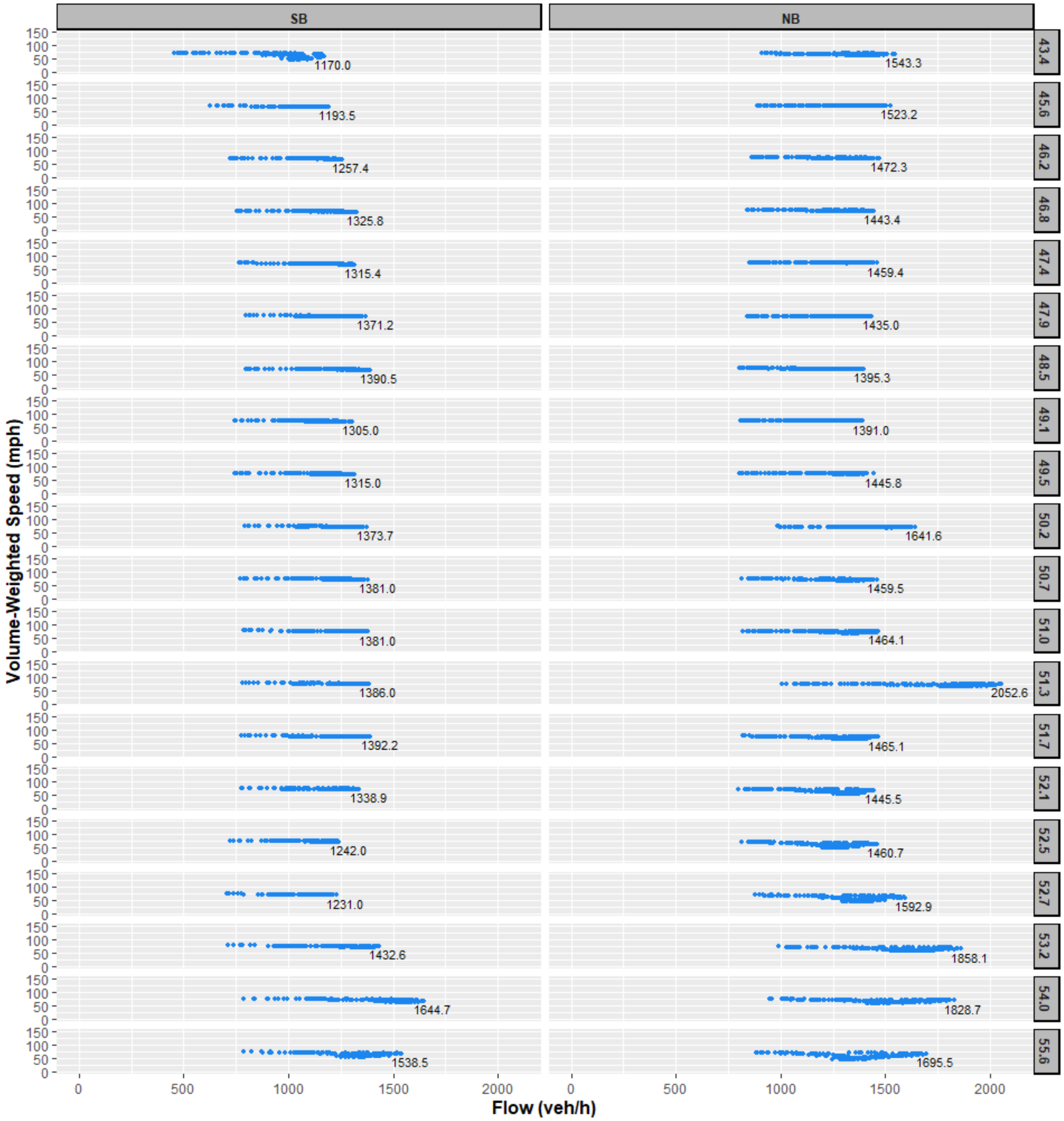
Figure A-3 Speed -flow curve for US-23 Flex route in 2018 (24 hours)



a. Left shoulder (Flex lane)

