MID-AMERICA TRANSPORTATION CENTER

Report # MATC-UNL: 004-54

Final Report

WBS: 27-1121-0005-004-54

Performance Reliability and Safety Index for Region VII Highways

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2024

A Cooperative Research Project sponsored by
U.S. Department of Transportation- Office of the Assistant Secretary for Research and Technology

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A Report on Research Project Sponsored by

Mid-America Transportation Center

University of Nebraska–Lincoln

June 30, 2024

1. Report No. WBS # 25-1121-0005-004-54	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Performance Reliability and Safety Index for Region VII Highways	5. Report Date September 2024
	6. Performing Organization Code
7. Author(s) Aemal J. Khattak, MM Shakiul Haque, Li Zhao	8. Performing Organization Report No. 25-1121-0005-004-54
9. Performing Organization Name and Address Mid-America Transportation Center Prem S. Paul Research Center at Whittier School 2200 Vine St. Lincoln, NE 68583-0851	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. 69A3551747107
12. Sponsoring Agency Name and Address Office of the Assistant Secretary for Research and Technology 1200 New Jersey Ave., SE Washington, D.C. 20590	13. Type of Report and Period Covered Final Report June 2021 – September 2023
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract
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17. Key Words Reliability, travel time, travel time reliability, reliability index, INRIX, safety, planning time index, travel time index, level of travel time reliability, buffer index, coefficient of variation	18. Distribution Statement

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

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Acknowledgments

The research team acknowledges the contributions of Dr. Ernest Tufuor on field data collection and consultation for this project. The team would also like to thank the Nebraska Department of Transportation for their assistance in accessing the NPMRDS data platform and the City of Lincoln for coordinating data collection along Nebraska Highway 2 in Lincoln, Nebraska.

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated in the interest of information exchange. The report is funded, partially or entirely, by a grant from the U.S. Department of Transportation's University Transportation Centers Program. However, the U.S. Government assumes no liability for the contents or use thereof.

List of Abbreviation

AADT: Annual average daily traffic

BI: Buffer Index

CDF: Cumulative Distribution Function

COV: Coefficient of Variation

COVID-19: Coronavirus disease 2019

DOT: Department of Transportation

FAST: Fixing America's Surface Transportation

FHWA: Federal Highway Administration

HCM: Highway Capacity Manual

IQR: Interquartile Range

LOTTR: Level of Travel Time Reliability

MAC: Media Access Control

MAP-21: Moving Ahead of Progress in the 21st Century

NPMRDS: National Performance Management Research Data Set

PTI: Planning Time Index,

SHRP: Strategic Highway Research Program

TRB: Transportation Research Board

TTD: Travel Time Distribution

TTI: Travel Time Index

TTR: Travel Time Reliability

Abstract

Roadway performance measures are used for operating, planning, and design purposes to improve services for road users. Simple statistics of the performance metrics such as measures of central tendency (e.g., mean, median) are often used for making operational and planning decisions. Even though such statistics are useful, they are, more than often, not comprehensive enough for making insightful operational and planning decisions. Consequently, performance reliability measures, which attempt to capture the day-to-day variability in performance, have the potential to benefit the areas of operation, planning, and design. Traffic data from Intelligent Transportation System facilitates the measurement of the reliability of transportation systems.

This project analyzes and verifies the accuracy of INRIX traffic data using a testbed located in Nebraska. In addition, different travel time reliability (TTR) metrics such as travel time index (TTI), planning time index (PTI), level of travel time reliability (LOTTR), buffer index (BI), and coefficient of variation (COV) were measured for Region VII highways. The project evaluates TTR metrics under various weather conditions (such as normal weather, rain, and snow), time of day (AM peak and PM peak), and global events like the COVID-19 pandemic. Out of the five TTR metrics, in general, INRIX measured the TTI, PTI, and LOTTR metrics with the most accuracy, compared to the ground truth data. In most cases, LOTTR was most accurately measured by INRIX. On the other hand, INRIX measured BI and COV with the least accuracy, compared to the ground truth data.

One of the most notable findings from this project was whether the transportation system's reliability increased or decreased or to what extent the reliability changed depended on which metric was used to measure it. Therefore, engineers and transportation agencies require a

deeper understanding of the travel time related statistics and transportation system's characteristics to understand the actual changes that occurred in travel time reliability.

Chapter 1 Introduction

1.1 Background

Roadway performance measures are used for operating, planning, and design to improve services for road users. However, simple statistics of the performance metrics such as measures of central tendency (e.g., mean, median), while useful, are not robust enough for transportation agencies to make all planning or operation decisions. Consequently, performance reliability measures, which attempt to capture the day-to-day variability in performance, have received considerable research interest over the past decade. There are many roadway performance metrics (e.g., travel time, speed, delay, congestion, crash) that can be examined from a reliability perspective without losing generality. The basis of all performance reliability measures is the underlying distribution of the performance measure over time.

This project first assessed the data on performance measures of state Departments of Transportation (DOT) within Region VII by using existing Intelligent Transportation System data sources such as the National Performance Management Research Data Set (NPMRDS). Specifically, the study focused on data available to identify potential performance reliability metrics for different state DOT functions (e.g., operations versus planning). The goal was to determine if the existing data can be used for performance reliability monitoring. This would support Region VII state DOTs to continuously meet the federal requirement on reporting performance reliability on the National Highway System as stipulated in both the Fixing America's Surface Transportation (FAST) Act (FHWA, 2015) and the Moving Ahead of Progress in the 21st Century (MAP-21) (FHWA, 2012).

The project determined whether the existing travel data can be used to develop a performance reliability and safety index for Region VII highways. Furthermore, the project assessed how the performance reliability metrics were impacted by events like adverse weather and drastic changes in travel demand.

1.2 Problem Statement

Roadway performance reliability can be defined as the consistency or dependability of performance measures as determined by the day-to-day variability. The variability in performance is caused by both recurrent and nonrecurrent events. Recurrent events occur each day during the same time and location (e.g., peak periods) of which road users are usually familiar with and can plan accordingly. However, non-recurrent events (e.g., inclement weather, incidents), by definition, are unpredictable and cause the most frustration to road users (Tan et al., 2015). Therefore, understanding how to accurately estimate and predict the variability in performance or reliability is important in roadway performance analysis.

In recent years, performance reliability has been recognized as a valuable service and has grown in popularity among transportation agencies (FHWA, 2017). For example, the FHWA has identified travel time reliability as a key road performance mobility indicator in the Fixing America Surface Transportation (FAST) Act (FHWA, 2015) and Moving Ahead for Progress in the 21st Century (MAP21) Act (FHWA, 2012). However, the ability to obtain reliable real-time travel data has been a major limitation in achieving a robust reliability metric.

Fortunately, recent advancements in Intelligent Transportation System (ITS), computer systems, and internet-of-things have made it possible to collect and analyze more detailed and consistent real-time travel time data for reliability analysis.

Three following research needs were identified for this project:

1. **Need to assess the dependability of existing ITS data**: Some of the existing ITS data sources include NPRMDS, RITIS, StreetLight, WAVE, Google Traffic, etc.

There is a need to assess their dependability and consistency to be used in long-term reliability analysis. It is important to compare these data sources with observed data to check whether the data quality such as the accuracy is appropriate. This project determined whether the existing data sources can be used to set up a reliability monitoring system to provide roadway performance information.

2. **Need to evaluate the effect of various events on performance**: Random events are a prime contributor to unreliable roadways. For example, nearly 60% of road congestion occurs because of random events, which includes 25% from traffic incidents, 15% from inclement weather, 10% from work zones, and 10% because of special events and other effects (FHWA, 2005). Furthermore, global events like the COVID-19 pandemic is known to impact trave demand and driver behavior. Intuitively, reliability estimation and forecasting methods should explicitly account for these random events, as well as global events for future preparation. This project evaluated the effect of these events on mobility and safety.
3. **Need to investigate the best performance reliability measure**: One of the major challenges for transportation professionals is to select the best ways to convey performance reliability information that is usable and effective. Furthermore, different reliability metrics should be studied under Region VII conditions to find out which metric captures the travel time characteristics most accurately and efficiently. This research supported the efforts of Region VII state DOTs to communicate performance measures to the public. Finding the best travel time

reliability metric is useful for road users and logistic operators for effective trip scheduling and arrivals.

1.3 Research Tasks

This project was conducted following the four major research tasks:

Task 1 (Literature review):

A review of published literature was made to note the latest developments on 1) ITS travel data collection systems for reliability analysis, 2) reliability estimation methodologies, and 3) common reliability metrics used for travel time including recommended metrics in the MAP-21 current rules. Literature sources, such as the Transportation Research International Documentation (TRID) and Transport database, were utilized for the literature review. The purpose of this task was to ensure that no research that might contribute to this study was overlooked or duplicated.

Task 2 (Analysis of existing travel time data):

ITS travel data collection systems were evaluated in terms of their accuracy during normal and inclement weather conditions. The ITS data was evaluated and compared to the ground truth data collected by the research team. Different statistical measures such as central tendency (i.e., mean and median), dispersion (e.g., standard deviation, interquartile range), and different widely used travel time reliability metrics were used for the comparison of ITS and ground truth data.

The purpose of this task was to determine the Region VII data source that was sustainable for reliability analysis.

Task 3 (Estimate performance reliability metrics):

Mobility and safety performance reliability metrics were estimated. These included the required reliability metrics defined in MAP-21. Common reliability metrics were statistically analyzed, including but not limited to the planning time index, travel time index, safety reliability index. The purpose of this task was to determine a robust reliability index under Region VII conditions.

Task 4 (Relate reliability metrics to safety):

The project estimated different reliability metrics under conditions that impact roadway safety. Examples of such conditions include inclement weather, work zones, and global events like COVID-19. This task evaluated the travel time reliability metrics under such conditions and explored which metric best captured the traffic condition with the highest potential impact on safety.

1.4 Research Objectives

The major goal of this research project was to investigate the travel time reliability metrics for Region VII highways. The objectives of this project were as follows:

1. Validate the accuracy of ITS travel time data compared to the observed ground truth data in different weather and traffic conditions.

2. Measure the travel time reliability metrics in different weather and traffic conditions.

3. Provide insights on the statistics of travel time and corresponding reliability metrics to understand how the reliability of highways should be understood and expressed.

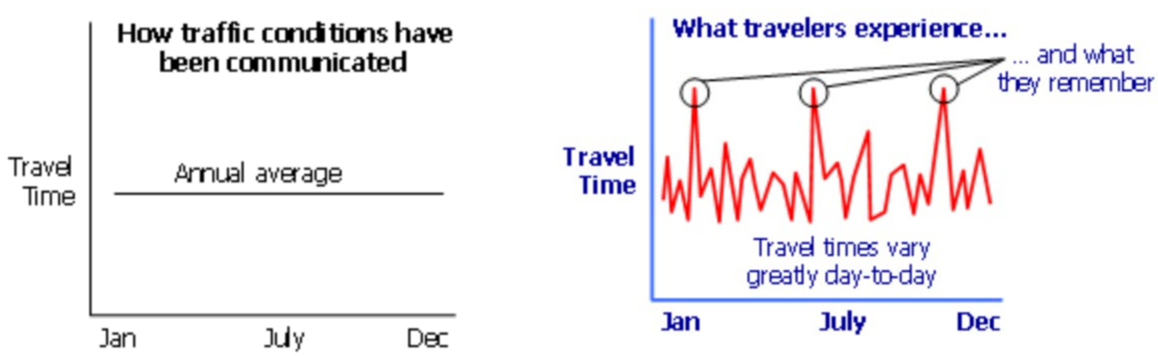
1.5 Report Organization

This report is structured as follows. Chapter 2 conducts the literature review. Chapter 3 discusses the research methodology and data collection efforts for this project. Chapters 4 and 5 present the validation study of ITS data sources compared to the ground truth data for normal and inclement weather, respectively. Chapter 6 presents travel time reliability metrics studies conducted under traffic conditions that impact safety. Finally, Chapter 7 concludes with a summary of the key findings and a discussion of potential directions for future research.

This report provides additional figures of ITS data validation for incremental segments for various weather and traffic conditions in Appendix A.

Chapter 2 Literature Review

Roadway performance measures are used during operation, planning, and design to improve services for road users (Turnbull, 2013). Simple statistics of the performance metrics such as measures of central tendency (e.g., mean, median) are often used for making operational and planning decisions. Even though such statistics are useful, they are often not comprehensive enough for making insightful operational and planning decisions (Tufuor and Rilett, 2022). Figure 2.1 shows an example of how traffic conditions are often communicated versus how commuters remember them (FHWA 2017). Figure 2.1 (a) shows an example of how average travel conditions can be communicated to users. Figure 2.1 (b) indicates the traveler's day-to-day experiences, and they more often tend to remember their worst experience. While both graphs are "true" information, Figure 2.1 (a) may not provide adequate information for the decision-making process.



(a) (b)

Figure 2.1 How traffic conditions are communicated and experienced (FHWA, 2017)

As transportation agencies and researchers have access to broader and comprehensive travel information due to the advancement of modern technology, studies regarding the reliability of performance measures received considerable research interest over the past decade (Taylor, 2013; Tufuor and Rilett, 2020, Rilett et al., 2021). Since decade, transportation officials have started to utilize the concept of travel time reliability to categorize how their systems are performing. US Federal Highway Administration identified travel time reliability as a key roadway mobility performance indicator (FHWA 2012, 2015). In addition, the 6^{th} version of the Highway Capacity Manual includes an arterial travel time reliability estimation methodology for the first time (HCM, 2016).

This chapter will provide a comprehensive overview of the concepts and research conducted on the distribution of travel time, as well as the reliability, validity, and selection of appropriate metrics to measure reliability, all of which are directly relevant to the scope of this project.

2.1 Travel Time Distribution and Reliability

Travel time is one of the most used metrics to analyze the performance of transportation systems (Yang and Cooke 2018). This is because travel time can be easily understood by both roadway users and traffic system managers (Lomax and Schrank 2002). As travel time may vary across space and time (Liao et al., 2020), the underlying characteristics of the travel time can be expressed spatially (i.e., link, segment, corridor, system, etc.), by the time of the day (i.e., morning peak, evening peak and off-peak hours), aggregation level (i.e., individual vehicle, 5 minutes, 15 minutes or an hour), analysis period (i.e., number of days, weekdays, weekends, etc.), and road condition (i.e., dry or wet), etc. Therefore, travel time may vary based on these factors and for this reason, reliability of travel time is an important transportation research topic.

There are different definitions of travel time reliability in the literature. The FHWA defined travel time reliability as “the consistency or dependability in travel times, as measured from day-to-day and/or across different times of the day" (FHWA 2017). The Highway Capacity Manual (HCM) states that "travel time reliability reflects the distribution of trip travel time over an extended period" (Transportation Research Board 2016). This distribution is a function of several factors that impact travel time, including weather events, incidents, work zones, etc. (Transportation Research Board 2016). The Strategic Highway Research Program (SHRP) defined travel time reliability as aiming "to quantify the variation of travel time." It is defined using the entire range of travel times for a given trip, for a selected time period (e.g., the PM peak hours during weekdays) over a selected horizon (e.g., a year). To measure reliability, a trip can be defined as occurring on a specific segment, facility (combination of multiple consecutive segments), or any subset of the transportation network. The definition can also be broadened to include a traveler's initial origin and final destination. Measuring travel time reliability requires describing a sufficient history using the travel time distribution for a given trip (Zegeer et al. 2014). The Future Strategic Highway Research Program (F-SHRP) defined travel time reliability as the variation of travel times over a period based on hour-to-hour or day-to-day variation (NCHRP 20-58(3), 2003).

A commonality across the definitions above is that travel time may be modeled using a continuous distribution (Rilett et al., 2021). Therefore, standard statistical metrics can be used to describe the characteristics of travel time distribution, which includes measures of central tendency (e.g., mean and median), measures of dispersion (e.g., standard deviation and interquartile range), and measures of symmetry (e.g., skewness). Traditionally, transportation officials have used point measures of travel time distribution to characterize how the systems are operating. These were either central tendency measures, like the mean and median, or extreme value measures, like the 90th percentile travel time (Rilett, Tufuor and Murphy, 2021). However, most transportation agencies do not use a single statistical measure such as mean and median to define travel time reliability (Tufuor and Rilett, 2022). Among various reasons, one of the key reasons is that a single measure cannot express the holistic performance of roadways (Rilett, Tufuor and Murphy, 2021; FHWA, 2017). This is especially relevant now, given that recent developments in travel time data collection have provided transportation authorities with far more extensive and robust information.

As noted earlier, there are several travel time distribution statistical measures, such as mean, median, standard deviation, and coefficient of variation, that can be used to quantify the performance of a transportation system. However, it has been suggested that these measures are not straightforward for a nontechnical audience to understand and that they may treat early and late arrivals equally (Pu, 2011; FHWA, 2017). As a result, travel time reliability metrics, including the travel time index, the planning time index, the level of travel time reliability, and the buffer index, have been developed and recommended to be used (FHWA 2012, 2017).

2.2 Travel Time Reliability Data and Validation

Traditionally, travel time data were collected by public sector agencies. Recently, due to the advancements in data collection technologies, travel data are being obtained from a variety of data collection devices such as GPS in cell phones, Bluetooth devices, Wi-Fi devices, probe vehicles, etc. Most of these new and high-level travel time data sets are from private sector sources such as StreetLight Data (2024), Iteris (2024), and INRIX (2024). However, validation of these private sector data is crucial as the data quality will impact the decision-making process when used by transportation agencies.

Hu et al. (2016) provided a list of validation studies conducted for private sector data for freeways as shown in Table 2.1.

Table 2.1 Past studies investigating private sector data accuracy (Hu et al., 2016)

Location	Road Type	Length (mile)	Duration	Ground truth	Measure of effectiveness	Accuracy	Reference
I-295, Florida	Freeway	7.89	3 h	Floating car	Percent error	5–38%	Elefteriadou et al. (2014, p. 90)
I-71, Ohio	Freeway	14	6 months	Loop detectors	Congestion onset	Lag of 6 min	Coifman and Kim (2013, p. 60)
I-287, New Jersey	Freeway	20.5	1 day	Toll tag reidentification	Average absolute speed error	3–6 mph	Kim and Coifman (2014, p. 19)
I-78, New Jersey	Freeway	17.5	1 day	Toll tag reidentification	Speed error bias	−2 to 4 mph	Kim and Coifman (2014, p. 19)
SR 522, Washington	Arterial	3	7 days	License plate readers	Mean absolute percent error (speed)	17–73%	Wang et al. (2014, p. 122)
I-90, Washington	Freeway	77	7 days	License plate readers	Reaction to road closure	Quick response	Wang et al. (2014, p. 122)
I-91, Massachusetts	Freeway	N/A	2 days	License plate matching	Mean absolute percent error (travel time)	1–1.5%	Jia et al. (2013, p. 16)
I-10, Florida	Freeway	20	4 days	Floating car	Average absolute speed error	6.27 mph	Lattimer and Glotzbach (2012, p. 8)
I-95 Maryland, Virginia, Delaware, and New Jersey	Freeway	92	4 months	Floating car	Average absolute speed error	1.96 mph	Haghani et al. (2009)

Hu et al. (2016) examined the quality of private sector data on arterials by utilizing Bluetooth travel-time data as the ground truth using three signalized arterials in the state of Virginia. The evaluation was conducted from two perspectives, i) the ability to track real-time conditions, and ii) the ability to identify long-term traffic state changes. Hu et al. (2016) concluded that the private sector data were not suitable for real-time applications. However, it can be used to measure long-term traffic state changes for performance measurement programs.

A study by Haghani et al. (2009) compared Bluetooth-based ground truth data with INRIX for the I-95 corridor coalition and suggested that the speed data provided by INRIX was generally of good quality. The quality of data generated by INRIX improved with increasing speed. Also, the results consistently showed that INRIX overestimated speeds below 45 miles per hour (mph) and underestimated speeds beyond 60 mph.

Kim and Coifman (2014) used two months of the concurrent loop detector data to evaluate INRIX performance on 14 miles of I-71 in Columbus, Ohio, including both recurrent and non-recurrent events. This study noted three major findings, i) the reported INRIX speeds lagged the loop detector measurements by almost six minutes and this latency appeared to be within INRIX specifications, ii) even though INRIX reported speed every minute, the reported speed was often identical to the prior sample, demonstrating that INRIX was effectively calculating the speeds over a longer period than it used to report the speeds, and iii) although INRIX reported two measures of confidence, these confidence measures did not appear to reflect the latency or the occurrence of repeated INRIX reported speeds.

Zhang et al. (2015) proposed a novel validation methodology based on the coefficient of variation using two independent data sources (i.e., GPS probe and Bluetooth) for arterial travel time. This study presented a context-dependent travel time fusion framework to improve the reliability of travel time information by fusing data from multiple sources. All 2012 data from a busy arterial corridor in Maryland were used to test the proposed methodology.

Sharma et al. (2017) conducted a study regarding the usage of INRIX data for real-time and historical trend assessment using I-80 in Nebraska. The two findings from this study were i) there was almost always a speed bias between data streaming from probes and traditional infrastructure-mounted sensors, and ii) real-time probe data had confidence score of 30, proving to be a critical issue since it is better to have precise data for incident detection, roadway performance assessment, travel time estimation, and other traffic analyses.

2.3 Choice of Reliability Index

Selection and recommendation of using a particular reliability index may differ based on different transportation facilities, studies, and agencies.

Turner and Teresa (2013) used 2011 historical traffic speed data from INRIX for arterial roads in the Twin Cities Metropolitan Area. This study recommended that multiple performance measures should be used to quantify and monitor the mobility of arterial roads, including delay per mile, travel time index, and planning time index for peak hour periods. This research found a travel time index of 1.07 and 1.08 and a planning time index of 1.36 and 1.41, for the AM and PM peak periods, respectively, for arterials of the Minnesota Department of Transportation.

Pu (2011) analytically examined different reliability measures and explored the corresponding mathematical relationships and interdependences. This study suggested that the coefficient of variation, instead of the standard deviation, was a good proxy for several other travel time reliability measures.

In the 2011 study, Pu listed the reliability measures encouraged (or discouraged) by different sources. These findings are shown in Table 2.2.

Table 2.2 Travel time reliability measures recommended by different sources (Pu, 2011)

Travel Time Reliability Measure	Lomax et al. (2003)	FHWA (2024)	NCHRP Report 618 (2008)	SHRP 2 (2008)
95th or other percentile travel time	N/A	√	N/A	N/A
Standard deviation	N/A	×	×	N/A
Coefficient of variation	N/A	×	×	N/A
Percent variation	√	N/A	√	N/A
Skew statistic	N/A	N/A	N/A	√
Buffer index	√	√	√	√
Planning time index	N/A	√	√	√
Frequency of congestion	N/A	√	N/A	N/A
Failure rate (percent on-time arrival)	N/A	N/A	√	√
Misery index	√	N/A	√	√

NOTE: √ = use encouraged; × = use discouraged; N/A = not applicable.

As discussed earlier, using a single statistical measure, such as mean or median, to define the travel time reliability is no longer recommended by transportation agencies. Several researchers explored the functionality of different travel time reliability metrics, such as TTI, PTI, LOTTR, BI, and COV, etc.

Schrank et al. (2019) considered TTI to be one of the most widely used travel time reliability metrics, particularly when analyzing the effect of roadway operational improvements. TTI measures the ratio of the mean travel time compared with the mean travel times under free-flow conditions. By this definition, a more reliable roadway will have TTI values close to one and higher TTI values would mean greater congestion and travel delays.

PTI is the ratio of the 95th percentile travel time to the mean travel time under free-flow conditions. Therefore, PTI compares the “near worst” travel time conditions (i.e., 95^{th} percentile travel time) to the free-flow travel time. This means PTI quantifies the extra time needed by motorists, beyond what is needed with free flow conditions, to ensure on-time arrival 95% of the time. This 95th percentile travel time or the PTI is listed by FHWA (2017), among few other metrics.

The BI is a ratio-based travel time reliability metric. The numerator is the difference between the 95th percentile travel time and the mean travel time, known as buffer time, and the denominator is the mean travel time. Therefore, the BI metric quantifies the extra time a motorist might need in addition to the mean travel time to ensure on-time arrival (FHWA, 2017; Sharma et al., 2017).

The LOTTR metric is the ratio of the 80th percentile travel time to the 50th percentile travel time of the travel time distribution. Therefore, LOTTR is the measure of the ratio of dispersion and central tendency of the travel time distribution. Note that LOTTR is used as one of the key mobility indicators recommended in the MAP-21 Act (FHWA, 2012) and the FAST Act (FHWA, 2015) to assess the performance of national highways in the US.

COV is the ratio of the standard deviation and mean of the travel time distribution. COV was proposed as a measure of travel time reliability in a previous study (Pu, 2011). However, according to the FHWA, it is difficult for the public to comprehend the meaning of COV and FHWA does not advocate its use (FHWA 2017).

2.4 Literature Summary

While there are several traffic data collection sources from the private sector, INRIX gained the attention of transportation agencies and researchers. Note that INRIX is responsible for developing the US NPMRDS for the US Federal Highway Administration. The NPMRDS is currently used by state DOTs and metropolitan planning organizations for research, operations, and performance analyses (Siddiqui and Dennis 2019).

INRIX was used in validation research where the reported speed and travel time were examined. However, to the best of the authors' knowledge, no research was found that scrutinized the statistical measures (e.g., central tendency, dispersion) and dispersion of travel time and travel time reliability metrics (e.g., TTI, PTI, LOTTR, BI, COV, etc.) using the INRIX and ground truth data. On the other hand, Sharma et al. (2017) examined the INRIX data for freeways in Nebraska and recommended future validation efforts using urban arterials. Therefore, this project aims to conduct a study to validate the INRIX data using the Highway 2 testbed located in Lincoln, Nebraska. This validation effort will consider the standard statistical metrics and different travel time reliability metrics for both normal and adverse weather conditions.

Chapter 3 Data Collection and Research Methodology

3.1 Testbed Selection

This project requires travel time data along Region VII highways. The research team selected Nebraska Highway 2 (also known as Nebraska Parkway) segments from 27th Street to 84th Street (Figure 3.1) to test the ITS data quality and measure travel time statistics and corresponding reliability metrics. Highway 2 is a four-lane divided highway located in Lincoln, Nebraska. This testbed deals with high traffic demand and substantial congestion during peak hours. The annual average daily traffic (AADT) ranges from around 25,000 to 42,000 (NDOT 2024; INRIX, 2024) and the speed limit ranges from 45 mph to 55 mph. The length of this testbed is 4.71 miles.

Figure 3.1 Testbed on Nebraska Highway 2

The 4.71-mile testbed (i.e., corridor) is divided into four segments to facilitate analysis over different segments. The four segments are 27th Street to 40th Street, 40th Street to 56th Street, 56th Street to 70th Street, and 70th Street to 84th Street. These segments are denoted as segment 27_40, segment 40_56, segment 56_70, and segment 70_84, respectively, in this report. The lengths of these segments are 1.18, 1.09, 1.24, and 1.20 miles, respectively. The estimated AADTs for segments 27_40, 40_56, 56_70, and 70_84 are 42,000, 29,000, 27,000, and 25,000, respectively.

Note that these segments are also rearranged and combined into segment 27_56, segment 27_70, and segment 27_84 to realize the impact of incremental lengths in this project.

Each intersection of 27th Street, 40th Street, 56th Street, 70th Street, and 84th Street meeting Highway 2 are signalized four-legged intersections. Furthermore, there is one four-legged signalized intersection between 27th and 40th Street, and one between 40th Street and 56th Street, along the Highway 2 testbed. There are two signalized intersections (one is four-legged, and the other is three-legged) between 56th Street and 70th Street along the Highway 2 testbed. However, there are no signalized intersections between 70th and 84th Street on the Highway 2 testbed.

3.2 Data Collection and Processing

The travel time data using Miovision Scouts (Miovision Scout, 2024) were collected from November to December in 2021. Five sets of Miovision units were used at the intersections of 27th Street, 40th Street, 56th Street, 70th Street, and 84th Street along the Highway 2 testbed corridor.

The Miovision Scout portable units consist of two types of detectors to capture traffic data: cameras and WiFi receivers. Cameras within the portable units were used to obtain video data of traffic traversing the roadway. The WiFi receivers were used to capture Media Access Control (MAC) addresses and their associated time stamps from passing vehicles. Any electronic unit in a passing vehicle that has i) short-range communication capabilities, and ii) is enabled, would provide MAC addresses. Examples of these electronic units are laptops, tablets, mobile/cell phones, and communication systems within the vehicle.

There are two ways of collecting the travel time data from these Miovision units: i) manual video observation, and ii) matching the MAC address. Travel time data from manual observation involves detecting vehicles from one Miovision camera unit to another and using time stamps from the video camera to extract the travel time. Figure 3.2 shows screenshots of traffic footage from Miovision video cameras installed at each segment of the Highway 2 testbed.

Figure 3.2 Screenshots of traffic footage from video cameras installed at segments on Highway 2 testbed

The other method of finding travel time is to match the unique MAC addresses of passing vehicles from different Miovision sets installed at each segment. When a match was found, the time difference was calculated. Using the time difference, the travel time between Miovision unit locations was estimated. The MAC address matching algorithm was programmed using the R statistical software package. Note that the travel time data found from manual observation or MAC matching will be used as the ground truth travel time data for this project.

This ground truth travel time data will be compared to ITS travel time data. This project used INRIX data for the Highway 2 testbed. Note that INRIX is responsible for developing the US National Performance Management Research Data Set (NPMRDS) for the US Federal Highway Administration. The NPMRDS is currently used by state DOTs and metropolitan planning organizations for research, operations, and performance analyses (Siddiqui and Dennis 2019). The NPMRDS road network covers major highways and urban arterial roadways in Nebraska. Note that Chapter 6 of this report briefly discusses other relevant studies conducted using testbeds from Nebraska.

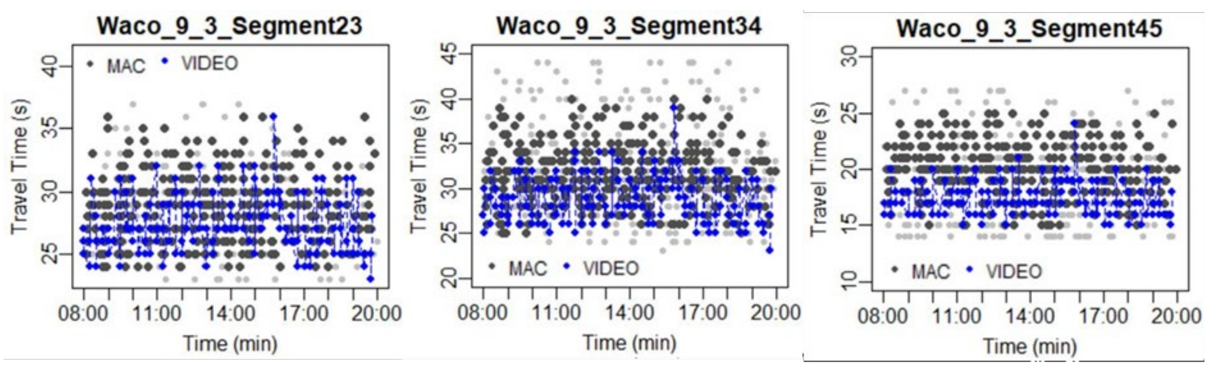
3.3 Comparison of Travel Time from Video Observation and MAC Matching

This project used travel time data from November to December of 2021. The travel time data are aggregated to produce 15 minutes mean travel time data to be used for the statistical analysis. Manual observation of hundreds of hours of data is time-consuming and not feasible, therefore, the majority of the travel time data was collected through the MAC matching procedure. The authors of this project used travel time data using MAC matching in previous published research (e.g., Zhao et al., 2022a; Zhao et al., 2022b; Khattak et al., 2023; Haque et al., 2023; Haque et al., 2024; Haque 2022; Tufuor et al., 2022).

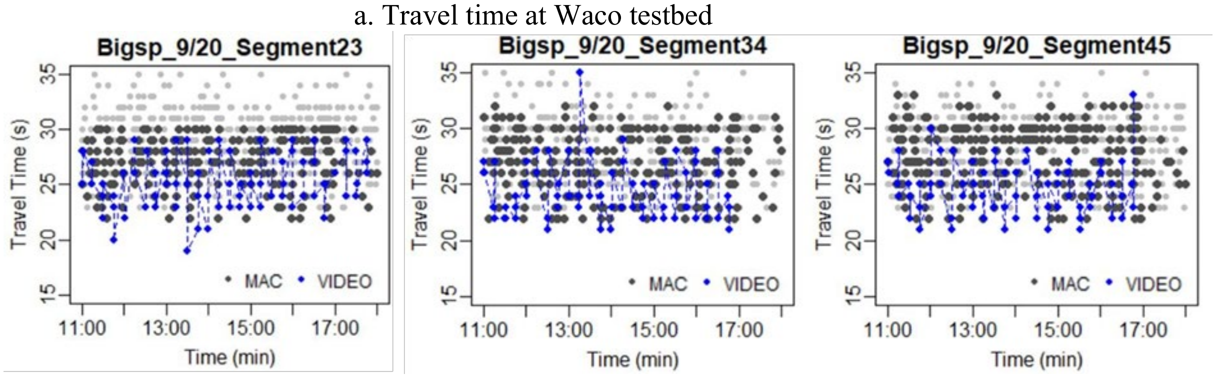
This section presents two validation studies regarding manual observation and MAC matching, which include i) a study conducted for work zones on I-80 (Nebraska) (Zhao et al., 2022a; Zhao et al., 2022b), and ii) a study conducted for this project's Highway 2 testbed, as shown in Figures 3.1 and 3.2.

3.3.1 Validation from Work Zone Site from Waco and Big Springs, Nebraska

Zhao et al. (2022a) and Zhao et al. (2022b) validated manual travel time compared to the MAC matching approach for work zone related research. The purpose of the study was to verify if the automatic queue detection system was operating correctly in Waco and Big Springs, Nebraska testbeds. Segment travel time data at the Waco and Big Springs testbeds were collected by the research team. Five Miovision Scouts recorded the MAC address of vehicles traveling through them. Therefore, travel time data in four road segments were obtained, which were segment 12, segment 23, segment 34, and segment 45 (e.g., segment 12 measures from Miovision Scout 1 to Miovision 2). The details of the data collection site can be found elsewhere (Zhao et al, 2022a; Zhao et al., 2022b).



a. Travel time at Waco testbed



b. Travel time at Big Springs testbed

Figure 3.3 Travel time obtained by MAC matching vs manual observation – no queue (Zhao et al., 2022a)

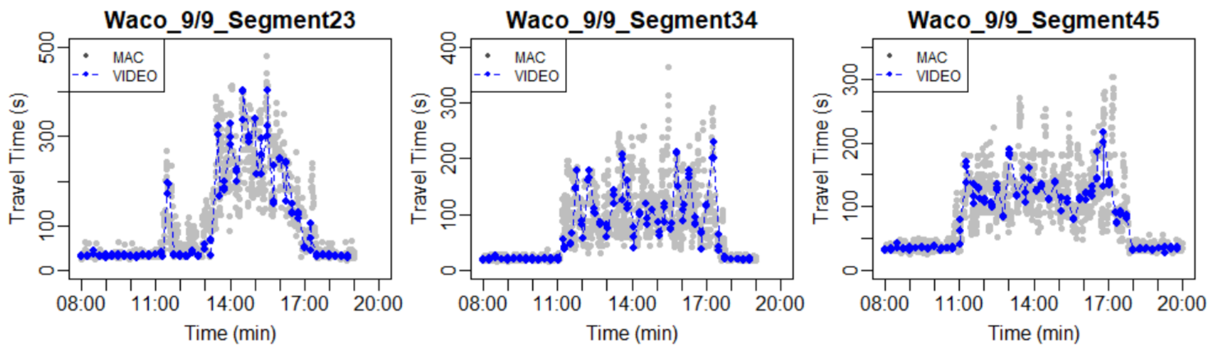


Figure 3.4 Travel time obtained by MAC matching vs manual observation – with queues (Zhao et al., 2022a)

The camera at each Miovision Scout location recorded footage during the data collection time. Videos were used to verify the validity of the travel time automatically measured by the MAC address matching. Figure 3.3 and Figure 3.4 show the travel times obtained by automatically matching the MAC addresses (i.e., grey color) and by manually checking the corresponding video (i.e., blue color) for uncongested and congested traffic conditions, respectively.

A t-test was conducted to check if the mean travel time found via MAC matching was statistically different from the video observed travel time at a 5% level of significance. Statistical results are shown in Table 3.1 for the Waco-Utica testbed and in Table 3.2 for the Big Springs testbed, respectively.

Table 3.1 t-test of the travel time at Waco-Utica on Sep. 3rd, 2020

	Segment_23		Segment_34		Segment_45	
	MAC Match	Video Observation	MAC Match	Video Observation	MAC Match	Video Observation
Mean (s)	28.7	27.4	31.5	28.8	20.1	17.4
Adjust (s)	-1	0	-2.5	0	-2.5	0
t statistic	1.3959		0.96077		0.32433	
df	323.8		316.69		401	
p-value	0.1637		0.3374		0.7459	
95% CI	(-0.139, 0.816)		(-0.280, 0.815)		(-0.288, 0.401)	

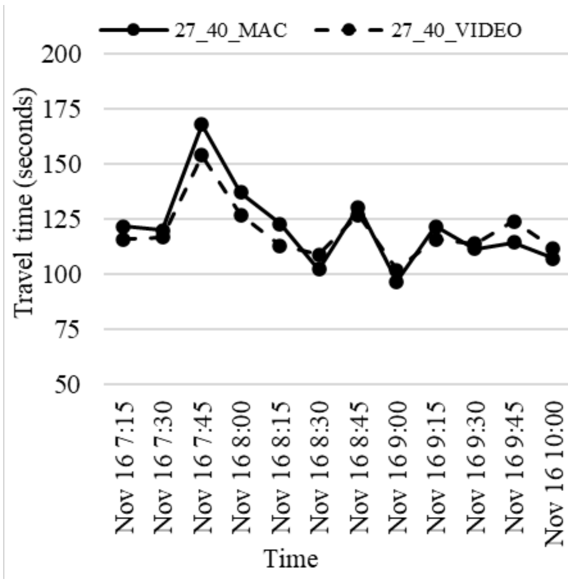
Table 3.2 t-test of the travel time at Big Springs on Sep. 20th, 2020

	Segment_23		Segment_34		Segment_45	
	MAC Match	Video Observation	MAC Match	Video Observation	MAC Match	Video Observation
Mean (s)	26.7	25.4	27.1	24.5	27.7	24.7
Adjust (s)	-1	0	-2.5	0	-2.5	0
t statistic	1.2776		0.18215		1.7991	
df	86.178		73.069		73.011	
p-value	0.2048		0.856		0.07613	
95% CI	(-0.182, 0.839)		(-0.538, 0.646)		(-0.054, 1.055)	

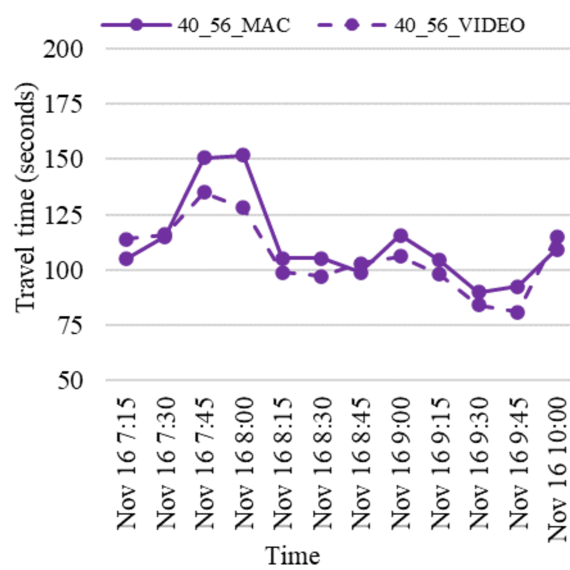
Tables 3.1 and 3.2 show that there was no statistically significant difference between the mean values of video observation and MAC match methods.

3.3.2 Validation from Highway 2 testbed, Lincoln, Nebraska

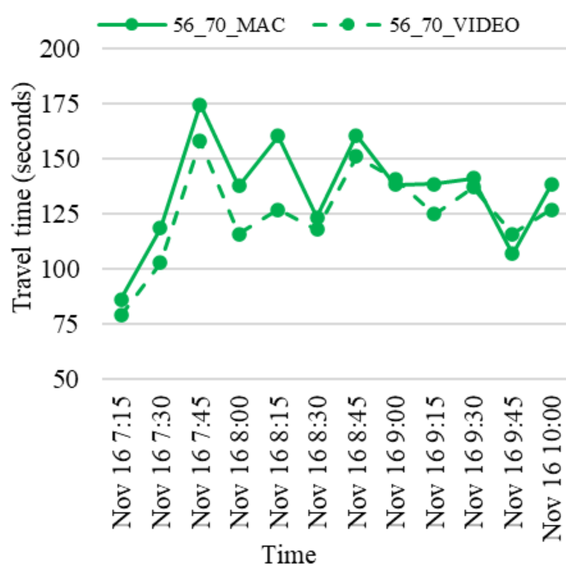
The travel time derived from video observation and MAC matching process was also analyzed for westbound traffic in segments 27_40, 40_56, 56_70, and 70_84 of the Highway 2 testbed. Travel time was measured starting from November 16 during the morning peak period of 7:00 a.m. to 10:00 a.m. Figure 3.5 displays the travel time results obtained through two different methods.



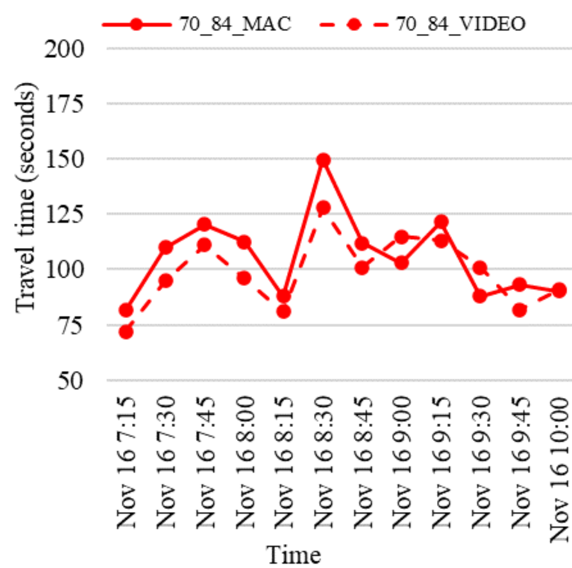
Segment 27_40



Segment 40_56



Segment 56_70



Segment 70_84

Figure 3.5 Comparisons of travel time obtained by MAC matching and manual observation from Highway 2 testbed

The travel timelines in Figure 3.5 show that the video-observed travel time matched the manual observation. Table 3.3 shows the statistical comparisons between the travel time of segments found between MAC matching and video observation.

Table 3.3 Statistical comparisons of MAC matching and video observation for segments from Highway 2 testbed

	Segment 27_40		Segment 40_56		Segment 56_70		Segment 70_84	
	MAC	VIDEO	MAC	VIDEO	MAC	VIDEO	MAC	VIDEO
Mean	121.2	119.3	111.9	106.3	135.4	124.8	105.9	98.8
% Difference	1.7		5.3		8.5		7.1	
P-value (t-test)	0.76		0.45		0.26		0.34	

Table 3.3 shows that there was no statistically significant difference between the mean values of video observation and MAC match methods at a 5% significance level.

Due to the necessity of extracting a substantial amount of travel time samples from Miovision, manual observation throughout the entire analysis period from November to December is not feasible. Therefore, the automatic MAC address-derived travel time data was used as the ground truth travel time for this project. Note that from Chapter 4 and onwards, the travel time data collected using the MAC matching approach from the Highway 2 testbed will be described as ground truth or field observed travel time data when compared to the INRIX data source.

3.4 Research Methodology

As discussed earlier, this project will utilize INRIX as the ITS data source and Miovision Scout devices as the ground truth data source. The INRIX travel time data will be compared with ground truth data using different statistical measures and travel time reliability metrics.

According to the Federal Highway Administration (FHWA, 2017) and other research, the most common travel time reliability (TTR) metrics are travel TTI, PTI, LOTTR, and BI. Including COV, these five TTR metrics are defined by Equations 3.1, 3.2, 3.3, 3.4 and 3.5, respectively.

$$TTI = \frac{T_{mean}}{T_{freeflow}} \tag{3.1}$$

$$PTI = \frac{T_{95}}{T_{freeflow}} \tag{3.2}$$

$$LOTTR = \frac{T_{80}}{T_{50}} \tag{3.3}$$

$$BI = \frac{T_{95} - T_{mean}}{T_{mean}} \tag{3.4}$$

$$COV = \frac{T_{SD}}{T_{mean}} \tag{3.5}$$

Where,

TTI = travel time index

PTI = planning time index

LOTTR = level of travel time reliability

BI = buffer index

COV = coefficient of variation

T_{mean} = mean travel time

$T_{freeflow}$ = travel time at free flow condition

T_{95} = 95th percentile travel time

T_{50} = 50th percentile travel time

T_{SD} = standard deviation of travel time

Note that the travel time distribution will be based on mean travel time aggregated from 15-minute data for both directions of traffic on the Highway 2 testbed. Using the travel time distribution based on 15-minute data samples, the central tendency (e.g., mean and median), dispersion (e.g., standard deviation, interquartile range), and five travel time metrics discussed above will be measured from INRIX and the field observed data source for this project.

The objectives of this comparison are, i) validation of the ITS data, ii) measurement of travel time reliability metrics under Region VII highways for different traffic and weather conditions, and iii) selection of the best reliability metrics.

Chapter 4 Analysis and Validation of Performance Index Under Normal Weather

The goal of this chapter is to analyze and compare the field-observed travel time and corresponding TTR metrics with INRIX based data under normal weather conditions during morning and evening peak hour periods. While it is important to consider non-normal conditions (e.g., inclement weather, work zone, incident, etc.) for the reliability of the transportation system, it is the normal condition that prevails the majority of the time. Therefore, the measurement of travel time reliability under normal conditions, especially during peak hour periods, is equally crucial for operation and planning purposes.