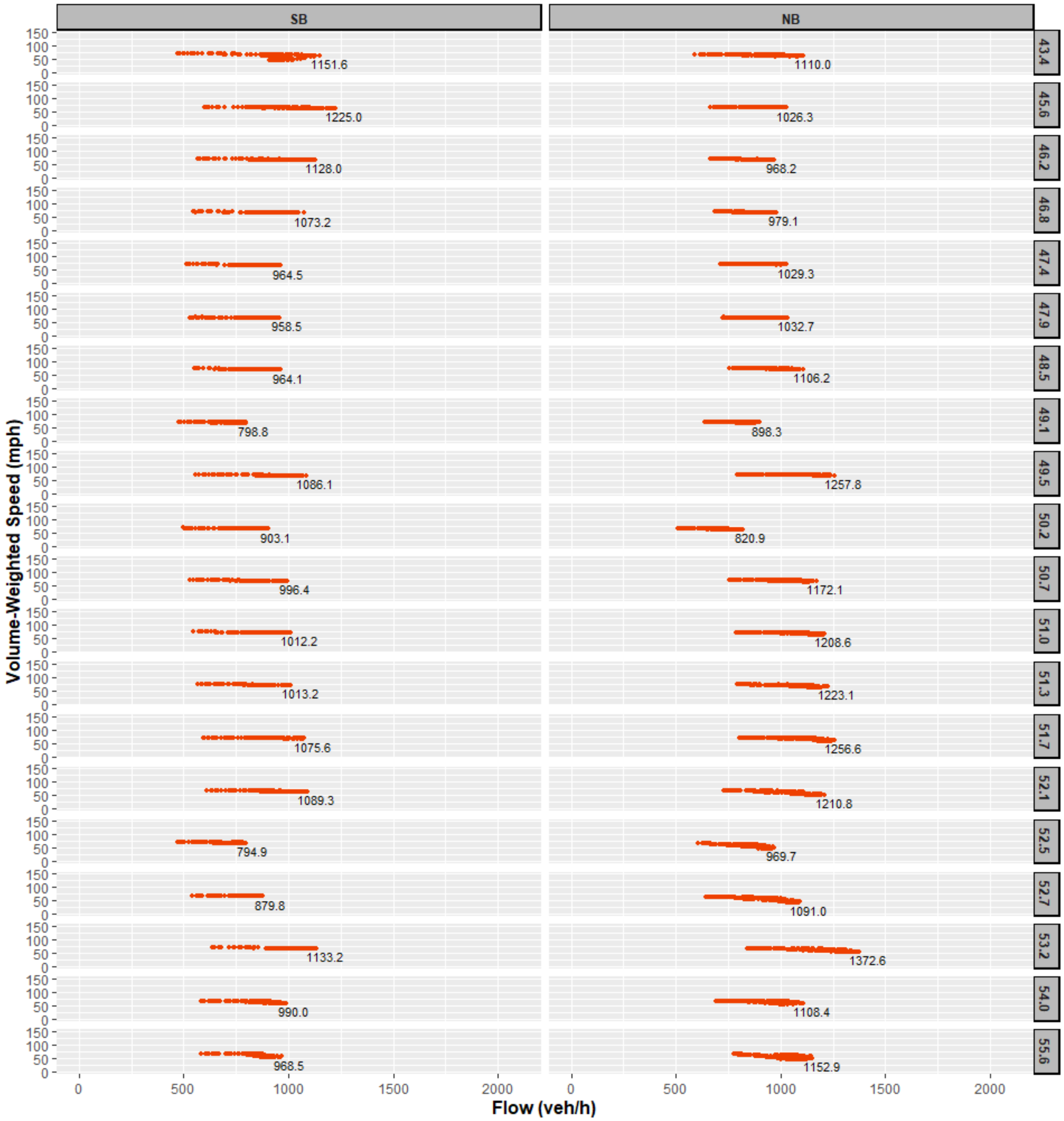
Figure A-4 Speed - flow curves for US-23 Flex route during peak hours on lane-by-lane basis in 2018

Figure A-4 cont'd



b. Left lane

Figure A-4 cont'd



c. Right lane

REFERENCES

REFERENCES

Aron, M., Seidowsky, R., & Cohen, S. (2013). Safety impact of using the hard shoulder during congested traffic. The case of a managed lane operation on a French urban motorway. *Transportation Research Part C: Emerging Technologies*, *28*, 168–180. https://doi.org/10.1016/j.trc.2010.12.006

Balogh, M. (2012). *I-5 Variable Speed Limits and Lane Control* (TSM&O Category: Active Traffic Management). Washington State Department of Transportation.