4.1 Travel Time Data Collection Under Normal Weather

The travel time data during the weekdays of November 2021 under normal weather (e.g., no rain and snow) conditions were collected from the Highway 2 testbed along the four segments (i.e., segment 27_40, 40_56, 56_70, and 70_84) for both eastbound (EB) and westbound (WB) directions of traffic. Three hours (7:00 a.m. – 10:00 a.m.) from the morning peak (i.e., AM peak) and three hours (4:00 p.m. – 7:00 p.m.) from the evening peak (i.e., PM peak) were collected during these weekdays. To be specific, for AM peak hour periods, travel time data from November 5, 10, 11, 12, 16, 17 and 18 were used. For PM peak hour periods, travel time data from November 5, 9, 11, 12, 15, 16, 17 and 18 were used. Note that for PM peak hour periods, data from November 10 was not used as it was raining during the afternoon and evening periods. Note that the travel time data are averaged over 15-minute intervals. Both field and INRIX data were collected for the time and days mentioned above.

Furthermore, travel time data with increased segment lengths, 27_40, 27_56, 27_70, and 27_84, was also collected using field and INRIX sources from both directions of traffic. The increase in segment length evaluated whether the change in length of the segment impacted the accuracy of INRIX data compared to the field observed data.

4.2 Analysis and Validation of Travel Time Reliability Under AM Peak Hour Periods

The goal of this section is to compare the travel time from both field and INRIX sources and represent them visually with comparison charts, measuring statistics, and reliability metrics during the AM peak period.

The comparison charts show the change in travel time over time from two data sources. On the other hand, the statistical observation reveals the performance of two sources for the measures of central tendency (e.g., mean and median), dispersion (e.g., standard deviation, interquartile range, cumulative distribution function, boxplots), and reliability metrics (e.g., travel time index, planning time index, level of travel time reliability, buffer index, and coefficient of variation).

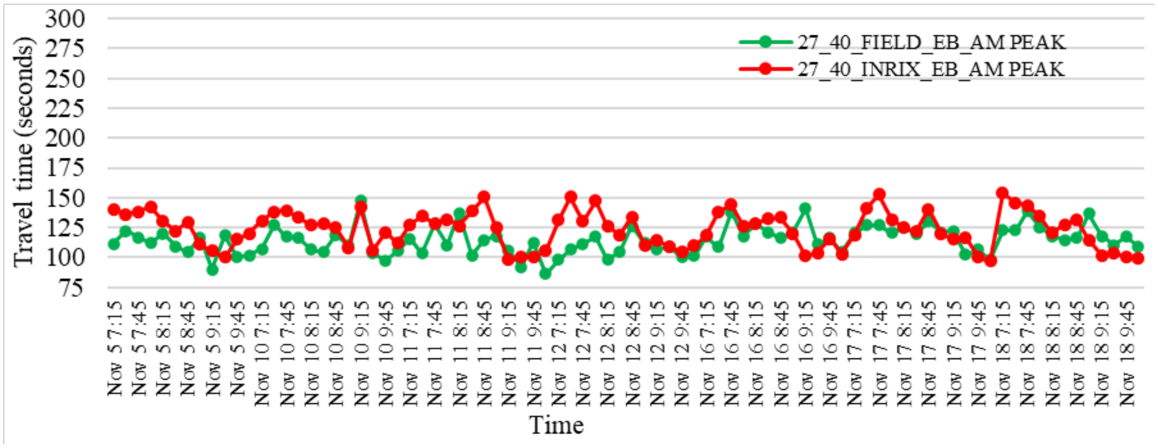
4.2.1 Segment-wise Analysis of AM Peak Hour Periods

The segment-wise analysis refers to the analysis of each segment (i.e., 27_40, 40_56, 56_70, and 70_84) separately. Segment-wise comparison charts, measures of central tendency, dispersion, and reliability metrics during AM peak periods on weekdays are presented below.

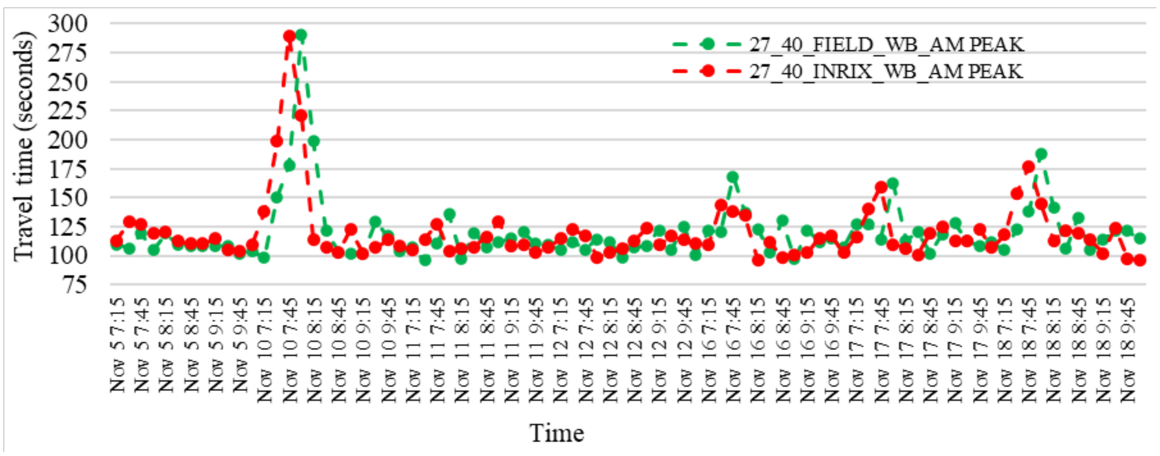
4.2.1.1 Comparison Charts

Figure 4.1 shows the travel time during AM peak hour periods for segment 27_40 for EB direction (Figure 4.1.a), WB direction (Figure 4.1.b), and combination of both directions (Figure 4.1.c) from field and INRIX data sources. The legends of Figure 4.1 denote both directions, data sources, and segment names. For example, the legends of Figure 4.1(a), which are 27_40_FIELD_EB and 27_40_INRIX_EB, represent the travel time of segment 27_40 from EB traffic from the field and INRIX sources, respectively. Note that the travel time for both directions in Figure 4.1(c) is derived from the average travel time of EB and WB direction. For example, the legends of Figure 4.1(c), which are 27_40_FIELD_AVG and 27_40_INRIX_AVG, represent the travel time derived from the average travel times of EB and WB directions for segment 27_40.

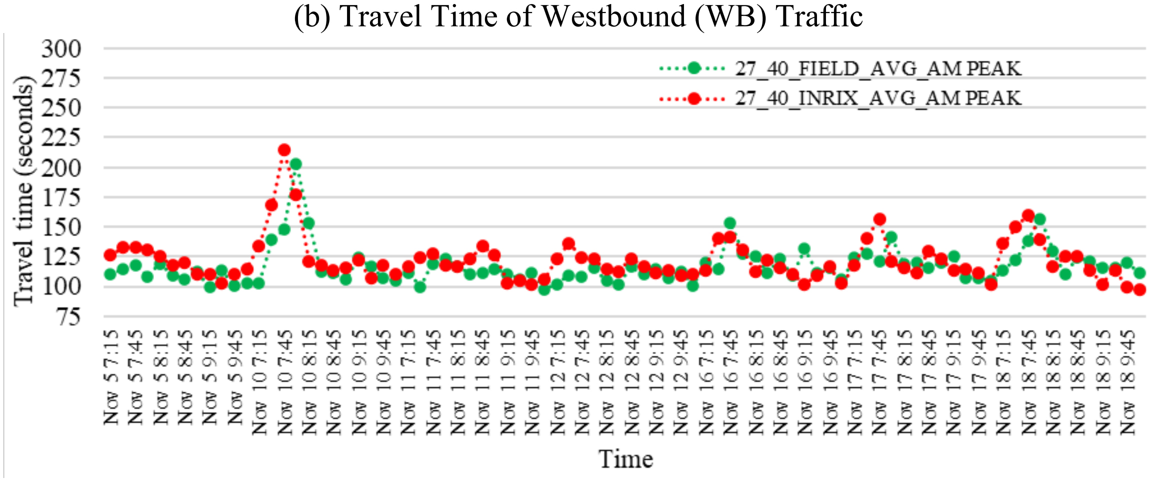
Similarly, Figures 4.2, 4.3, and 4.4 show the travel time comparison between the two sources for segment 40_56, 56_70, and 70_84, respectively.



(a) Travel Time from Eastbound (EB) Traffic

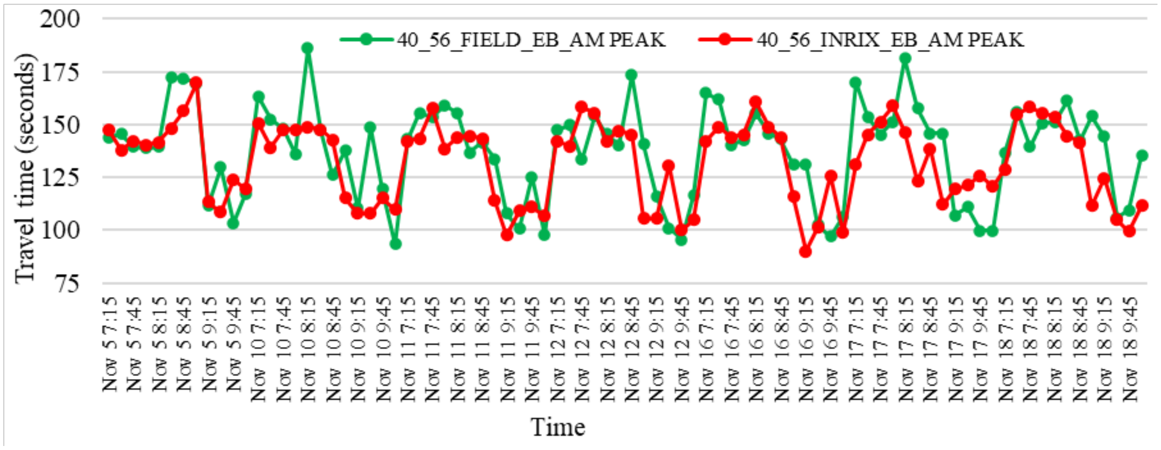


(b) Travel Time of Westbound (WB) Traffic

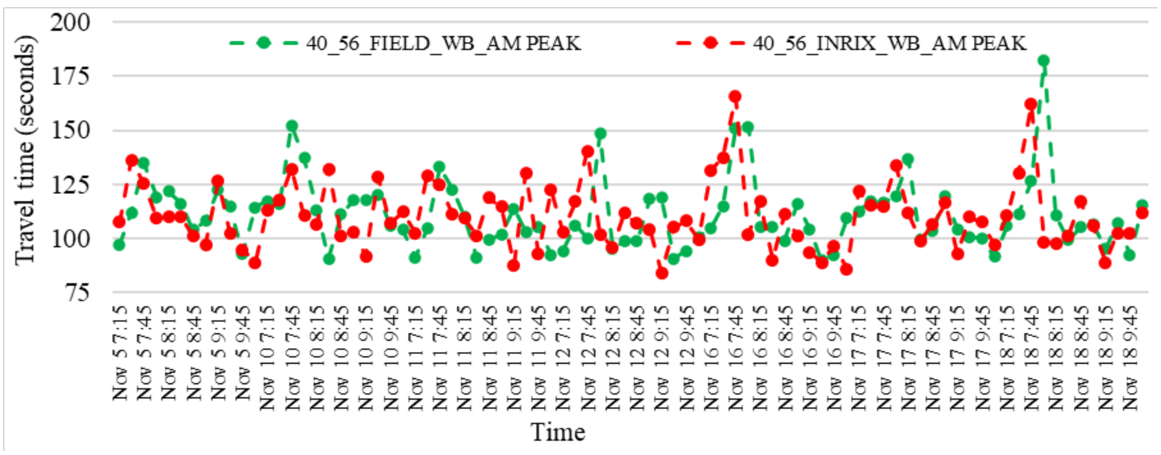


(c) Average Travel Time of EB and WB Traffic

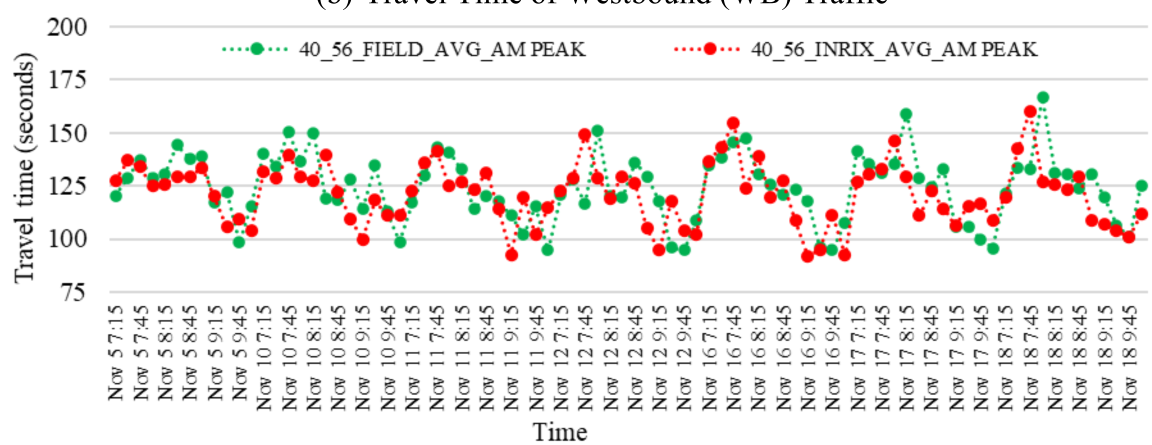
Figure 4.1 Comparisons of travel time for Segment 27_40 during weekday AM peak hours



(a) Travel Time from Eastbound (EB) Traffic

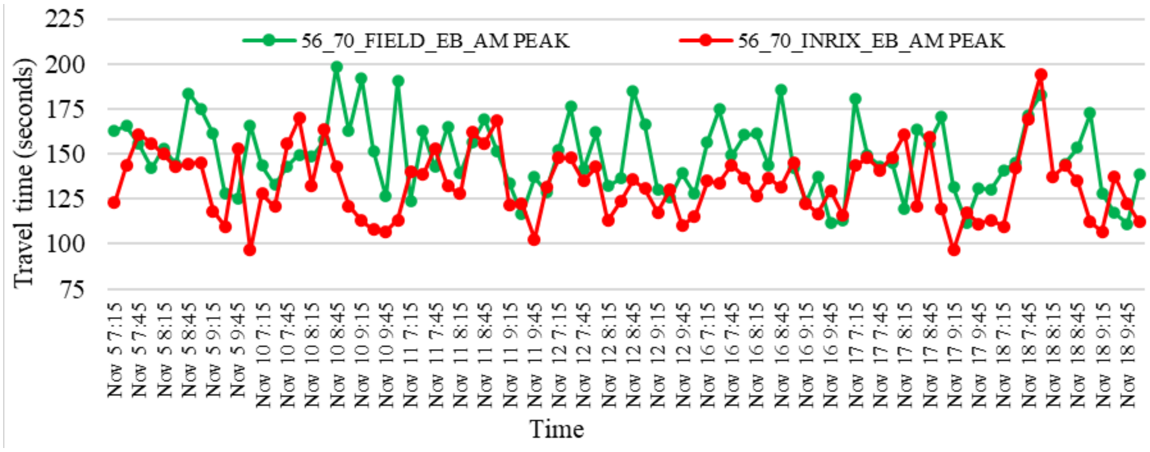


(b) Travel Time of Westbound (WB) Traffic

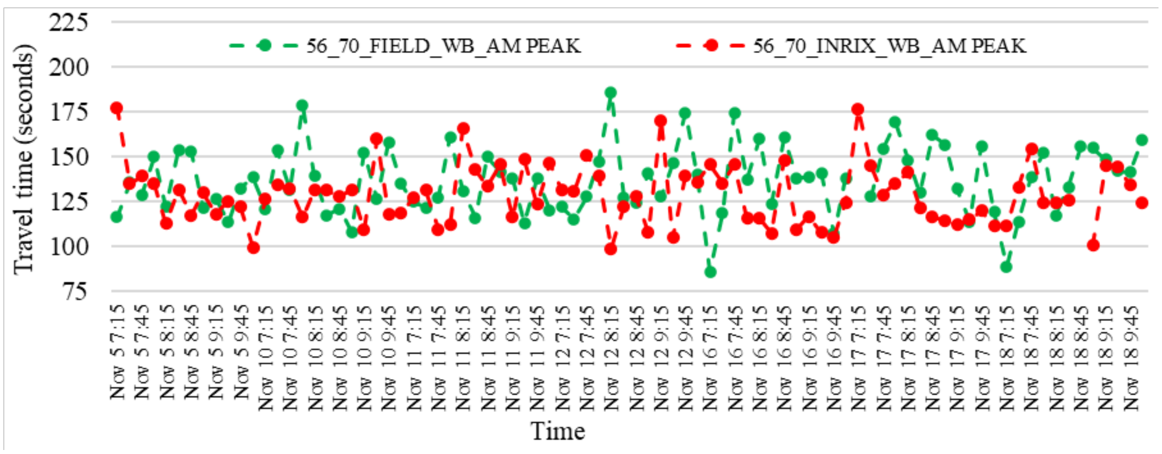


(c) Average Travel Time of EB and WB Traffic

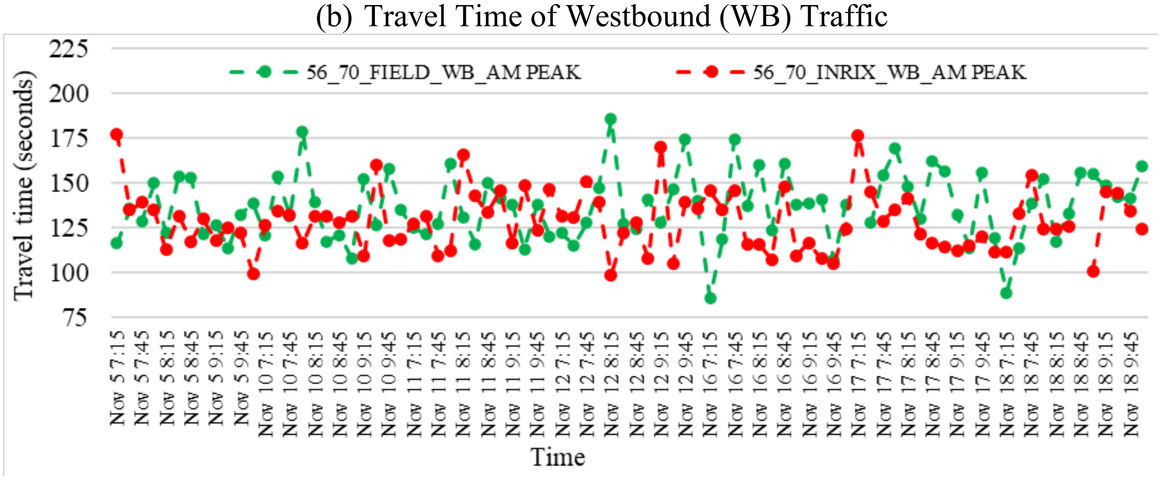
Figure 4.2 Comparisons of travel time for Segment 40_56 during weekday AM peak hours



(a) Travel Time from Eastbound (EB) Traffic

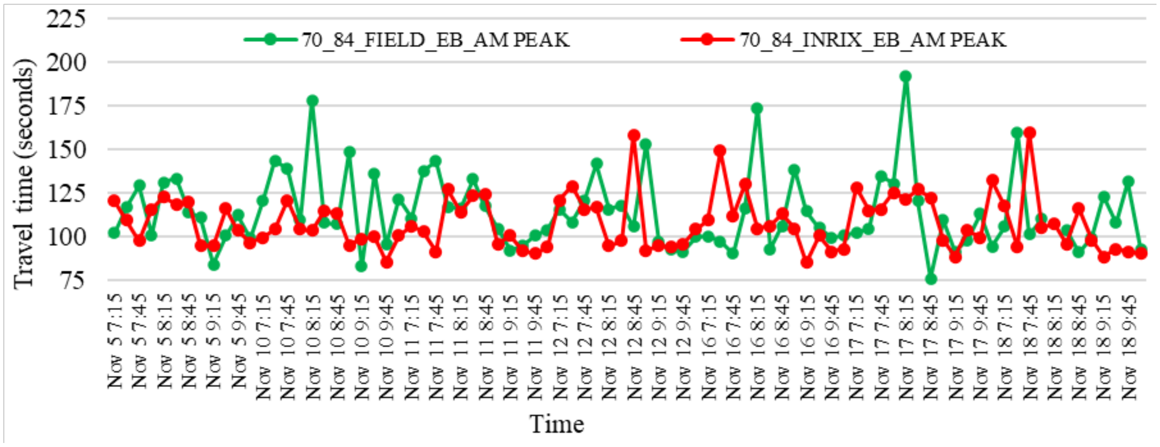


(b) Travel Time of Westbound (WB) Traffic

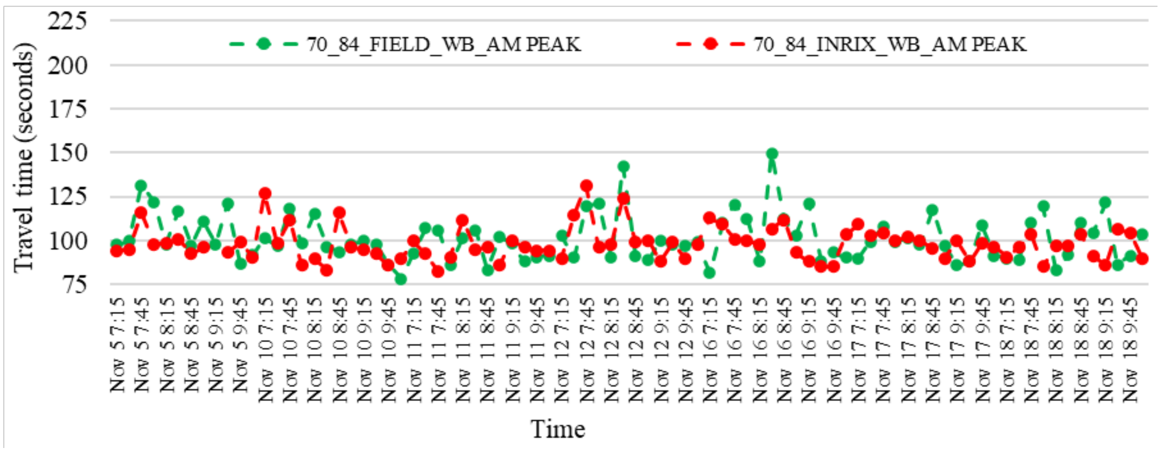


(c) Average Travel Time of EB and WB Traffic

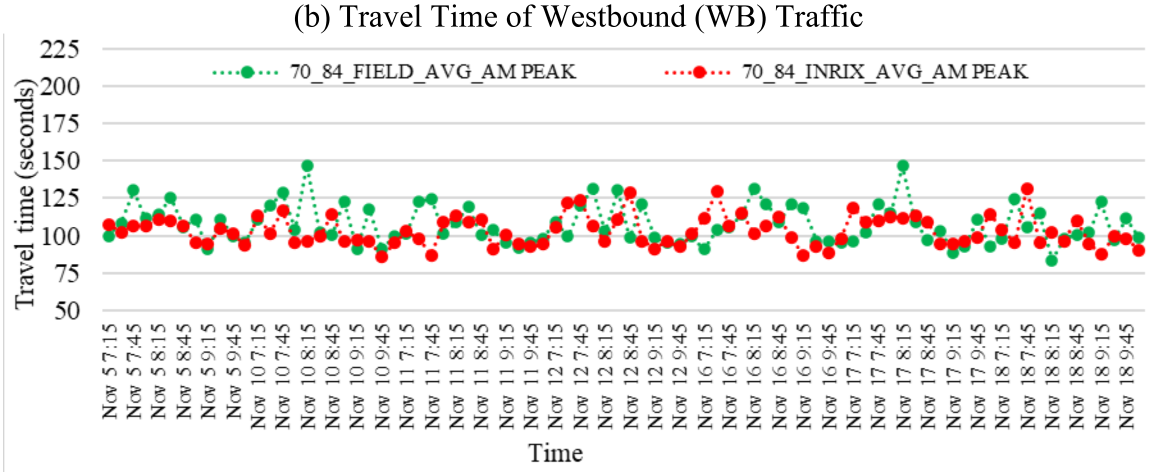
Figure 4.3 Comparisons of travel time for Segment 56_70 during weekday AM peak hours



(a) Travel Time from Eastbound (EB) Traffic



(b) Travel Time of Westbound (WB) Traffic



(c) Average Travel Time of EB and WB Traffic

Figure 4.4 Comparisons of travel time for Segment 70_84 during weekday AM peak hours

In Figures 4.1, 4.2, 4.3, and 4.4, the INRIX's travel time follows the pattern of field observation for EB, WB, and combined directions of traffic. The following sections discuss and compare the statistics and reliability metrics related to travel time during AM peak hour periods.

4.2.1.2 Measures of Central Tendency

Table 4.1 lists the measures of central tendency, which are mean and median, for each segment for both directions of traffic. Note that the length of four segments varies from 1.09 to 1.24 miles, and speed limits vary from 45 to 55 mph. Therefore, the difference in travel time among these segments is expected.

Table 4.1 Measures of central tendency of travel time of four segment during AM peak hours

	Segment 27_40		Segment 40_56		Segment 56_70		Segment 70_84	
	EB	WB	EB	WB	EB	WB	EB	WB
	Mean (seconds)							
Field	114.5	119.8	137.6	110.9	148.9	136.7	114.5	101.2
INRIX	123.6	119.8	132.3	110.3	133.3	128.8	108.1	98.1
% Difference	8.0	0.0	-3.8	-0.6	-10.4	-5.7	-5.6	-3.1
Avg % Difference	3.9		-2.4		-8.2		-4.4	
	Median (seconds)							
Field	116.0	112.0	141.6	106.9	147.0	137.7	109.7	98.1
INRIX	125.4	112.8	140.1	107.7	133.2	127.8	104.4	97.2
% Difference	8.1	0.8	-1.1	0.7	-9.4	-7.2	-4.8	-0.9
Avg % Difference	2.8		-1.7		-7.4		-2.9	

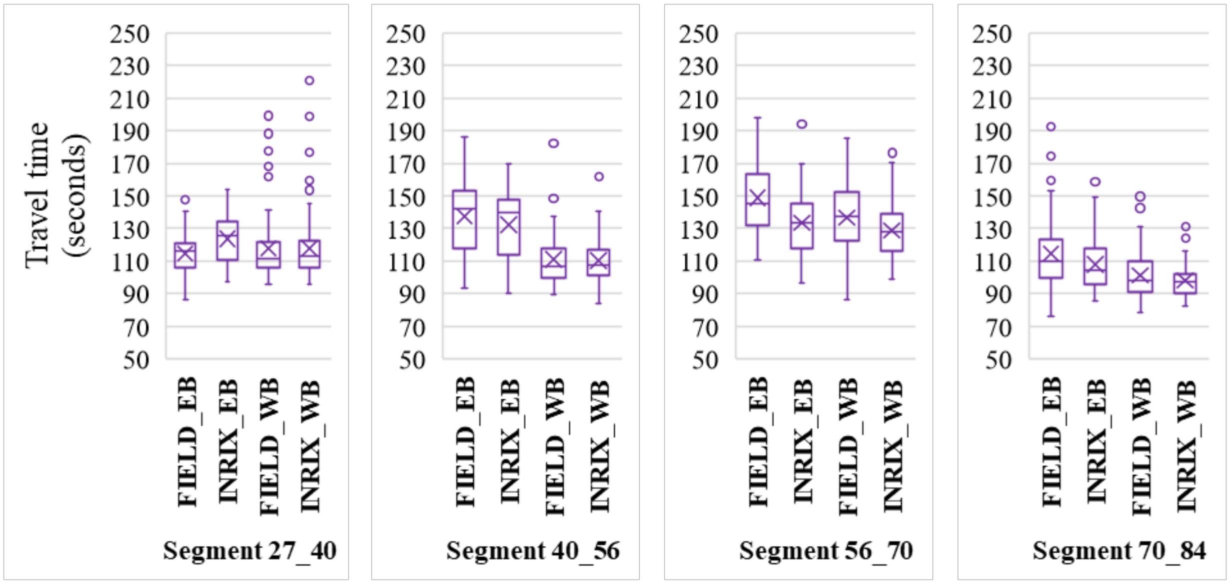
Table 4.1 shows that the mean travel time for segments 27_40, 40_56, 56_70, and 70_84 for EB from field observation was 114.5, 137.6, 148.9, and 114.5 seconds, respectively. In comparison, INRIX travel time was 123.6, 132.3, 133.3, and 108.1 seconds, respectively, for these four segments for EB. Therefore, the percentage (%) difference between field observation and INRIX travel time was 8.0%, -3.8%, -10.4%, and -5.6%, respectively, for EB. The positive percentage difference means that INRIX measured higher travel times than field observation. For WB traffic, the INRIX measured the mean travel time with even more accuracy, which was 0.0%, -0.6%, -5.7%, and -3.1%, respectively. Combining both directions of traffic, for each of

the segments of the testbed, the average (avg) percentage (%) difference was 3.9%, -2.4%, -8.2%, and -4.4%, respectively. This means that INRIX measured the mean travel time with an accuracy of -8.2% to 3.9% for these segments. Therefore, the mean travel time measurements from INRIX were closer to the field observation for four segments during weekday AM peak hour periods.

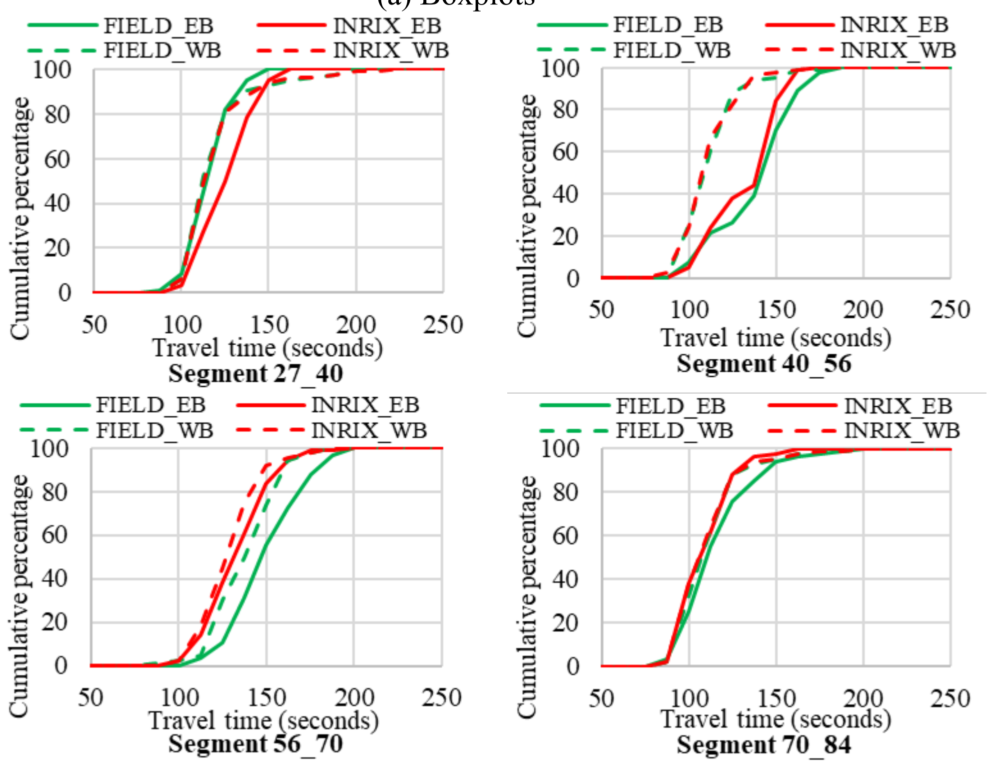
Similarly, Table 4.1 lists the median values. The average percentage difference for median travel time was 2.8%, -1.7%, -7.4%, and -2.9%, respectively, for segment 27_40, 40_56, 56_70, and 70_84. Therefore, similar to the mean, INRIX successfully captured the median travel time value with high accuracy (i.e., from -7.4% to 2.8%).

4.2.1.3 Measures of Dispersion

Figure 4.5 shows standard boxplots and the cumulative distribution function (CDF) of the travel time distribution (TTD) of four segments during AM peak periods for EB and SB direction of traffic from field and INRIX sources. The top, middle, and bottom of each box plot represent the 75th percentile, the median, and the 25th percentile travel time, respectively. The upper and the lower boundaries are 1.5 times the interquartile range (IQR) (e.g., the difference between the 75th and 25th percentile travel times).



(a) Boxplots



(b) CDF

Figure 4.5 Boxplot and CDF of travel time during AM peak hours

These boxplots and CDF charts in Figure 4.5 visually show the distribution characteristics of the travel time for four segments. For example, CDFs from segment 27_40, 40_56, and 70_84 show that TTDs for the field and INRIX from WB match very closely. CDFs for segment 40_56 shows that the TTD for EB traffic (for both field and INRIX sources) appears at the right side of its WB counterpart. Therefore, for most vehicles, the EB direction caused higher travel times for segment 40_56 compared to the WB traffic. Note that INRIX's TTD was able to capture the TTD from field observation for both EB and WB directions of traffic for segment 40_56. On the other hand, CDFs of segment 70_84 show that both directions of traffic had similar TTDs for both field and INRIX data sources.

Table 4.2 lists the measure of dispersion of the travel time distribution quantitatively: it includes standard deviation and interquartile range of field and INRIX travel time data for both EB and WB directions. Table 4.2 shows that the standard deviation of travel times for segments 27_40, 40_56, 56_70, and 70_84 in the EB direction was 11.8, 22.4, 20.7, and 21.6 seconds, respectively, when obtained from field observation. In comparison, INRIX's standard deviation of travel time was 15.1, 19.3, 18.9, and 15.4 seconds, respectively, for these four EB segments. Therefore, the percentage difference of the standard deviation of travel time between field observation and INRIX was 28.7%, -13.8%, -8.7%, and -28.8%, respectively, for the EB direction. For WB traffic, this percentage difference was -2.9%, -4.9%, -8.7%, and -28.6%, respectively. Therefore, INRIX captured standard deviations closer to the field observed standard deviations for WB traffic compared to its EB counterpart. When both directions of traffic are considered, INRIX's accuracy of capturing the standard deviation was 7.0%, -12.7%, -13.2% and -28.1%, respectively, for segments 27_40, 40_56, 56_70 and 70_84.

Table 4.2 Measures of dispersion of travel time during AM peak hours

	Segment 27_40		Segment 40_56		Segment 56_70		Segment 70_84	
	EB	WB	EB	WB	EB	WB	EB	WB
	Standard deviation (seconds)							
Field	11.8	26.9	22.4	16.4	20.7	19.1	21.6	13.5
INRIX	15.1	27.7	19.3	15.6	18.9	16.9	15.4	9.7
% Difference	28.7	2.9	-13.8	-4.9	-8.7	-11.5	-28.8	-28.6
Avg % Difference	7.0		-12.7		-13.2		-28.1	
	Interquartile range (seconds)							
Field	14.6	15.5	33.9	17.5	30.6	29.2	22.4	18.3
INRIX	23.1	15.8	33.3	15.6	26.7	21.3	21.3	10.5
% Difference	57.9	1.9	-1.7	-10.9	-12.7	-26.9	-4.7	-42.7
Avg % Difference	53.0		-7.3		-8.6		-21.6	

Table 4.2 also shows that INRIX measured the interquartile range of travel time of four segments with an accuracy of 53.0%, -7.3%, -8.6%, and -21.6%, respectively. Therefore, the INRIX captured the standard deviation better than the interquartile range for these four segments during morning peak periods of weekdays. However, INRIX captured the central tendency (shown in Table 4.1) with higher accuracy compared to the measure of dispersion during AM peak periods.

4.2.1.4 Travel Time Reliability Index

Table 4.3 analyzes and compares the TTR metric for four segments during weekday AM peak hour periods from field and INRIX data sources. Table 4.3 shows that the TTI values obtained from field observation for EB traffic were 1.48, 1.93, 1.83, and 1.59, respectively, for the four segments. The corresponding INRIX values were 1.60, 1.85, 1.64, and 1.50, respectively. Therefore, INRIX measured the TTI metric with an accuracy of 8.0%, -3.8%, -10.4%, and -5.6%, respectively, for EB traffic. If both directions are combined, INRIX measured the TTI metric with an accuracy of 3.9%, -2.4%, -8.2%, and -4.4%, respectively, for segments 27_40, 40_56, 56_70, and 70_84, respectively.

Table 4.3 Measures of travel time reliability metrics (unitless) during AM peak hours

	Segment 27_40		Segment 40_56		Segment 56_70		Segment 70_84	
	EB	WB	EB	WB	EB	WB	EB	WB
	Travel time index (TTI)							
Field	1.48	1.55	1.93	1.55	1.83	1.68	1.59	1.41
INRIX	1.60	1.55	1.85	1.55	1.64	1.59	1.50	1.36
% Difference	8.0	0.0	-3.8	-0.6	-10.4	-5.7	-5.6	-3.1
Avg % Difference	3.9		-2.4		-8.2		-4.4	
	Planning time index (PTI)							
Field	1.77	2.16	2.41	2.06	2.28	2.08	2.12	1.69
INRIX	1.91	2.05	2.22	1.90	2.01	1.97	1.81	1.61
% Difference	7.6	-5.0	-7.8	-7.5	-11.6	-5.4	-14.9	-4.9
Avg % Difference	6.5		-5.0		-9.3		-11.1	
	Level of travel time reliability (LOTTR)							
Field	1.05	1.12	1.09	1.11	1.13	1.12	1.20	1.14
INRIX	1.10	1.11	1.06	1.13	1.11	1.11	1.16	1.07
% Difference	4.4	-1.7	-3.3	1.8	-1.8	-0.3	-3.5	-6.3
Avg % Difference	5.7		-1.0		-2.4		-1.5	
	Buffer index (BI)							
Field	0.20	0.39	0.25	0.32	0.24	0.23	0.33	0.20
INRIX	0.19	0.32	0.20	0.23	0.23	0.24	0.20	0.18
% Difference	-2.1	-17.8	-20.5	-28.4	-6.6	1.9	-39.4	-11.2
Avg % Difference	14.8		-11.0		-5.9		-28.7	
	Coefficient of Variation (COV)							
Field	0.10	0.22	0.16	0.15	0.14	0.14	0.19	0.13
INRIX	0.12	0.23	0.15	0.14	0.14	0.13	0.14	0.10
% Difference	19.2	2.9	-10.3	-4.4	2.0	-6.1	-24.5	-26.3
Avg % Difference	2.9		-10.6		-5.5		-24.8	

The TTI metric analyzed above is the ratio of mean travel time and free flow travel time. We found that INRIX captured the central tendency of the TTD with relatively higher accuracy compared to the field observation. On the other hand, the free flow travel time is a constant value regardless of the data source used (i.e., field observation or INRIX). Therefore, by observing the central tendency the TTI metric was expected to be captured by INRIX with relatively higher accuracy (i.e., from -8.2% to 3.9%).

In terms of the PTI metric, INRIX captured its value within an accuracy of 6.5%, -5.0%, -9.3%, and -11.1%, respectively, for the four segments. Note that PTI is the ratio of 95th percentile travel time and free flow travel time. Therefore, compared to the TTI metric, PTI measures the dispersion characteristics through the 95th percentile value. The accuracy of the PTI metric measured by INRIX was from -11.1% to 9.3%. This means the range of accuracy of PTI is wider compared to the accuracy of the TTI metric, which was from -8.2% to 3.9%. This comparison reflects that INRIX captured the 95th percentile value of travel time with less accuracy than its mean value. In other words, INRIX captured the central tendency better than the dispersion.

For LOTTR, the accuracy of INRIX, compared to field observation, was 5.7%, -1.0%, -2.4%, and -1.5%, respectively. Note that LOTTR is the ratio of the 80th and 50th percentile travel time. Therefore, LOTTR is the ratio of dispersion and central tendency characteristics from the TTD. Compared to the PTI and TTI, the accuracy of the LOTTR metric (i.e., from -1.5% to 5.7%) measured by INRIX is higher.

For the rest of the two TTR metrics, BI and COV, INRIX accuracy was lower than the three metrics described above. The average percentage difference of INRIX's BI metric was 14.8%, -11.0%, -5.9%, and -28.7%, respectively, for segment 27_40, 40_56, 56_70, and 70_84, respectively. For COV, the average percentage difference was 2.9%, -10.6%, -5.5%, and -24.8%, respectively. Therefore, the accuracy of INRIX's BI and COV measurements lies from -28.7% to 14.8%, and from -24.8% to 2.9%, respectively.

Note that INRIX measured all five TTR metrics lower than the field observation (for two directions combined) for all segments except for 27_40 during AM peak hour periods. A lower value of the TTR metric means higher reliability. Therefore, except for segment 27_40, INRIX found that travel along the other segments of the Highway 2 testbed is more reliable during AM peak periods of weekdays.

Notably, among all five TTR metrics, INRIX measured the LOTTR most accurately compared to the field observed values. On the other hand, BI was the least accurately measured during AM peak periods of weekdays by INRIX.

4.2.2 Incremental Segment-wise Analysis of AM Peak Hour Periods

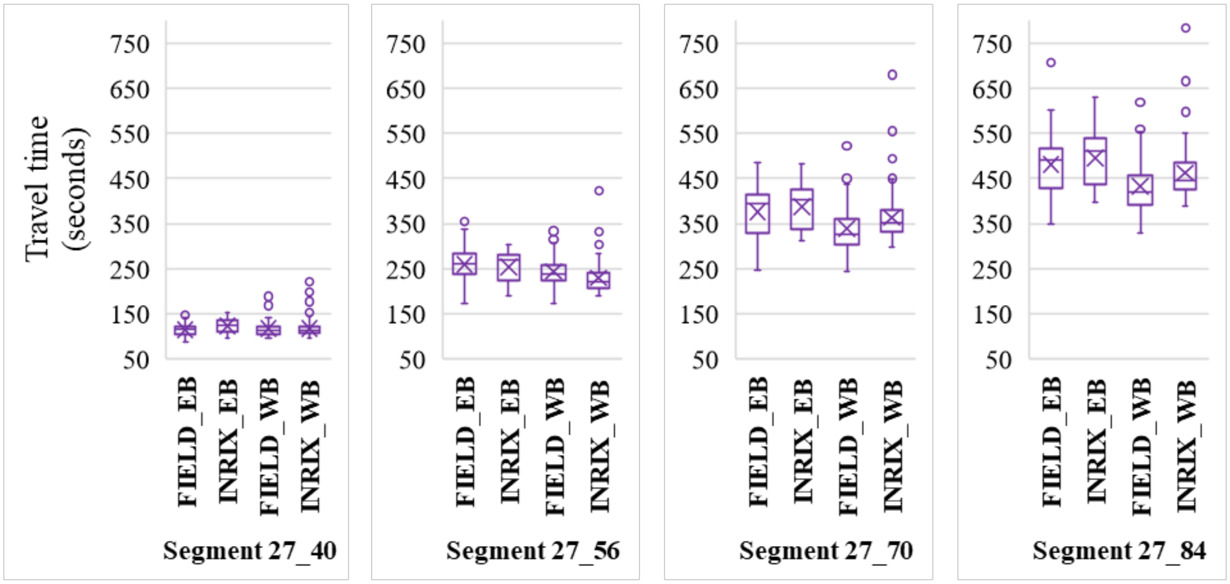
This section analyzes and compares travel time statistics when the segment length increases. Segments 27_40, 27_56, 27_70, and 27_84, which have the incremental length of 1.18, 2.27, 3.51, and 4.71 miles, respectively, were analyzed for weekday AM peak periods. The longest segment, 27_84, analyzes the entire corridor under AM peak periods.

Table 4.4 shows the mean and median values of the incremental segment for EB and WB traffic and the average value from both directions obtained from field observation (i.e., Avg Field) and the INRIX source (i.e., Avg INRIX). Table 4.4 shows that, as expected, the mean and median travel time for the incremental segments increased as the segment size got larger for both field and INRIX data sources. The mean travel time from field observation for segments 27_40, 27_56, 27_70, and 27_84 for both directions combined was 117.1, 243.4, 355.7, and 456.9 seconds, respectively. In comparison, INRIX's mean travel time was 121.7, 242.1, 375.1, and 473.0 seconds, respectively, for the four segments. Therefore, INRIX captured the increase of travel time along with bigger segments. The percentage difference of mean travel time between field observation and INRIX was 3.9%, -0.5%, 5.4%, and 4.8%, respectively. Similarly, INRIX was able to capture the median travel time with a precision of 2.8%, -2.8%, 5.7%, and 2.9%, respectively for segments 27_40, 27_56, 27_70, and 27_84.