Barichello, K., & Knickerbocker, S. (n.d.). *Using INRIX Data in Iowa*.

BMVI. (2011). *Projektplan Straßenverkehrstelematik 2015 (Traffic Telematics Project Plan 2015)*. German Federal Ministry of Transport, Building and Urban Development, Bonn.

Boardman, A. E., Greenberg, D. H., Vining, A. R., & Weimer, D. L. (2017). *Cost-benefit analysis: Concepts and practice*. Cambridge University Press.

Boston Region Metropolitan Planning Organization. (2018). *Travel Time Reliability Performance Measures and Targets*. Boston Region MPO.

Brinckerhoff, P. (2010). *Synthesis of Active Traffic Management in Europe and the United States* (FHWA-HOP-10-031). U.S. Department of Transportation Federal Highway Administration. https://ops.fhwa.dot.gov/publications/fhwahop10031/fhwahop10031.pdf

Buckeye, K. R. (2012). Innovations on Managed Lanes in Minnesota. *Public Works Management & Policy*, *17*(2), 152–169. https://doi.org/10.1177/1087724X11430001

Bureau of Transportation Statistics. (2020). *U.S. Vehicle-Miles*. U.S. Vehicle-Miles; Not Available. https://www.bts.gov/content/us-vehicle-miles

Cassidy, M. J., Kim, K., Ni, W., & Gu, W. (2015). A problem of limited-access special lanes. Part I: Spatiotemporal studies of real freeway traffic. *Transportation Research Part A: Policy and Practice*, *80*, 307–319. https://doi.org/10.1016/j.tra.2015.07.001

CAT Lab. (2021). *RITIS Introduction*. Regional Integrated Transportation Information System. https://ritis.org/intro

Census Bureau. (2019). *Mean travel time to work(minutes), workers age 16 years+*. The United States Census Bureau. https://www.census.gov/search-results.html

Charmaz, K. (2008). Grounded theory as an emergent method. *Handbook of Emergent Methods*, *155*, 172.

Chun, P., & Fontaine, M. D. (2016). *Evaluation of the impact of the I-66 active traffic management system*. Virginia Transportation Research Council.

Coffey, S., & Park, S. (2018). Operational Evaluation of Part-Time Shoulder Use for Interstate 476 in the State of Pennsylvania. *Advances in Civil Engineering*, *2018*, e1724646. https://doi.org/10.1155/2018/1724646

Culotta, K., Fang, V., Habtemichael, F., & Pape, D. (2019). *Does Travel Time Reliability matter* (FHWA-HOP-19-062). Fedaral Highway Administration.

Davis, E (2020). *Low U.S. Traffic Levels "Unprecedented" Amid Coronavirus*. US News & World Report.

Davis, G. A., Gao, J., & Hourdos, J. (2018). *Safety Impacts of Priced Dynamic Shoulder Lanes on I-35W and Nonlinear Effect of Traffic Congestion* (No. 18–01317). Article 18–01317. Transportation Research Board 97th Annual MeetingTransportation Research Board. https://trid.trb.org/view/1494845

Davis, E (2020). *Low U.S. Traffic Levels "Unprecedented" Amid Coronavirus*. US News & World Report.

Dillman, D. A. (2011). *Mail and Internet surveys: The tailored design method–2007 Update with new Internet, visual, and mixed-mode guide*. John Wiley & Sons.

Dutta, N., Boateng, R. A., & Fontaine, M. D. (2019). Safety and operational effects of the interstate 66 active traffic management system. *Journal of Transportation Engineering, Part A: Systems*, *145*(3), 04018089.

Kuhn,B (2010). *Efficient Use of Highway Capacity Summary Report to Congress* (FHWA-HOP-10-023).

FHWA. (2012). *ATDM Program Brief: An Introduction to Active Transportation and Demand Management* (FHWA-HOP-12-032). https://ops.fhwa.dot.gov/publications/fhwahop12032/

FHWA. (2014). *Development of Modeling Capabilities of Shoulders Using Part-Time Travel Lanes* (FHWA-HOP-14-017).

FHWA. (2016b). *Guide for Planning, Evaluating, and Designing Part-Time Shoulder Use as a Traffic Management Strategy* (FHWA-HOP-15-023).

FHWA. (2020a). *Active Traffic Management (ATM) Implementation and Operations Guide*. https://ops.fhwa.dot.gov/publications/fhwahop17056/chap1.htm#12a

Foley, J., Steffen, K., & Palmer, S (N.A.). US-23 Flex Route – first active traffic management (ATM) system in Michigan.

Fuhs, C., & Brinckerhoff, P. (2010). *Synthesis of active traffic management experiences in Europe and the United States*. United States. Federal Highway Administration.

Geistefeldt, J. (2012). Operational Experience with Temporary Hard Shoulder Running in Germany. *Transportation Research Record*, *2278*(1), 67–73. https://doi.org/10.3141/2278-08

Gordon, R. L., & Tighe, W. (2005). *Traffic Control Systems Handbook (2005 Edition)* (FHWA-HOP-06-006). Article FHWA-HOP-06-006. https://trid.trb.org/view/878030

Guerrieri, M., & Mauro, R. (2016). Capacity and safety analysis of hard-shoulder running (HSR). A motorway case study. *Transportation Research Part A: Policy and Practice*, *92*, 162–183.

Hadi, M., Shen, L., Zhan, C., Xiao, Y., Corbin, S., & Chen, D. (2008). Operation data for evaluating benefits and costs of advanced traffic management components. *Transportation Research Record*, *2086*(1), 48–55.

Huijser, M. P., Duffield, J. W., Clevenger, A. P., Ament, R. J., & McGowen, P. T. (2009). Cost–Benefit Analyses of Mitigation Measures Aimed at Reducing Collisions with Large Ungulates in the United States and Canada: A Decision Support Tool. *Ecology and Society*, *14*(2). https://www.jstor.org/stable/26268301

International Bridge, Tunnel and Turnpike Association. (2016). *Success Stories from the Tolling Industry*.

INTRIX. (2021). *Reference: Glossary*. INTRIX Documentation. http://docs.inrix.com/reference/glossary/

INRIX. Inc. INRIX: Congestion Costs Each American Nearly 100 hours, $1,400 A Year. https://inrix.com/press-releases/2019-traffic-scorecard-us/#:~:text=The%20report%20found%20that%20on,average%20of%20%241%2C377%20per%20year. Accessed June, 2022.

Jenior, P., Dowling, R., Nevers, B., & Neudorff, L. (2016). *Use of Freeway Shoulders for Travel – Guide for Planning,Evaluating, and Designing Part-Time Shoulder Use as a Traffic Management Strategy*. Fedar Highway Administration.

Jenior, P., James, B, Kittelson, W., & Donnell, E. (2021). *Safety Performance of Part-Time Shoulder Use on Freeways*. Transportation Research Board.

Johnson, P. (2018). *Active Traffic Management in Michigan*.

Kantar SRDS Media Planning Platform. (2019). http://next.srds.com.proxy2.cl.msu.edu/csearch/45887

Karraker, N. E., Gibbs, J. P., & Vonesh, J. R. (2008). Impacts of Road Deicing Salt on the Demography of Vernal Pool-Breeding Amphibians. *Ecological Applications*, *18*(3), 724–734. https://doi.org/10.1890/07-1644.1

Kary, B. (2016). *Evaluating the Use of Active Traffic Management Messages for Incident Management* (p. 2).