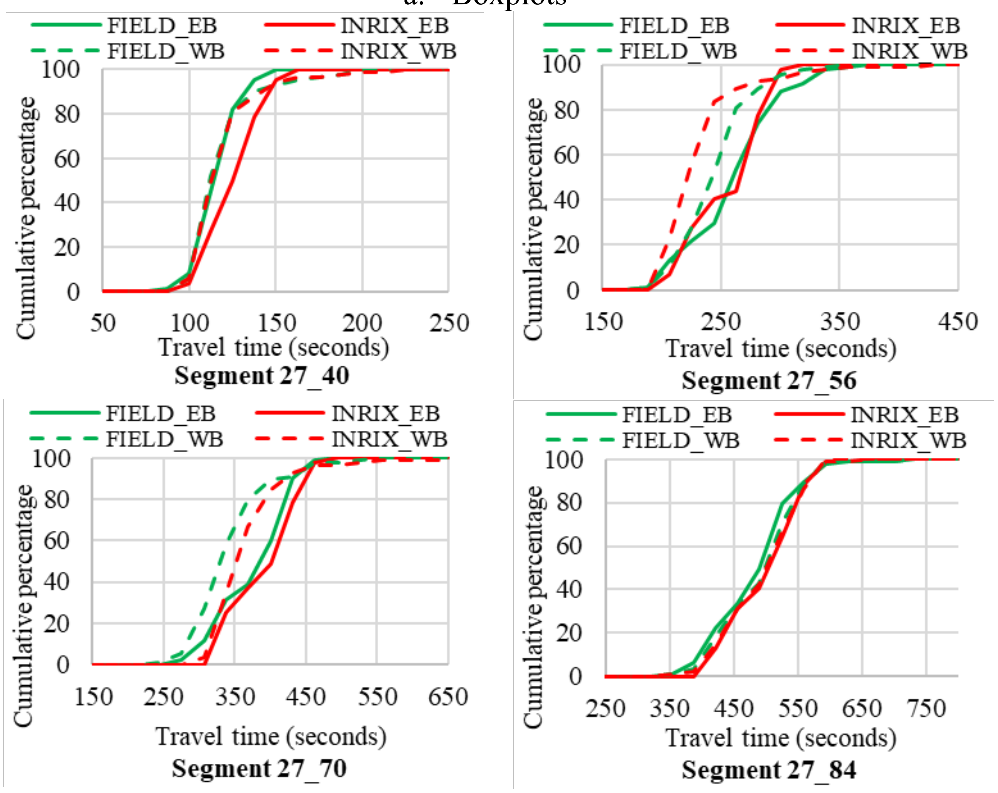
Table 4.4 Measures of central tendency of travel time of incremental segment during AM peak hours

	Segment 27_40		Segment 27_56		Segment 27_70		Segment 27_84	
	EB	WB	EB	WB	EB	WB	EB	WB
	Mean (seconds)							
Field	114.5	119.8	258.6	228.2	375.3	336.0	481.4	431.7
Avg Field	117.1		243.4		355.7		456.9	
INRIX	123.6	119.8	254.2	230.1	387.5	362.7	495.6	462.5
Avg INRIX	121.7		242.1		375.1		479.0	
% Difference	8.0	0.0	-1.7	0.8	3.3	7.9	3.0	7.1
Avg % Difference	3.9		-0.5		5.4		4.8	
	Median (seconds)							
Field	116.0	112.0	261.5	218.3	393.0	324.7	462.6	418.3
Avg Field	114.1		242.9		345.0		449.8	
INRIX	125.4	112.8	268.5	221.7	403.2	350.7	510.6	446.4
Avg INRIX	117.3		236.1		364.5		462.6	
% Difference	8.1	0.8	2.7	1.6	2.6	8.0	10.4	6.7
Avg % Difference	2.8		-2.8		5.7		2.9	

INRIX measured both mean and median travel time values for the four incremental segments with an accuracy of -0.5% to 5.7% for weekday AM peak periods. Note that for individual segments, this accuracy was -8.2% to 3.9%. Therefore, the increase in the length of the segment did not impact the accuracy of INRIX's central tendency of travel time distribution measurements for AM peak period traffic during weekdays.



a. Boxplots



b. CDF

Figure 4.6 Boxplot and CDF of travel time of incremental segment during AM peak hours

Figure 4.6 shows standard boxplots and CDF charts of TTD of four incremental segments during AM peak periods. As expected, boxplots shift to higher positions in their respective y-axis as the length of the segment increases from segments 27_40 to 27_84. Similarly, the CDFs from segments 27_40 to 27_84 shifted to the right on the x-axis to indicate the increase of travel time with incremental segment length. The figure shows TTD obtained using field observed data and using INRIX travel time data most closely match for segments 27_84, i.e., the entire corridor, for both directions of traffic, compared to other shorter incremental segments. However, quantitative statistics are required to verify this observation.

Table 4.5 lists quantitative information on the measures of dispersion of TTD for the incremental segment during AM peak periods. It shows that the average field standard deviation of travel time for segments 27_40, 27_56, 27_70, and 27_84 was 20.9, 43.4, 58.5, and 68.2 seconds, respectively. Note that as the length of segment increased, so did the standard deviation values in field observation. Similarly, INRIX's measurement of average standard deviation increases with segment length, which was 22.3, 36.1, 52.3, and 60.6 seconds, respectively. Therefore, the percentage difference between field observation and INRIX standard deviation was 7.0%, -16.7%, -10.5%, and -11.2%, respectively, for four incremental segments.

Table 4.5 Measures of dispersion of travel time of incremental segment during AM peak hours

	Segment 27_40		Segment 27_56		Segment 27_70		Segment 27_84	
	EB	WB	EB	WB	EB	WB	EB	WB
	Standard deviation (seconds)							
Field	11.8	26.9	40.1	41.3	52.2	58.2	64.4	63.1
Avg Field	20.9		43.4		58.5		68.2	
INRIX	15.1	27.7	31.6	36.5	45.9	55.6	55.8	61.1
Avg INRIX	22.3		36.1		52.3		60.6	
% Difference	28.7	2.9	-21.1	-11.7	-12.0	-4.4	-13.4	-3.2
Avg % Difference	7.0		-16.7		-10.5		-11.2	
	Interquartile range (seconds)							
Field	14.6	15.5	43.9	43.9	83.8	55.4	84.5	65.2
Avg Field	15.1		59.9		88.9		106.3	
INRIX	23.1	15.8	54.8	32.7	82.7	46.1	102.3	59.1
Avg INRIX	23.1		58.8		75.2		91.4	
% Difference	57.9	1.9	24.6	-25.6	-1.3	-16.8	21.1	-9.4
Avg % Difference	53.0		-1.8		-15.5		-14.0	

Similar to the pattern of standard deviation, the interquartile range found from both field observation and INRIX increased as the length of segment increased. The average percentage difference of INRIX's interquartile range was within -14.0% to 53.0% for the four incremental segments compared to the field observation.

Table 4.6 lists different TTR metrics of four incremental segments during AM peak periods. This table shows that the field observed value of the TTI metric for both directions combined was 1.52, 1.56, 1.50, and 1.48 respectively, for the four incremental segments. The INRIX value of TTI was 1.58, 1.56, 1.58, and 1.55, respectively. Therefore, INRIX measured the TTI with an accuracy of 3.9%, -0.5%, 5.4%, and 4.8%, respectively, compared to the field observation. The accuracy of the INRIX measurement for the PTI metric was 6.5%, -8.2%, 1.0% and 0.4%, respectively. On the other hand, for LOTTR, INRIX's accuracy was 5.7%, 4.3%, -3.5%, and 0.4%, respectively, for four incremental segments.

For the BI and COV metrics, INRIX's accuracy was lower than the three metrics described above. The average percentage difference of INRIX's BI measurement was 14.8%, -31.1%, -21.4%, and -22.1%, respectively, for segments 27_40, 27_56, 27_70, and 27_84. For COV, the average percentage difference was 2.9%, -16.2, -15.1% and -15.3%, respectively.

Table 4.6 Measures of travel time reliability metrics (unitless) during AM peak hours

	Segment 27_40		Segment 27_56		Segment 27_70		Segment 27_84	
	EB	WB	EB	WB	EB	WB	EB	WB
Travel time index (TTI)								
Field	1.48	1.55	1.66	1.47	1.58	1.42	1.56	1.40
Avg Field	1.52		1.56		1.50		1.48	
INRIX	1.60	1.55	1.63	1.48	1.63	1.53	1.61	1.50
Avg INRIX	1.58		1.56		1.58		1.55	
% Difference	8.0	0.0	-1.7	0.8	3.3	7.9	3.0	7.1
Avg % Difference	3.9		-0.5		5.4		4.8	
Planning time index (PTI)								
Field	1.77	2.16	2.08	1.86	1.87	1.85	1.84	1.80
Avg Field	1.83		2.08		1.87		1.83	
INRIX	1.91	2.05	1.87	1.93	1.87	1.89	1.84	1.78
Avg INRIX	1.95		1.91		1.89		1.84	
% Difference	7.6	-5.0	-9.9	3.7	0.1	2.5	0.2	-0.9
Avg % Difference	6.5		-8.2		1.0		0.4	
Level of travel time reliability (LOTTR)								
Field	1.05	1.12	1.11	1.13	1.06	1.13	1.14	1.11
Avg Field	1.08		1.12		1.18		1.14	
INRIX	1.10	1.11	1.05	1.10	1.07	1.11	1.07	1.10
Avg INRIX	1.14		1.17		1.14		1.15	
% Difference	4.4	-1.7	-5.1	-3.3	0.7	-1.9	-5.5	-0.5
Avg % Difference	5.7		4.3		-3.5		0.4	
Buffer index (BI)								
Field	0.20	0.39	0.25	0.27	0.18	0.30	0.18	0.29
Avg Field	0.21		0.33		0.25		0.24	
INRIX	0.19	0.32	0.15	0.31	0.15	0.24	0.15	0.19
Avg INRIX	0.24		0.23		0.19		0.18	
% Difference	-2.1	-17.8	-41.6	13.5	-20.0	-21.6	-17.7	-33.8
Avg % Difference	14.8		-31.1		-21.4		-22.1	
Coefficient of variation (COV)								
Field	0.10	0.22	0.16	0.18	0.14	0.17	0.13	0.15
Avg Field	0.18		0.18		0.16		0.15	
INRIX	0.12	0.23	0.12	0.16	0.12	0.15	0.11	0.13
Avg INRIX	0.18		0.15		0.14		0.13	
% Difference	19.2	2.9	-19.8	-12.4	-14.8	-11.5	-15.9	-9.6
Avg % Difference	2.9		-16.2		-15.1		-15.3	

Note that from the analysis of four individual segments from Table 4.3, the range of INRIX's accuracy to measure the TTI, PTI, LOTTR, BI, and COV metrics was -8.2% to 3.9%, -11.1% to 6.5%, -2.4% to 5.7%, -28.7% to 14.8%, and -24.8% to 2.9%, respectively. For the four incremental segments shown in Table 4.5, the accuracy of INRIX was -0.5% to 5.4%, -8.2% to 6.5%, -3.5% to 5.7%, -31.1% to 14.8%, and -16.2% to 2.9%, respectively. Therefore, for the traffic observed from AM peak periods, the incremental segment did not substantially impact the accuracy of INRIX's TTR metric measurement, except for COV, compared to those from individual segments. The range of accuracy of INRIX to measure COV was shorter, meaning higher accuracy, for incremental segments. Therefore, regardless of individual or incremental segments from AM peak period traffic, INRIX captured the PTI, TTI, and LOTTR metrics with the most precision, whereas, BI and COV were captured with less precision.

Note that segment 27_84 represents the corridor of the Highway 2 testbed (i.e., corridor 27_84). It was found that INRIX was able to measure the mean, median, standard deviation, and interquartile range of observed travel time with an accuracy of 4.8%, 2.9%, -11.2%, and -14.0%, respectively.

In terms of the TTR metric, for corridor 27_84, INRIX produced values of PTI, TTI, LOTTR, BI, and COV as 1.55, 1.84, 1.15, 0.18, and 0.13 against field observed value of 1.48, 1.83, 1.14, 0.24 and 0.15, respectively. Therefore, the accuracy of INRIX for the five TTR metrics becomes 4.8%, 0.4%, 0.4%, -22.1%, and -15.3%, respectively.

It can be seen that answering a question of how reliable travel is in AM peak periods depends on which TTR metric is used. Note that LOTTR is used as one of the key mobility indicators recommended in the MAP-21 Act (FHWA, 2012) and the FAST Act (FHWA, 2015) to assess the performance of national highways in the US. Based on field observed or INRIX data from AM peak periods, using the LOTTR metric will mean that corridor 27_84 is more reliable compared to the use of PTI or TTI.

4.3 Validation of Travel Time Reliability Under PM Peak Hour Periods

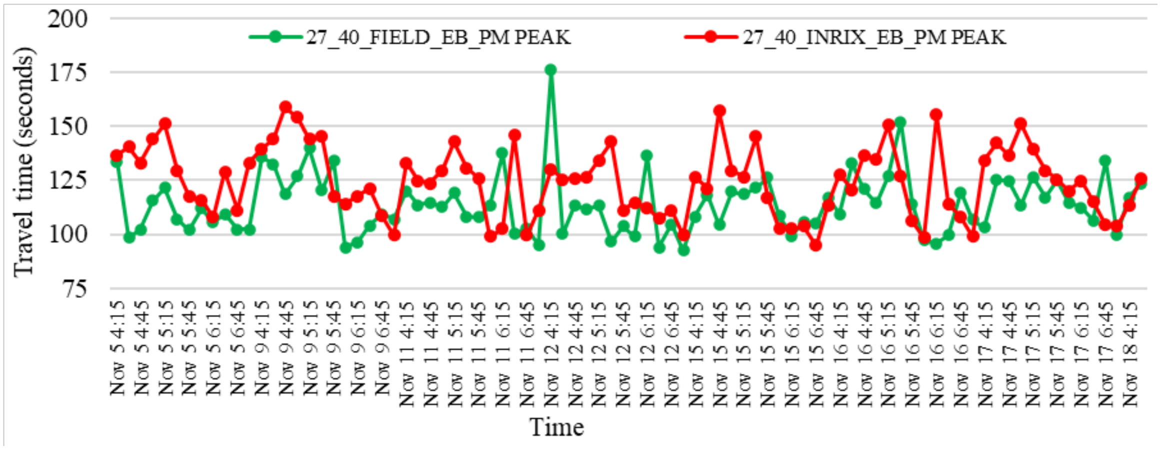
The goal of this section is to compare the travel time from both field and INRIX sources with visual representation by comparison charts and measuring statistics and reliability metrics during PM peak periods.

4.3.1 Segment-wise Analysis of PM Peak Hour Periods

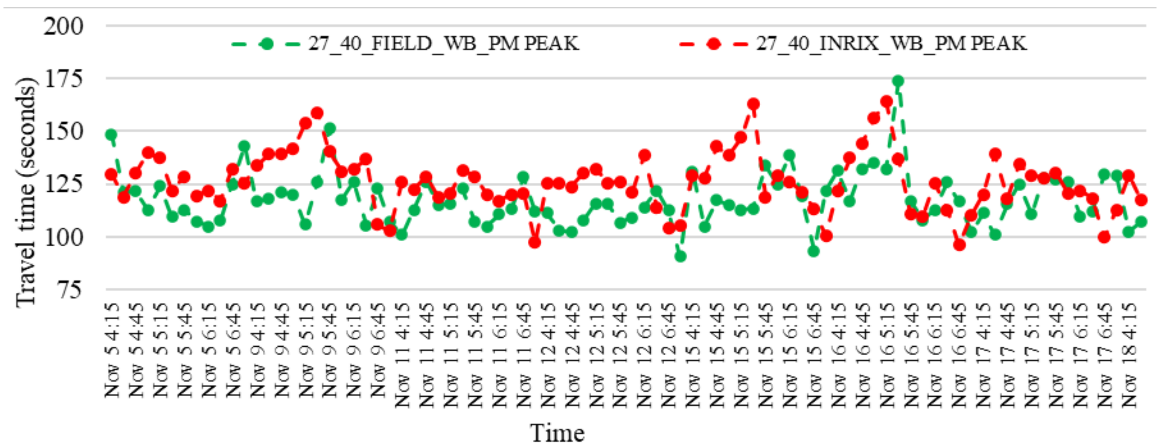
Segment-wise comparison charts, measures of central tendency, dispersion and reliability metrics during PM peak periods on weekdays are presented below.

4.3.1.1 Comparisons Charts

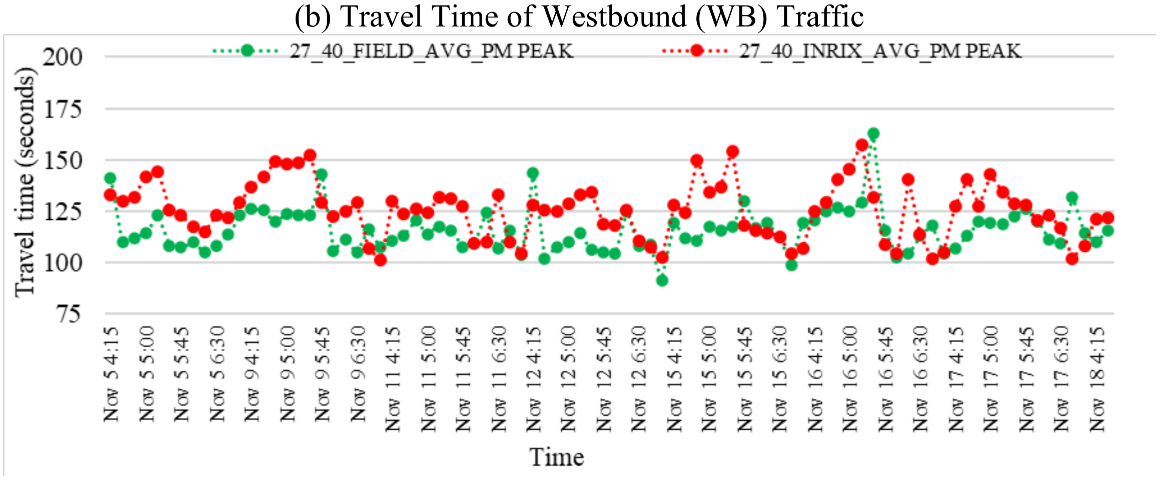
Figure 4.7 shows the travel time during PM peaks for segment 27_40 for EB, WB, and combination of both directions from field and INRIX data sources. Similarly, Figures 4.8, 4.9, and 4.10 show the travel time comparison between the two sources for segment 40_56, 56_70, and 70_84, respectively.



(a) Travel Time from Eastbound (EB) Traffic

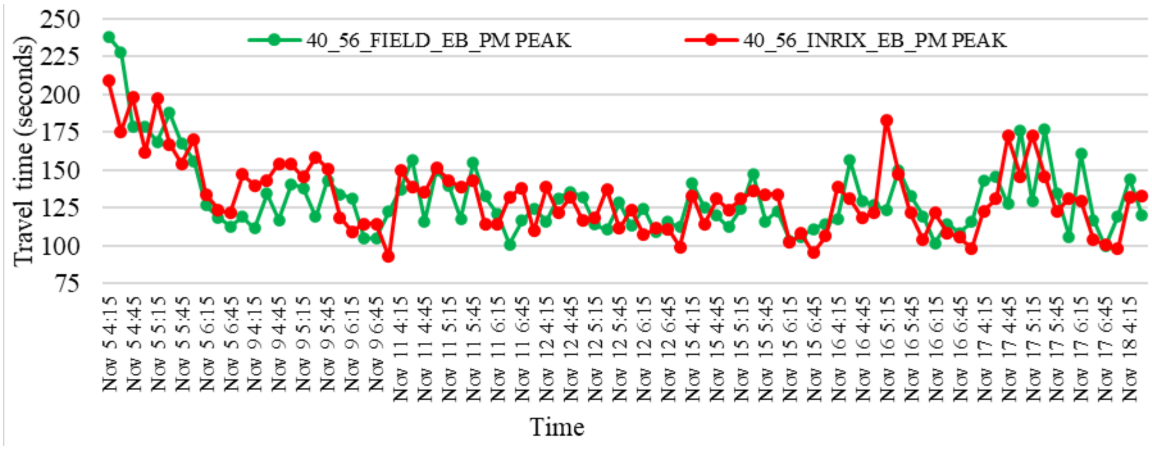


(b) Travel Time of Westbound (WB) Traffic

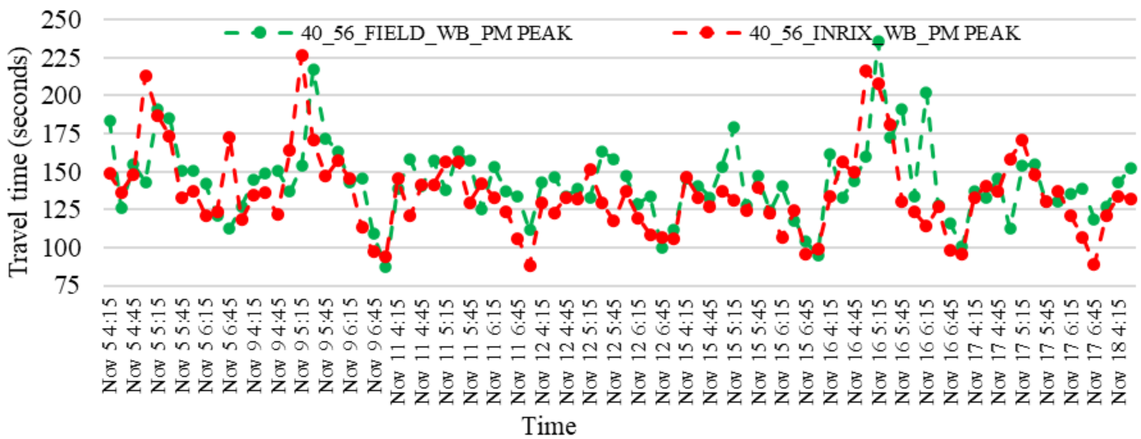


(c) Average Travel Time of EB and WB Traffic

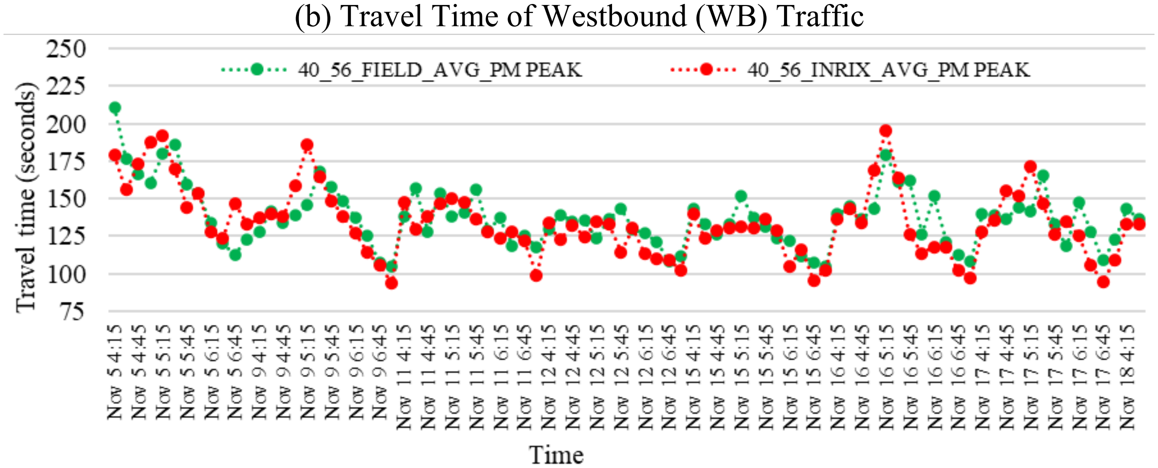
Figure 4.7 Comparisons of travel time for Segment 27_40 during weekday PM peak hours