Kononov, J., Hersey, S., Reeves, D., & Allery, B. K. (2012). Relationship between Freeway Flow Parameters and Safety and Its Implications for Hard Shoulder Running. *Transportation Research Record*, *2280*(1), 10–17. https://doi.org/10.3141/2280-02

Kuhn, B., Balke, K., & Wood, N. (2017). *Active traffic management (ATM) implementation and operations guide* (Report No. FHWA-HOP-17-056).). Washington, D.C.: Federal Highway Administration.

Lee, J.-T., Dittberner, R., & Sripathi, H. (2007). Safety Impacts of Freeway Managed-Lane Strategy: Inside Lane for High-Occupancy Vehicle Use and Right Shoulder Lane as Travel Lane During Peak Periods. *Transportation Research Record*, *2012*(1), 113–120. https://doi.org/10.3141/2012-13

Levecq, C., Kuhn, B., & Jasek, D. (2011). *Best practices and outreach for active traffic management*.

Ma, J., Hu, J., Hale, D. K., & Bared, J. (2016). Dynamic Hard Shoulder Running for Traffic Incident Management. *Transportation Research Record: Journal of the Transportation Research Board*, *2554*, Article 16–2776. https://trid.trb.org/view/1393032

MacDonald, M. (2008). *ATM monitoring and evaluation—4-lane variable mandatory speed limits—12 month report (primary and secondary indicators)*. https://trid.trb.org/view.aspx?id=871478

McCourt, R. (2015). *Advanced Traffic Management Systems- Getting the Most out of Congested Freeway Corridors*. https://www.westernite.org/annualmeetings/15_Las_Vegas/Papers/3B-McCourt.pdf

MDOT. (n.d.-a). *Freeway Courtesy Patrol*. Michigan Department of Transportation. https://www.michigan.gov/mdot/0,4616,7-151-31161-94564--F,00.html

MDOT. (n.d.-b). *Traffic Monitoring Information System (TMIS)*. Retrieved July 24, 2021, from https://traffic-monitoring-program-mdot.hub.arcgis.com/

MDOT. (2009). *US-23 Feasibility Study M-14 to I-96*.

MDOT. (2017). *Special Provision for Microwave Vehicle Detection System*.

Michigan Office of Highway Safety Planning. (2021). *Michigan Traffic Crash Facts*. https://www.michigantrafficcrashfacts.org/

Mirshahi, M., Obenberger, J., Fuhs, C. A., Howard, C. E., Krammes, R. A., Kuhn, B. T., Mayhew, R. M., Moore, M. A., Sahebjam, K., & Stone, C. J. (2007). *Active traffic management: The next step in congestion management*. United States. Federal Highway Administration.

Munnich, L. W. J., Karlsson, M. L., & Fure, M. (2015). Designing Minnesota’s I-35E MnPASS Managed Lane Extension: Addressing Public Perceptions of a Lane Take-Away. *Transportation Research Record*, *2484*(1), 173–181.

Neudorff, L. G., & McCabe, K. (2015). *Active traffic management (ATM) feasibility and screening guide*. United States. Federal Highway Administration.

Newburger, E (2020). *Air pollution drops 30% in Northeast US as coronavirus lockdown slows travel: NASA*. CNBC.

Office of Highway Policy Information. (2018a). *Average Annual Miles per Driver by Age Group*. https://www.fhwa.dot.gov/ohim/onh00/bar8.htm

Office of Highway Policy Information. (2018b). *Highway Performance Monitoring System Field Manual Supplemental Guidance: Travel Time Metric Data Reporting Requirements and Specifications*. Fedarl Highway Administration.

Office of Operations. (2005). *Travel Time Reliability: Making it There on Time, All the Time* (FHWA-HOP-06-070). Fedarl Highway Administration.

Office of Operations. (2015). *The Urban Congestion Report (UCR): Documentation and Definitions*. Fedaral Highway Administration.

Onwuegbuzie, A. J., Dickinson, W. B., Leech, N. L., & Zoran, A. G. (2009). A qualitative framework for collecting and analyzing data in focus group research. *International Journal of Qualitative Methods*, *8*(3), 1–21.