(a) Travel Time from Eastbound (EB) Traffic

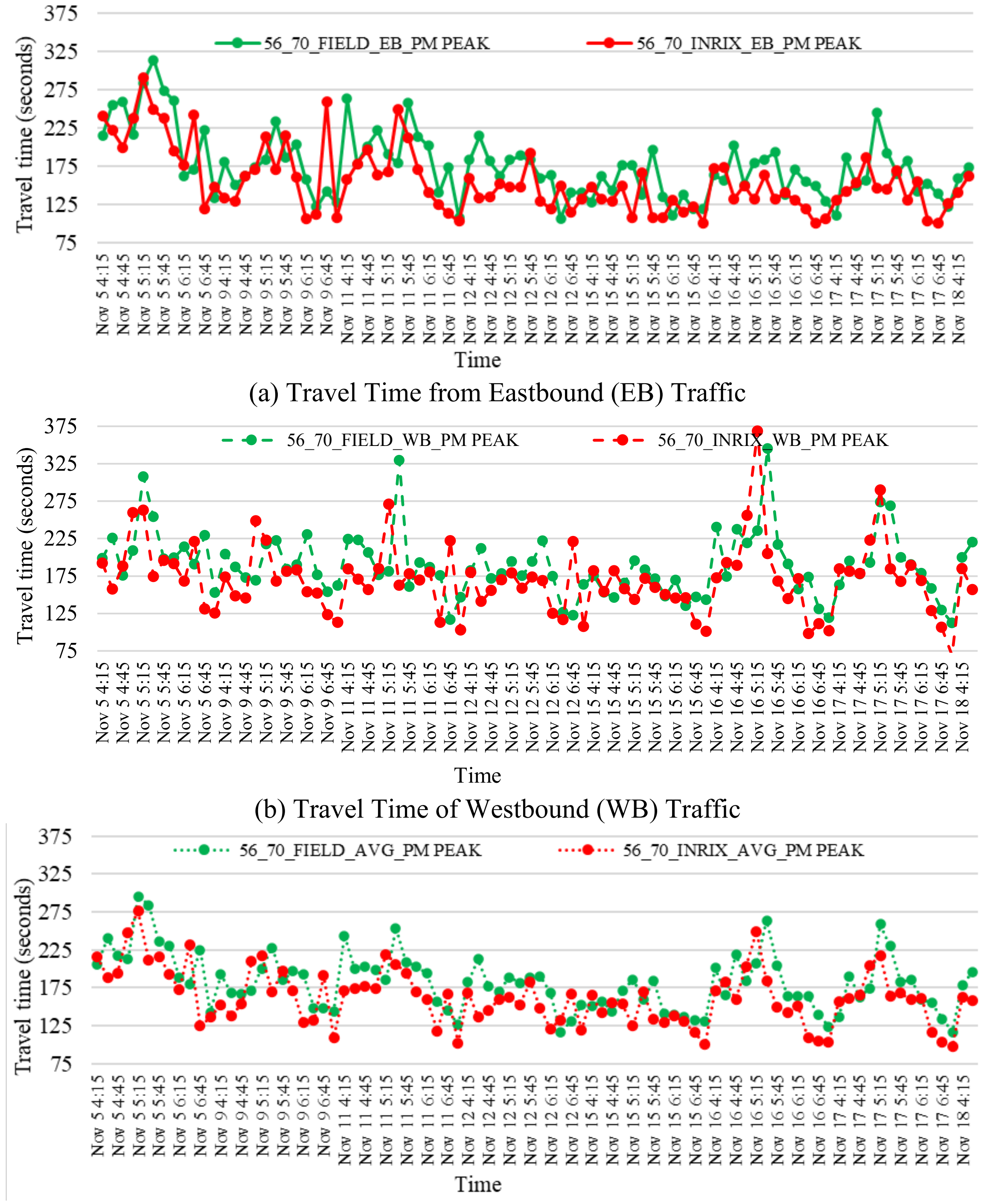


(b) Travel Time of Westbound (WB) Traffic



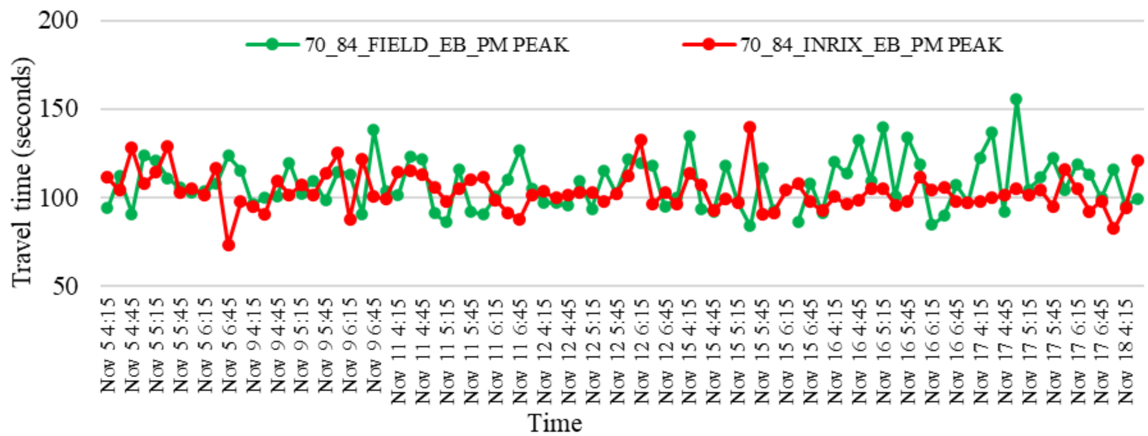
(c) Average Travel Time of EB and WB Traffic

Figure 4.8 Comparisons of travel time for Segment 40_56 during weekday PM peak hours

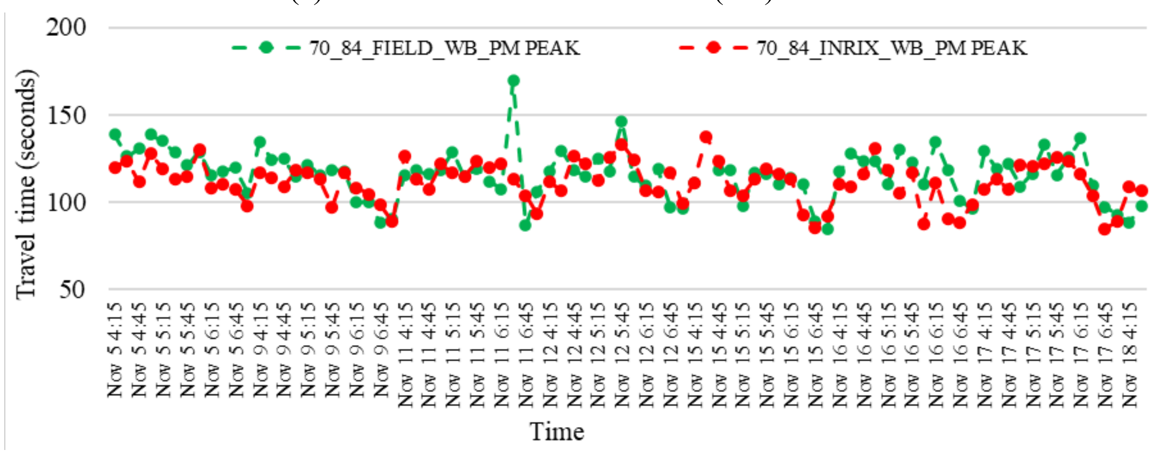


(c) Average Travel Time of EB and WB Traffic

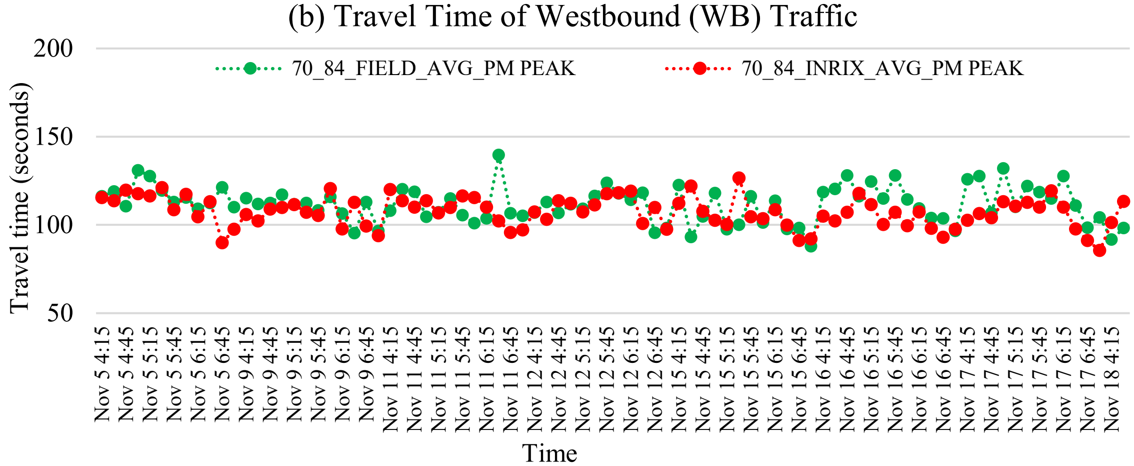
Figure 4.9 Comparisons of travel time for Segment 56_70 during weekday AM peak hours



(a) Travel Time from Eastbound (EB) Traffic



(b) Travel Time of Westbound (WB) Traffic



(c) Average Travel Time of EB and WB Traffic

Figure 4.10 Comparisons of travel time for Segment 70_84 during weekday PM peak hours

From Figures 4.7, 4.8, 4.9, and 4.10, it can be seen that the INRIX's travel time follows the pattern of field observation for EB, WB, and combined directions of traffic. The following sections discuss and compare the statistics and reliability metrics related to travel time during PM peak hour periods.

4.3.1.2 Measures of Central Tendency

Table 4.7 shows that the mean travel time EB for segments 27_40, 40_56, 56_70, and 70_84 obtained from field observation was 114.4, 131.4, 174.1, and 108.2 seconds, respectively. In comparison, INRIX travel time was 124.1, 131.0, 154.1, and 103.6 seconds, respectively, for these four EB segments. Therefore, the percentage difference between field observation and INRIX travel time was 8.5%, -0.3%, -11.5%, and -4.2%, respectively. For WB traffic, the INRIX measured the mean travel time with an accuracy of -6.6%, -4.4%, -10.3%, and -3.6%, respectively. Combining both directions of traffic, for each of the segments of the testbed, the average percentage difference was 7.6%, -2.5%, -10.9%, and -3.9%, respectively. This means that INRIX measured the mean travel time with an accuracy of -3.9% to 7.6% for these segments. Therefore, the mean travel time measurements from INRIX were closer to the field observation for four segments during weekday PM peak periods.

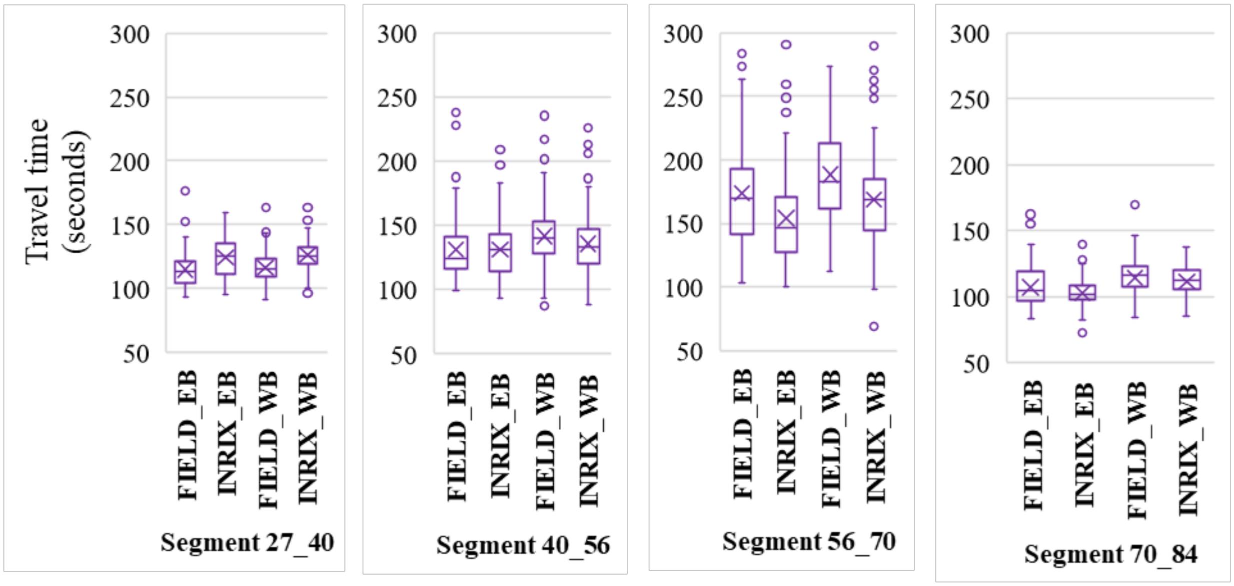
Table 4.7 Measures of central tendency of travel time of four segment during PM peak hours

	Segment 27_40		Segment 40_56		Segment 56_70		Segment 70_84	
	EB	WB	EB	WB	EB	WB	EB	WB
	Mean (seconds)							
Field	114.4	118.1	131.4	141.9	174.1	188.5	108.2	115.2
INRIX	124.1	125.9	131.0	135.6	154.1	169.0	103.6	111.1
% Difference	8.5	6.6	-0.3	-4.4	-11.5	-10.3	-4.2	-3.6
Avg % Difference	7.6		-2.5		-10.9		-3.9	
	Median (seconds)							
Field	113.2	116.4	124.5	140.3	170.3	182.6	105.2	116.7
INRIX	125.4	125.4	130.8	133.2	146.4	168.9	102.0	112.5
% Difference	10.8	7.8	5.1	-5.0	-14.0	-7.5	-4.2	-3.6
Avg % Difference	9.2		-1.4		-10.8		-6.4	

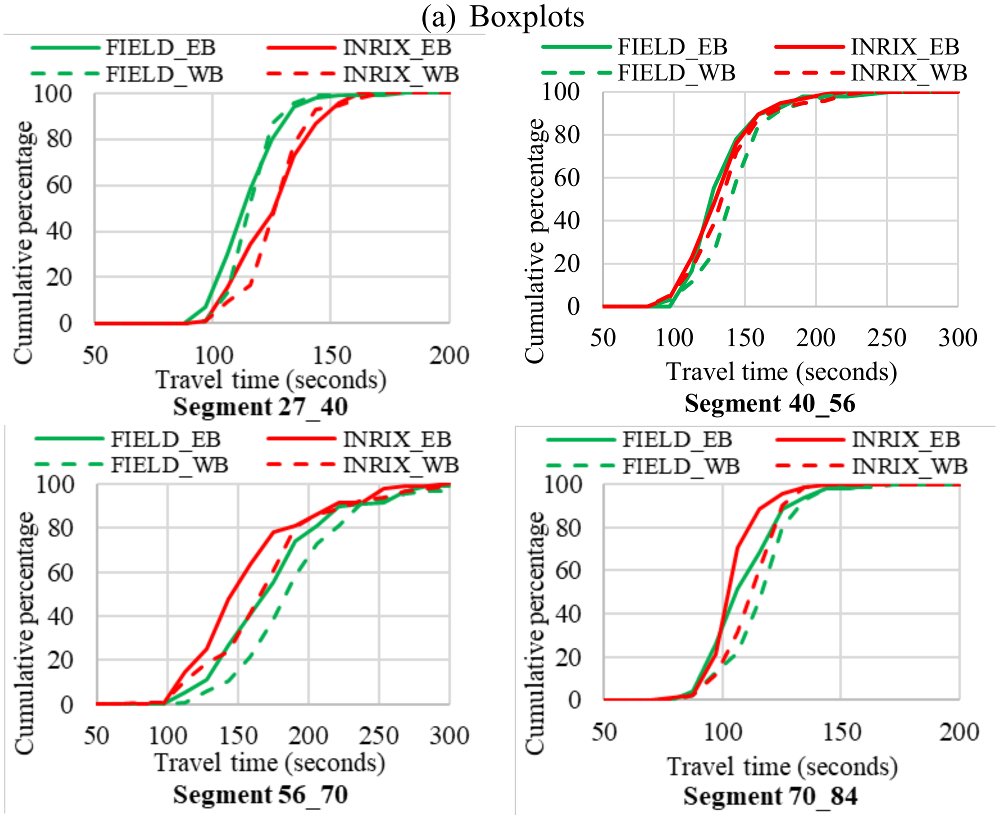
Table 4.7 also lists the median values. When considering both directions of traffic, INRIX was able to capture the median travel time with an accuracy of 9.2%, -1.4%, -10.8%, and -6.4%, respectively, for segments 27_40, 40_56, 56_70, and 70_84. Therefore, similar to the mean, INRIX successfully captured the median travel time values.

4.3.1.3 Measures of dispersion

Figure 4.11 shows standard boxplots and CDF of four segments' TTD during weekday PM peak periods for the EB and SB directions of traffic from both field and INRIX sources. These boxplots and CDF charts visually show the distribution characteristics of travel time for the four segments.



(a) Boxplots



(b) CDF

Figure 4.11 Boxplot and CDF of travel time during PM peak hours

Table 4.8 shows that the standard deviation of travel time for segment 27_40, 40_56, 56_70, and 70_84 for EB from field observation was 13.7, 24.5, 42.5, and 15.4 seconds, respectively. On the other hand, INRIX measured the standard deviation of travel time as 15.8, 23.7, 41.4, and 10.5 seconds, respectively, for EB traffic in these four segments. This quantified the percentage difference of the standard deviation of travel time between field observation and INRIX as 15.3%, -3.2%, -11.5%, and -31.6%, respectively. For WB traffic, INRIX had an accuracy of 7.0%, 10.8%, -10.3%, and -20.4%, respectively. When both directions of traffic were considered, INRIX's accuracy of capturing the standard deviation was 10.7%, 2.2%, 2.8%, and -24.1%, respectively, for segment 27_40, 40_56, 56_70, and 70_84.

Additionally, Table 4.8 shows that INRIX measured the interquartile range of travel time for the combined directions of the four segments with an accuracy of 3.2%, -8.4%, 7.0%, and -20.2%, respectively.

Table 4.8 Measures of dispersion of travel time during PM peak hours

	Segment 27_40		Segment 40_56		Segment 56_70		Segment 70_84	
	EB	WB	EB	WB	EB	WB	EB	WB
	Standard deviation (seconds)							
Field	13.7	12.6	24.5	24.8	42.5	42.7	15.4	14.4
INRIX	15.8	13.5	23.7	27.4	41.5	45.9	10.5	11.4
% Difference	15.3	7.0	-3.2	10.8	-11.5	-10.3	-31.6	-20.4
Avg % Difference	10.7		2.2		2.8		-24.1	
	Interquartile range (seconds)							
Field	17.2	16.6	24.7	25.4	50.7	49.7	22.1	14.3
INRIX	23.6	12.9	29.4	26.0	42.2	39.8	11.1	14.6
% Difference	36.7	-22.1	18.9	2.3	-16.9	-20.0	-49.7	1.7
Avg % Difference	3.2		-8.4		7.0		-20.2	

Therefore, INRIX's accuracy of capturing the standard deviation and interquartile range was higher for segment 27_40, 40_56, and 56_70 compared to that of segment 70_84 during PM peak periods of weekdays. Note that a similar observation was found from AM peak periods, where INRIX captured the standard deviation of segment 70_84 with lesser precision compared to other segments.

4.3.1.4 Travel Time Reliability Index

Table 4.9 compares the TTR metric for four segments during weekday PM peak periods from field and INRIX data sources. It shows that the value of the TTI metric for the EB traffic from field observation was 1.48, 1.84, 2.14, and 1.50 respectively, for the four segments. In the case of INRIX, the value of the TTI metric was 1.61, 1.84, 1.90, and 1.44 respectively, for the four segments. Therefore, INRIX measured the TTI with an accuracy of 8.5%, -0.3%, -11.5%, and -4.2%, respectively, compared to the EB field observation. Considering both directions, INRIX measured the TTI metric within an accuracy of 7.6%, -2.5%, -10.9%, and -3.9% for segment 27_40, 40_56, 56_70, and 70_84, respectively.

For the TTI metric, INRIX showed an accuracy of 11.1%, 0.3%, -4.5%, and -6.9%, respectively, for the four segments. For LOTTR, the accuracy of INRIX, compared to field observation, was -0.6%, -1.7%, -1.2%, and 1.9%, respectively.

Table 4.9 Measures of travel time reliability metrics (unitless) during PM peak hours

	Segment 27_40		Segment 40_56		Segment 56_70		Segment 70_84	
	EB	WB	EB	WB	EB	WB	EB	WB
	Travel time index (TTI)							
Field	1.48	1.53	1.84	1.99	2.14	2.32	1.50	1.60
INRIX	1.61	1.63	1.84	1.90	1.90	2.08	1.44	1.54
% Difference	8.5	6.6	-0.3	-4.4	-11.5	-10.3	-4.2	-3.6
Avg % Difference	7.6		-2.5		-10.9		-3.9	
	Planning time index (PTI)							
Field	1.76	1.76	2.48	2.62	3.20	3.20	1.88	1.88
INRIX	1.96	1.93	2.43	2.68	2.96	3.16	1.71	1.76
% Difference	11.3	9.6	-2.0	2.6	-7.5	-1.2	-8.9	-6.3
Avg % Difference	11.1		0.3		-4.5		-6.9	
	Level of travel time reliability (LOTTR)							
Field	1.10	1.09	1.17	1.12	1.18	1.21	1.14	1.07
INRIX	1.10	1.09	1.12	1.12	1.22	1.12	1.10	1.08
% Difference	-0.3	0.0	-3.8	0.2	2.8	-6.9	-4.2	0.5
Avg % Difference	-0.6		-1.7		-1.2		1.9	
	Buffer index (BI)							
Field	0.19	0.15	0.35	0.32	0.49	0.38	0.25	0.17
INRIX	0.22	0.18	0.32	0.41	0.56	0.52	0.19	0.14
% Difference	15.9	21.0	-6.7	30.5	13.8	37.0	-24.5	-18.7
Avg % Difference	22.7		11.6		23.8		-17.9	
	Coefficient of variation (COV)							
Field	0.12	0.11	0.19	0.17	0.24	0.23	0.14	0.12
INRIX	0.13	0.11	0.18	0.20	0.27	0.27	0.10	0.10
% Difference	6.2	0.4	-2.9	15.9	10.2	20.1	-28.6	-17.5
Avg % Difference	3.0		4.8		15.3		-21.0	

INRIX accuracy was lower for BI and COV, compared to the three metrics discussed above. The average percentage difference of INRIX's measurement of BI was 22.7%, 11.6%, 23.8%, and -17.9% for segment 27_40, 40_56, 56_70, and 70_84, respectively. For the COV metric, the average percentage difference was 3.0%, 4.8%, 15.3%, and -21.0%, respectively. Out of the five TTR metrics, INRIX measured the LOTTR most accurately compared to the field observed values. On the other hand, BI was least accurately measured by INRIX during weekday PM peak periods . Note that for the AM peak periods, the same observation was made.

4.3.2 Incremental Segment-wise Analysis of PM Peak Hour Periods

This section analyzes segments 27_40, 27_56, 27_70, and 27_84, which have the incremental length of 1.18, 2.27, 3.51, and 4.71 miles, respectively, for weekday PM peak periods. The biggest segment, 27_84, analyzes the entire corridor under PM peak periods.