Reponen, T., Grinshpun, S. A., Trakumas, S., Martuzevicius, D., Wang, Z.-M., LeMasters, G., Lockey, J. E., & Biswas, P. (2003). Concentration gradient patterns of aerosol particles near interstate highways in the Greater Cincinnati airshed. *Journal of Environmental Monitoring*, *5*(4), 557–562. https://doi.org/10.1039/B303557C

Rudin-Brown, C. M., & Noy, Y. I. (2002). Investigation of Behavioral Adaptation to Lane Departure Warnings. *Transportation Research Record*, *1803*(1), 30–37. https://doi.org/10.3141/1803-05

Schaefer, L., Upchurch, J., & Ashur, S. A. (1998). An evaluation of freeway lane control signing using computer simulation. *Mathematical and Computer Modelling*, *27*(9), 177–187. https://doi.org/10.1016/S0895-7177(98)00058-2

Shannon, J., L. Reyes & D. Rice (2020). *Are Lockdowns Being Relaxed in My State? Here's How America Is Reopening amid the Coronavirus Pandemic*. USA TODAY

Sorrell, C. (2014). Task 1 Literature Review. http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP03-114_LiteratureReview-Revised.pdf

Sullivan, A., & Fadel, G. (2010). *Implementing active traffic management strategies in the US*. University Transportation Center for Alabama.

Taale, H. (2006). REGIONAL TRAFFIC MANAGEMENT – METHOD AND TOOL. *IFAC Proceedings Volumes*, *39*(12), 457–462. https://doi.org/10.3182/20060829-3-NL-2908.00079

Taylor, R., & Change, C. (2017). *Overview of Performance Measures: Travel Time Reliability (NHPP) and Annual Hours of Peak Hour Excessive Delay (CMAQ)*. Transportation Performance Management Implmentation Workshop, Phoenix.

Transportation Research Board. (2010). *Highway Capacity Manual 2010*.

Tomer, A. and L. Fishbane 2020). *Coronavirus has shown us a world without traffic. Can we sustain it?* Brookings.

Turner, S. M., Eisele, W. L., Benz, R. J., & Holdener, D. J. (1998). *Travel time data collection handbook*. United States. Federal Highway Administration.

University of Michigan. (2021a). *Data Query Tool*. Michigan Traffic Crash Facts. https://www.michigantrafficcrashfacts.org/querytool#q1;0;2020;;

University of Michigan. (2021b). *Football Schedule*. University of Michigan Athletics. https://mgoblue.com/sports/football/schedule

Walker, J. (2014, December 1). *New £250m motorway junction to boost Birmingham Airport and high speed rail*. BirminghamLive. http://www.birminghammail.co.uk/news/midlands-news/new-250m-motorway-junction-boost-8205552

Wang, Y., Ma, W., Henrickson, K. C., Wang, Y., & Yang, X. (2015). Dynamic lane assignment approach for freeway weaving segment operation. *Transportation Research Record*, *2484*(1), 39–49.

Washington State Department of Transportation. (2009). *Building Smarter Highways- Active Traffic Management*. https://www.youtube.com/watch?v=cd0doR0Ga-I

Washington State Department of Transportation. (2011). *I-5 Express Lanes Toll Feasibility Study*. https://app.leg.wa.gov/ReportsToTheLegislature/Home/GetPDF?fileName=I-5_ExpressLanesReport_063011_web_6b0cc9e9-ed6e-4d31-8947-c401ebd1fa17.pdf

Weather Underground. (2021). *Ann Arbor, MI Weather History*. https://www.wunderground.com/history/daily/us/mi/ann-arbor

WHMI. (2018). *US-23 Flex Route Project In National Contest*. https://whmi.com/news/article/us-23-flex-route-aashto-competition

World Health Organization (2020). *Timeline of WHO's Response to COVID-19*. https://www.who.int/news-room/detail/29-06-2020-covidtimeline. Accessed July 8, 2020.

Xiong, C., Yang, X. T., Zhang, L., Lee, M., Zhou, W., & Raqib, M. (2021). An integrated modeling framework for active traffic management and its applications in the Washington, DC area. *Journal of Intelligent Transportation Systems*, *0*(0), 1–19. https://doi.org/10.1080/15472450.2021.1878891