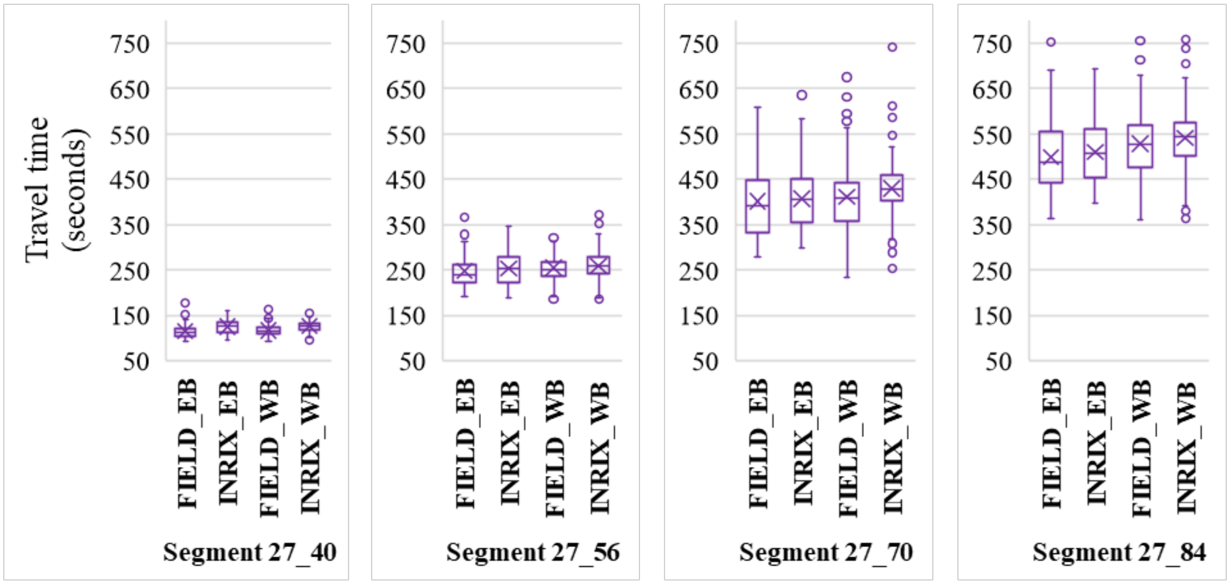
Table 4.10 demonstrates that the mean and median travel time for the incremental segment increased with segment size for both field and INRIX data sources. The mean field observed travel times for segments 27_40, 27_56, 27_70 and 27_84 for both directions combined was 116.2, 251.2, 406.1, and 512.3 seconds, respectively. In comparison, mean travel time for INRIX was 125.0, 257.6, 418.5 and 525.5 seconds, respectively, for the four segments. Consequently, the average percentage difference in mean travel time between field observation and INRIX was 10.7%, 2.5%, 3.0%, and 2.6%, respectively. Similarly, INRIX was able to capture the median travel time with a precision of 9.2%, 4.0%, -5.7%, and 3.8%, respectively for segments 27_40, 27_56, 27_70, and 27_84.

Table 4.10 Measures of central tendency of travel time of incremental segment during PM peak hours

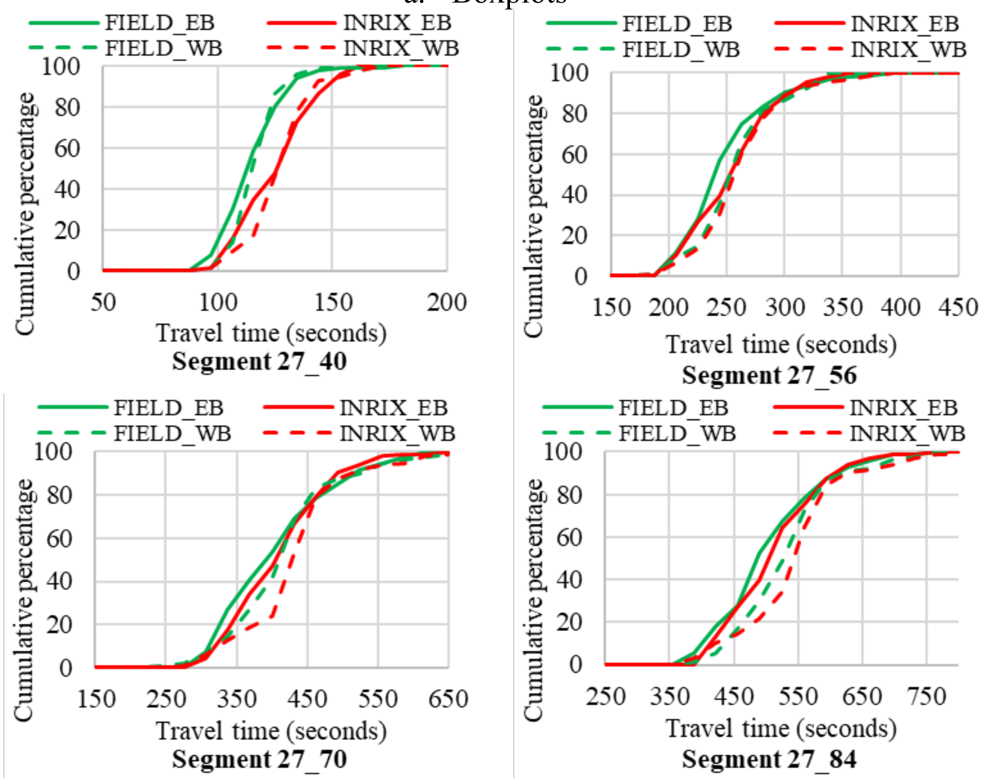
	Segment 27_40		Segment 27_56		Segment 27_70		Segment 27_84	
	EB	WB	EB	WB	EB	WB	EB	WB
	Mean (seconds)							
Field	114.4	118.1	247.3	255.0	400.8	411.7	499.0	528.5
Avg Field	116.2		251.2		406.1		512.3	
INRIX	124.1	125.9	253.5	261.7	407.5	429.5	510.4	540.5
Avg INRIX	125.0		257.6		418.5		525.5	
% Difference	8.5	6.6	2.5	2.6	1.7	4.3	2.3	3.9
Avg % Difference	10.7		2.5		3.0		2.6	
	Median (seconds)							
Field	113.2	116.4	239.1	250.4	390.0	409.0	487.5	527.2
	114.9		245.8		402.5		506.5	
INRIX	125.4	125.4	252.0	258.6	405.0	429.0	506.4	543.6
Avg % Difference	125.4		255.6		415.8		525.9	
% Difference	10.8	7.8	5.4	3.3	3.8	4.9	2.3	2.3
Avg % Difference	9.2		4.0		-5.7		3.8	

INRIX measured both mean and median values of travel time for the four incremental segments with an accuracy of -5.7% to 10.7% for weekday PM peak periods. Note that for individual segments, this accuracy was -10.9% to 9.2%. Therefore, the increase in the segment length did not substantially impact the accuracy of INRIX's measurements of the central tendency of TTD for PM peak period traffic during weekdays.

Figure 4.12 shows standard box plots and CDF charts of the TTD of four incremental segments during PM peak periods. As anticipated, the boxplots move higher on the y-axis as the segment length increases from segment 27_40 to segment 27_84. Similarly, the CDFs shift to the right on the x-axis from segment 27_40 to segment 27_84, indicating an increase in travel time with longer segment lengths.



a. Boxplots



b. CDF

Figure 4.12 Boxplot and CDF of incremental segment during PM peak hours

Table 4.11 lists quantitative information on measures of travel time dispersion for the incremental segments during PM peak periods. It shows that the average field standard deviation of travel time for segments 27_40, 27_56, 27_70 and 27_84 was 13.3, 36.2, 79.0, and 80.1 seconds, respectively. Note that as the segment length increased, the standard deviation values obtained from field observation also increased. Similarly, INRIX's measurement of average standard deviation rose with segment length to be 14.7, 36.6, 73.9, and 80.8 seconds, respectively. Therefore, the percentage difference between field observation and INRIX standard deviation was 10.7%, 0.9%, -6.4%, and 0.9%, respectively, for the four incremental segments.

Table 4.11 Measures of dispersion of travel time of incremental segment during PM peak hours

	Segment 27_40		Segment 27_56		Segment 27_70		Segment 27_84	
	EB	WB	EB	WB	EB	WB	EB	WB
	Standard deviation (seconds)							
Field	13.7	12.6	38.4	33.7	79.3	78.6	80.5	77.0
Avg Field	13.3		36.2		79.0		80.1	
INRIX	15.8	13.5	35.8	37.0	68.5	77.8	73.8	85.0
Avg INRIX	14.7		36.6		73.9		80.8	
% Difference	15.3	7.0	-6.8	10.1	-13.6	-1.0	-8.3	10.4
Avg % Difference	10.7		0.9		-6.4		0.9	
	Interquartile range (seconds)							
Field	17.2	16.6	37.8	31.7	111.9	81.7	106.8	88.2
Avg Field	17.7		38.3		97.8		98.5	
INRIX	23.6	12.9	53.6	35.4	92.0	56.7	104.0	71.4
Avg INRIX	18.3		44.1		92.3		102.3	
% Difference	36.7	-22.1	41.8	11.7	-17.8	-30.6	-2.7	-19.0
Avg % Difference	3.2		15.1		-5.7		3.9	

Interquartile range found from both field observation and INRIX increased as the length of segment increased. The average percentage difference of INRIX's interquartile range was 3.2%, 15.1%, -5.7%, and 3.9%, for the four incremental segments compared to the field observation.

Table 4.12 lists different travel time reliability metrics of four incremental segments during PM peak periods. Table 4.12 shows that the five TTR metrics' values from both field observation and INRIX increased as the segment length increased from segment 27_40 to segment 27_70. This means that as the length of segment increased, the reliability of travel time decreased. However, for all the TTR metrics, their values increased for segment 27_84 compared to the values from segment 27_70. Therefore, the addition of segment 70_84 improved the reliability of segment 27_84. This may be due to the less variable travel time of segment 70_84 (i.e., lower standard deviation values) as there are no signalized intersections between 70th and 84th Street, along the Highway 2 testbed.

Table 4.12 shows that the INRIX measured the TTI metric with an accuracy of 7.6%, 2.5%, 3.0%, and 2.6%, respectively, compared to the field observation, for the four incremental segments. The accuracy of the PTI INRIX measurement was 11.1%, -1.9%, -3.2%, and -0.2% respectively. For LOTTR, INRIX's accuracy was -0.6%, -0.5%, and -2.2%, respectively, for the four incremental segments. In the case of COV, the average percentage difference was 3.0%, -1.6%, -9.1%, and -1.6%, respectively.

On the other hand, INRIX accuracy was lower for the BI index. The BI accuracy was 22.7%, -18.7%, -21.6%, and -11.7%, respectively, for segment 27_40, 27_56, 27_70, and 27_84. Among all five TTR metrics, INRIX measured the LOTTR most accurately compared to the field observed values.

Table 4.12 Measures of travel time reliability metrics (unitless) of incremental segment during PM peak hours

	Segment 27_40		Segment 27_56		Segment 27_70		Segment 27_84	
	EB	WB	EB	WB	EB	WB	EB	WB
	Travel time index (TTI)							
Field	1.48	1.53	1.59	1.64	1.69	1.74	1.62	1.71
Avg Field	1.50		1.59		1.71		1.66	
INRIX	1.61	1.63	1.63	1.68	1.72	1.81	1.66	1.75
Avg INRIX	1.62		1.65		1.77		1.70	
% Difference	8.5	6.6	2.5	2.6	1.7	4.3	2.3	2.3
Avg % Difference	7.6		2.5		3.0		2.6	
	Planning time index (PTI)							
Field	1.76	1.76	2.11	2.09	2.35	2.36	2.10	2.20
Avg Field	1.76		2.10		2.37		2.17	
INRIX	1.96	1.93	2.01	2.09	2.24	2.48	2.08	2.29
Avg INRIX	1.96		2.06		2.30		2.16	
% Difference	11.3	9.6	-4.8	0.0	-4.8	5.1	-0.9	4.2
Avg % Difference	11.1		-1.9		-3.2		-0.2	
	Level of travel time reliability (LOTTR)							
Field	1.10	1.09	1.15	1.09	1.20	1.10	1.15	1.09
Avg Field	1.10		1.11		1.12		1.13	
INRIX	1.10	1.09	1.11	1.11	1.14	1.09	1.13	1.07
Avg INRIX	1.09		1.11		1.12		1.10	
% Difference	-0.3	0.0	-3.3	1.6	-4.9	-1.5	-1.8	-1.6
Avg % Difference	-0.6		-0.5		-0.6		-2.2	
	Buffer index (BI)							
Field	0.19	0.15	0.33	0.28	0.39	0.36	0.30	0.28
Avg Field	0.17		0.30		0.39		0.31	
INRIX	0.22	0.18	0.23	0.24	0.30	0.37	0.26	0.31
Avg INRIX	0.21		0.24		0.30		0.27	
% Difference	15.9	21.0	-28.9	-11.9	-22.5	2.9	-13.5	8.4
Avg % Difference	22.7		-18.7		-21.6		-11.7	
	Coefficient of variation (COV)							
Field	0.12	0.11	0.16	0.13	0.20	0.19	0.16	0.15
Avg Field	0.11		0.14		0.19		0.16	
INRIX	0.13	0.11	0.14	0.14	0.17	0.18	0.14	0.16
Avg INRIX	0.12		0.14		0.18		0.15	
% Difference	6.2	0.4	-9.0	7.2	-15.0	-5.1	-10.4	7.9
Avg % Difference	3.0		-1.6		-9.1		-1.6	

From the analysis of the four individual segments represented in Table 4.9, the range of INRIX's accuracy to measure the TTI, PTI, LOTTR, BI and COV metrics was -10.9% to 7.6%, -6.9% to 11.1%, -1.7% to 1.9%, -17.9% to 23.8%, and -21.0% to 15.3%, respectively. For the four incremental segments shown in Table 4.9, the accuracy of INRIX was 2.5% to 7.6%, -3.2% to 11.1%, -2.2% to -0.5%, -21.6% to 22.7%, and -9.1% to 3.0%, respectively. Therefore, for PM peak period traffic, the incremental segment did not substantially impact the accuracy of INRIX's measurement of TTR metrics, except for COV, compared to those from individual segments. The range of accuracy of INRIX to measure COV was shorter, meaning accuracy increased for incremental segments at PM peak periods. The same observation was made for the AM peak period. Therefore, regardless of individual or incremental segments from AM and PM peak period traffic, INRIX captured the PTI, TTI, and LOTTR metrics with the most precision, whereas, BI and COV were captured with less precision.

Note that segment 27_84 represents the Highway 2 testbed corridor (i.e., corridor 27_84). It was found that INRIX was able to measure the mean, median, standard deviation, and interquartile range of observed travel time with an accuracy of 2.6%, 3.8%, 0.9%, and 3.9%, respectively.

During PM peak periods, for corridor 27_84, INRIX produced PTI, TTI, LOTTR, BI, and COV values of 1.70, 2.16, 1.10, 0.27, and 0.15 against field observed values of 1.66, 2.17, 1.13, 0.31 and 0.16, respectively. Therefore, the accuracy of INRIX for the five TTR metrics becomes 2.6%, -0.2%, -2.2%, -11.7%, and -1.6%, respectively. Note that during AM peak periods, these accuracies from INRIX for the five TTR metrics were 4.8%, 0.4%, 0.4%, -22.1%, and -15.3%, respectively. Therefore, while the accuracy for PTI, TTI, and LOTTR remain similar for both peak periods, the accuracy of the COV and BI metrics increased for the PM peak period compared to that of the AM peak period.

Apart from accuracy, if we compare the TTR metrics for the AM and PM peak periods, it was found that, except for LOTTR, all TTR metric values were higher in the PM peak periods. The same is true for both field observed data and INRIX data. Therefore, based on all metrics except LOTTR, travel is less reliable for the PM peak period.

4.4 Analysis Summary

This chapter analyzed and compared statistics and TTR metrics found from field observed and INRIX travel time data for both AM and PM peak periods under normal weather. Some of the key findings from this chapter are listed below.

1. For four individual segments, INRIX measured the mean travel time with an accuracy of -8.2% to 3.9% (AM peak) and -10.9% to 7.6% (PM peak). For median travel time, INRIX's accuracy was -7.4% to 2.8% (AM peak) and -10.8% to 9.2% (PM peak).

2. For the four individual segments, INRIX measured the standard deviation of travel time with an accuracy of -28.1% to 7.0% (AM peak) and -24.1% to 10.7% (PM peak). For the interquartile range, INRIX's accuracy was -21.6% to 53.0% (AM peak) and -20.2% to 7.0% (PM peak). Overall, INRIX captured the central tendency of TTD with higher accuracy compared to measures of dispersion characteristics.

3. Based on analysis of the four individual segments, out of the five TTR metrics, INRIX measured the LOTTR metric with the most accuracy and BI with the least accuracy for both AM and PM peak periods.

4. As the length of the segment increased, in general, the value of standard deviation and interquartile range of travel time increased for both AM and PM peak periods.

The increase in the length of the segment did not impact the accuracy of INRIX's measurements of the central tendency of travel time distribution for AM or PM peak periods. However, the precision of the dispersion measurement by INRIX was higher during the PM peaks compared to the AM peaks as the length of the segment increased.

5. For the PM periods, as the length of the segment increased from segment 27_40 to 27_70, in general, the value of all five TTR metrics increased (for both data sources). This may be explained by the presence of several signalized intersections between 27^{th} and 70^{th} Street along the testbed, which increased the variability of travel time. The same could not be said for the AM peak period. It can be hypothesized that the PM peak periods suffered higher traffic demand compared to the AM peak periods, and it caused higher values of TTR metrics as segment length increased during the PM peak.

6. Regardless of individual or incremental segments from AM peak period traffic, in general, INRIX captured the PTI, TTI, and LOTTR metrics with the most precision, whereas, BI and COV were captured with less precision.

7. Considering both data sources and both peak periods and both directions of traffic, the value of the PTI, TTI, and LOTTR metrics of the four individual segments ranged from 1.44 to 2.14, 1.61 to 3.20, and 1.05 to 1.22, respectively.

8. For corridor 27_84, considering both data sources both peak periods, and both directions of traffic, the value of the PTI, TTI, and LOTTR metrics of the four individual segments ranged from 1.50 to 1.75, 1.78 to 2.29, and 1.07 to 1.15, respectively.

9. For corridor 27_84, regardless of the data sources, all TTR metric values except for LOTTR were higher in the PM peak periods compared to the AM peak periods. Therefore, based on all metrics except LOTTR, travel is less reliable for the PM peak period.

Chapter 5 Analysis and Validation of Performance Index Under Inclement Weather

It is well established that adverse weather disrupts the transportation system. Catastrophic disasters like floods, tornadoes, and hurricanes can cause devastating damage and profoundly impact travel conditions. However, more typical weather such as rain, snow, and ice can also have significant detrimental effects on the transportation system by impacting normal traffic and driver behaviors (Pang et al., 2017; Jackson et al., 2016). The goal of this chapter is to analyze and compare the field-observed travel time and corresponding TTR metrics with INRIX based data under rain and snow conditions.

5.1 Travel Time Data Collection Under Inclement Weather

The travel time data during both rain and snow conditions were collected from the testbed on Highway 2. Travel time data on November 10, 2021 from 3:00 p.m. to 7:00 p.m., during rainy conditions, were collected from the Highway 2 testbed along the four segments (i.e., 27_40, 40_56, 56_70, and 70_84) for both EB and WB directions. Note that the travel time data are averaged over 15-minute intervals. Both field and INRIX data sources were used for data collection. Furthermore, travel time data for the increased segment lengths, 27_40, 27_56, 27_70, and 27_84, was also collected using field and INRIX sources for both directions of traffic. The increase in segment length was considered to evaluate if the length of the segment impacted the accuracy of the two data sources mentioned under inclement weather conditions.

Travel time data for December 10, 2021 from 6:00 p.m. to 12:00 a.m., during snowy conditions, were collected from the Highway 2 testbed along the four segments 27_40, 40_56, 56_70, and 70_84 for both directions of traffic. Unfortunately, it was later found that during snow, the video camera located at 56th Street on Highway 2 malfunctioned and did not record any footage or collect MAC addresses. Therefore, only segments 27_40 and 70_84 were used for analysis and comparison. In terms of incremental segment, segments 27_70 and 27_84 were used.

5.2 Analysis and Validation of Travel Time Reliability Under Rain Condition

The goal of this section is to compare the travel times from both field and INRIX sources through charts, measuring statistics, and reliability metrics during rainy conditions.

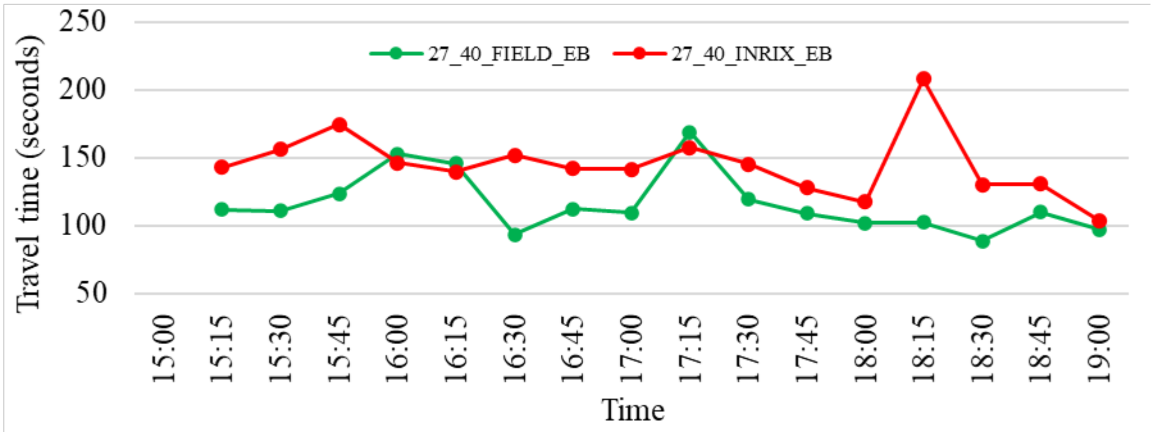
The comparison charts show the change of travel time over time from two data sources. On the other hand, the statistical observation reveals the performance of two sources for the measures of central tendency (e.g., mean and median), dispersion (e.g., standard deviation, interquartile range, cumulative distribution function, boxplots) and reliability metrics (e.g., travel time index, planning time index, level of travel time reliability, buffer index, and coefficient of variation).

5.2.1 Segment-wise Analysis During Rainy Condition

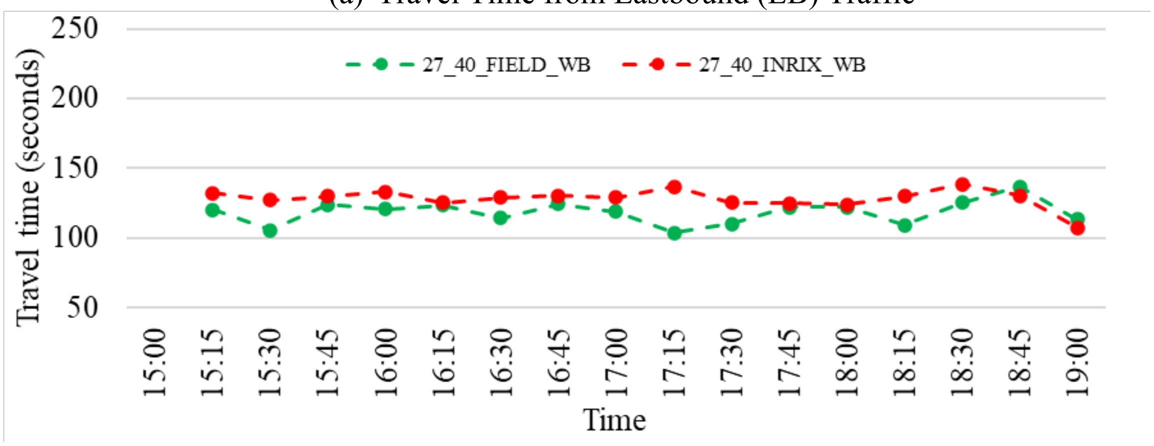
The segment-wise analysis refers to the analysis of each segment (i.e., 27_40, 40_56, 56_70, and 70_84) separately and compares them. The comparison charts, measures of central tendency, dispersion, and reliability index for segment-wise analysis are presented below.

5.2.1.1 Comparison Charts

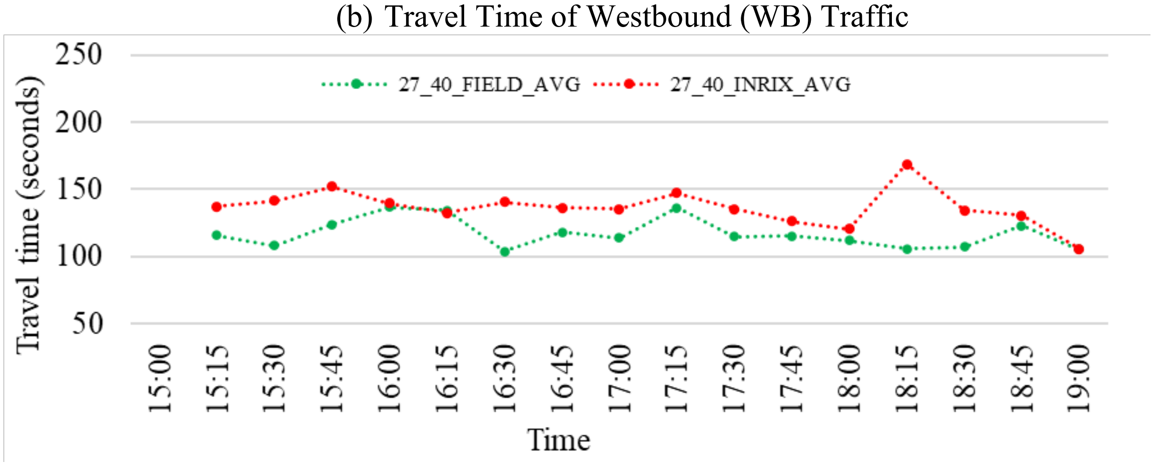
Figure 5.1 shows the travel time during rainy conditions for segment 27_40 for the EB direction, (Figure 5.1.a), WB direction (Figure 5.1.b), and combination of both directions (Figure 5.1.c). Similarly, Figures 5.2, 5.3, and 5.4 show the travel time comparison between the two sources for segment 40_56, 56_70, and 70_84, respectively.



(a) Travel Time from Eastbound (EB) Traffic

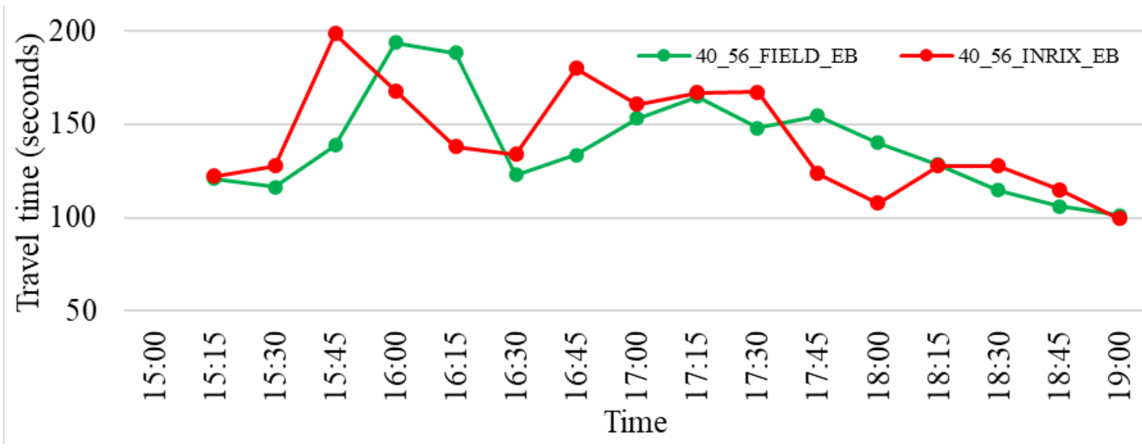


(b) Travel Time of Westbound (WB) Traffic

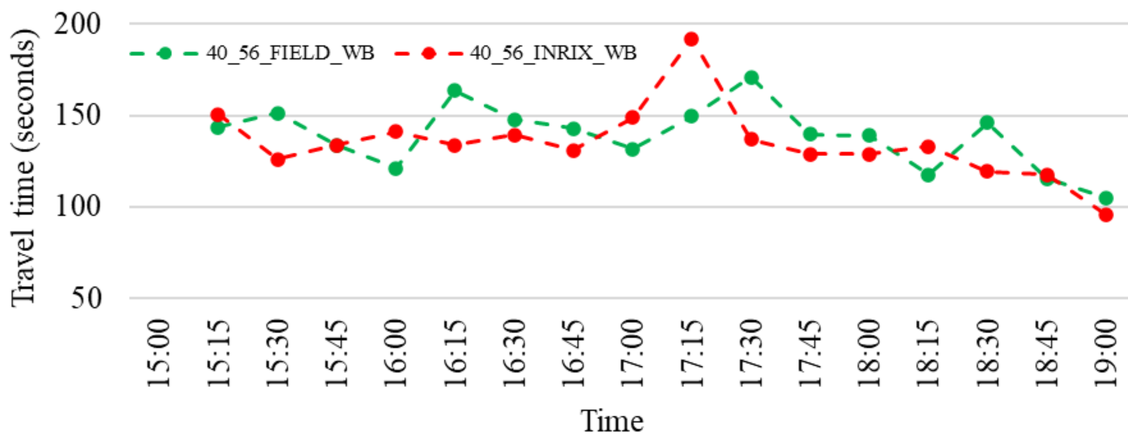


(c) Average Travel Time of EB and WB Traffic

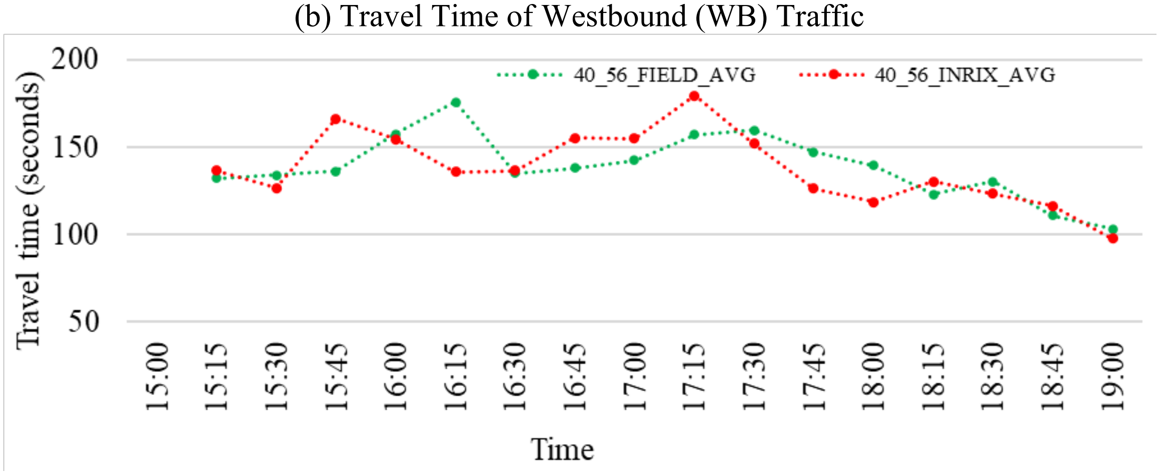
Figure 5.1 Comparisons of travel time for Segment 27_40 during rainy condition



(a) Travel Time from Eastbound (EB) Traffic

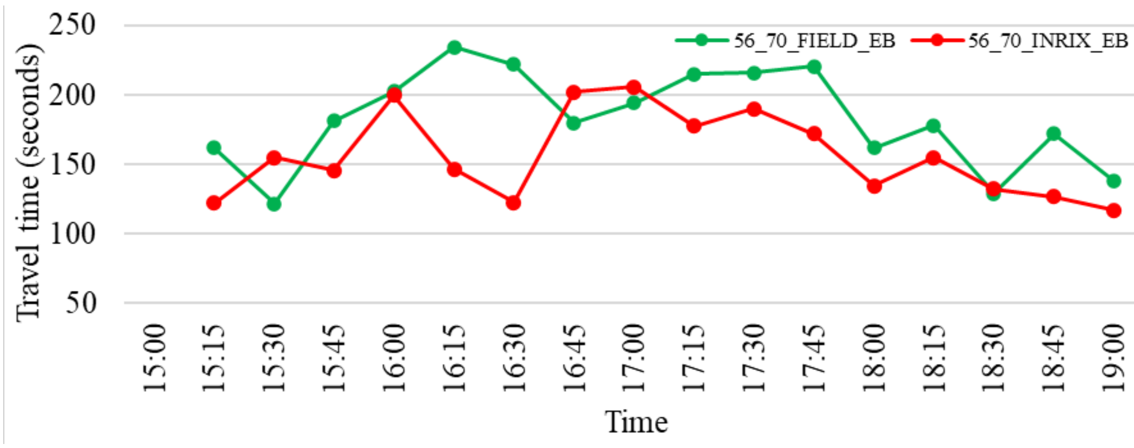


(b) Travel Time of Westbound (WB) Traffic

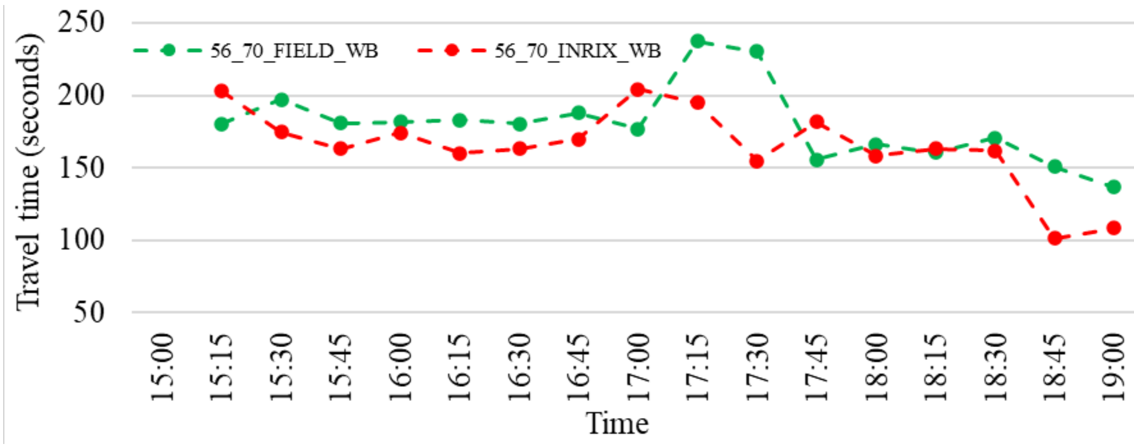


(c) Average Travel Time of EB and WB Traffic

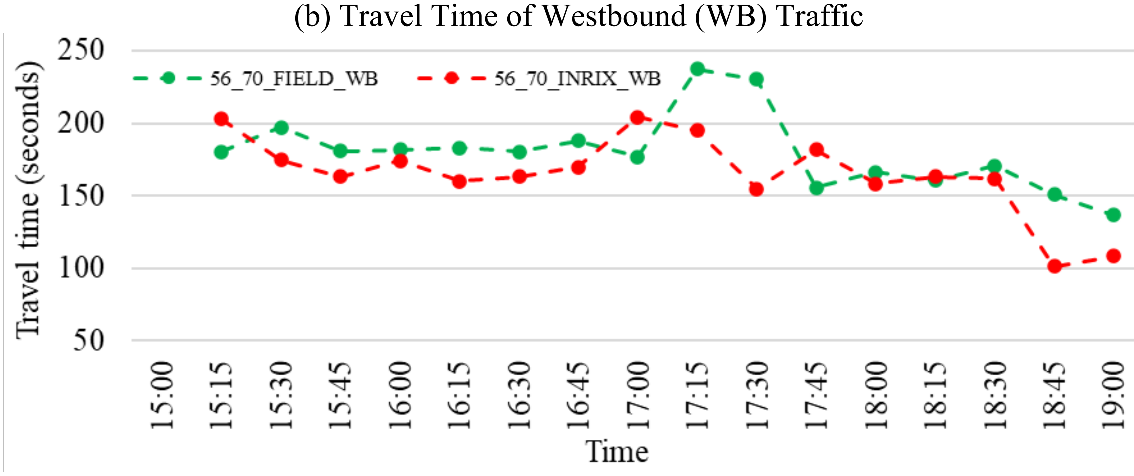
Figure 5.2 Comparisons of travel time for Segment 40_56 during rainy condition



(a) Travel Time from Eastbound (EB) Traffic

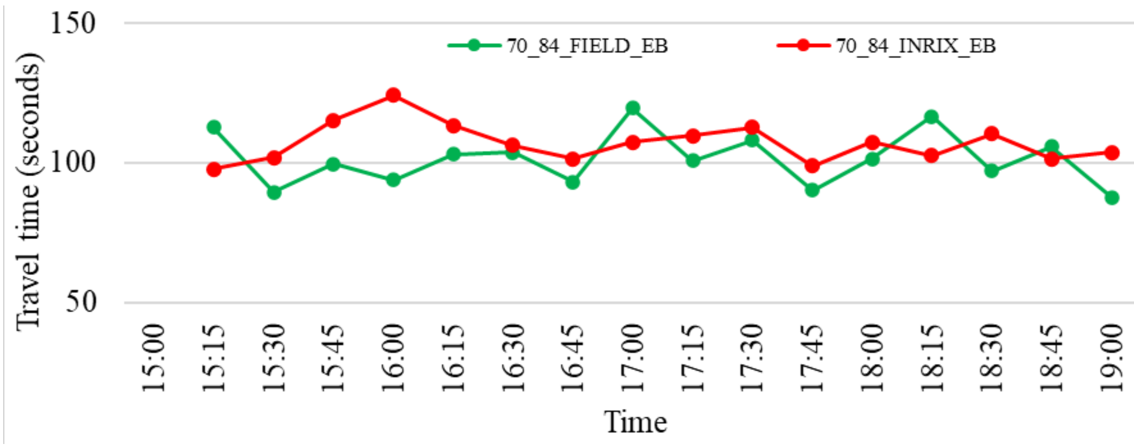


(b) Travel Time of Westbound (WB) Traffic

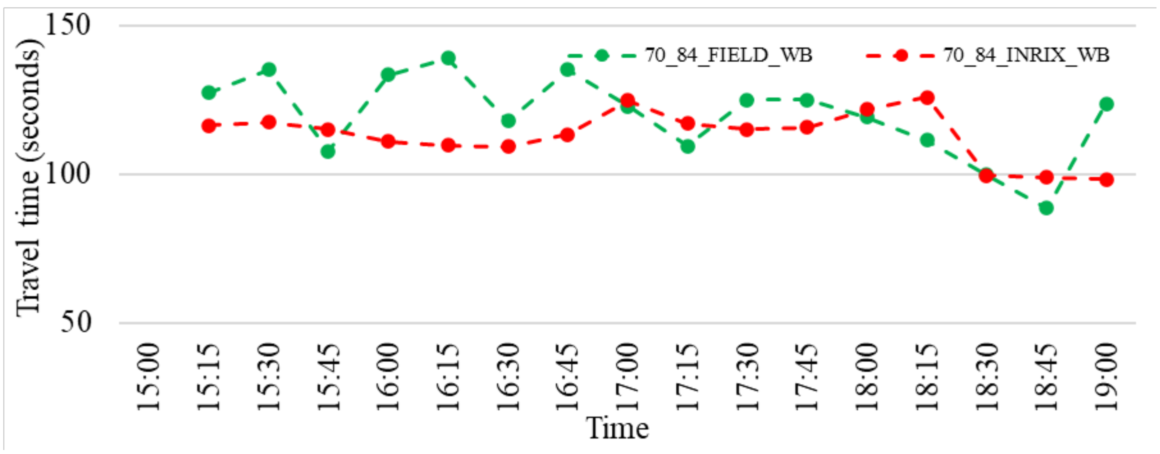


(c) Average Travel Time of EB and WB Traffic

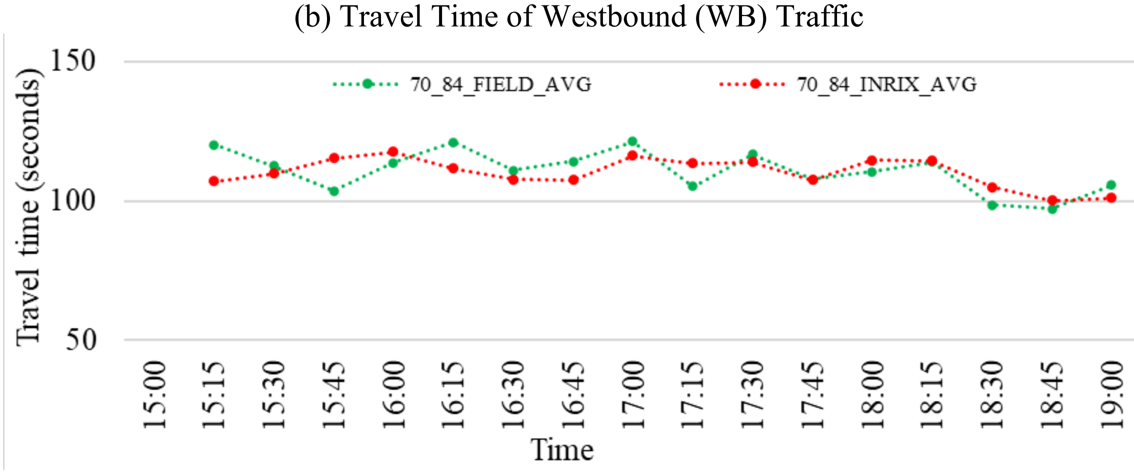
Figure 5.3 Comparisons of travel time for Segment 56_70 during rainy condition



(a) Travel Time from Eastbound (EB) Traffic



(b) Travel Time of Westbound (WB) Traffic



(c) Average Travel Time of EB and WB Traffic

Figure 5.4 Comparisons of travel time for Segment 70_84 during rainy condition

From Figures 5.1, 5.2, 5.3, and 5.4, INRIX's travel time, overall, follows the pattern of field observation for EB, WB, and combined directions of traffic. The following sections discuss and compare the statistics and reliability metrics related to travel time during rainy conditions.

5.2.1.2 Measures of Central Tendency

Table 5.1 lists the measures of central tendency, which are the mean and median, for each segment for both directions of traffic. As previously noted, the length of the four segments varies from 1.09 to 1.24 miles, and speed limits vary from 45 to 55 mph. Therefore, differences in travel time among these segments are expected.

Table 5.1 Measures of central tendency of travel time of four segments during rainy condition

	Segment 27_40		Segment 40_56		Segment 56_70		Segment 70_84	
	EB	WB	EB	WB	EB	WB	EB	WB
	Mean (seconds)							
Field	116.1	118.3	139.2	138.7	183.0	179.8	101.4	120.1
INRIX	144.8	128.3	141.6	134.8	156.5	164.8	107.2	113.1
% Difference	24.7	8.4	1.7	-2.8	-14.5	-8.3	5.7	-5.8
Avg % Difference	16.5		-0.5		-11.4		-0.5	
	Median (seconds)							
Field	110.5	120.4	136.2	141.3	180.7	180.5	101.1	123.3
INRIX	142.5	129.3	130.8	133.5	150.6	163.2	106.8	115.2
% Difference	29.0	7.4	-3.9	-5.5	-16.7	-9.6	5.6	-6.5
Avg % Difference	14.8		-4.3		-9.9		1.2	

Table 5.1 shows that the mean travel time obtained from field observation for segments 27_40, 40_56, 56_70, and 70_84 in the EB direction was 116.1, 139.2, 183.0, and 101.4 seconds, respectively. In comparison, INRIX travel time was 144.8, 141.6, 156.5, and 107.2 seconds, respectively, for these four segments. Therefore, the percentage difference between field observation and INRIX travel time was 24.7%, 1.7%, -14.5%, and 5.7%, respectively. As noted

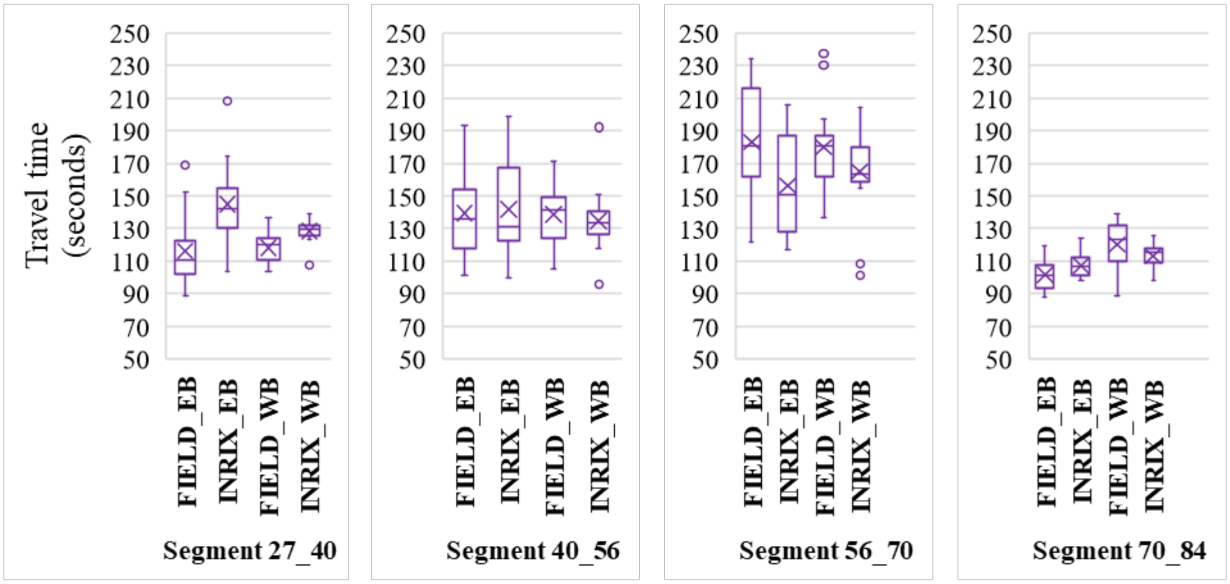
before, the positive percentage difference means that INRIX measured higher travel times than the field observation. The percentage difference for WB traffic was 8.4%, -2.8%, -8.3%, and -5.8%, respectively. If the average travel time of both directions was considered then the average percentage difference was found to be 16.5%, -0.5%, -11.4%, and -0.5%, respectively. This means that INRIX measured the mean of travel time with an accuracy of -0.5% to 16.5% during rainy conditions. Note that in Chapter 4, we found that for the PM peak period (i.e., 4:00 p.m. – 7:00 p.m.) under normal weather, INRIX's mean travel time accuracy was -3.9% to 7.6%. To reiterate, the rain duration was from 3:00 p.m. to 4:00 p.m., therefore the accuracy from PM peak periods under normal weather conditions is mentioned here.

Table 5.1 lists the median travel time values. The average percentage difference for median travel time was 14.8%, -4.3%, -9.9%, and 1.2% for segment 27_40, 40_56, 56_70, and 70_84, respectively. Therefore, INRIX's accuracy was within a range of -9.9% to 14.8%. Under normal weather conditions during PM peak periods, this accuracy was -10.8% to 9.2%.

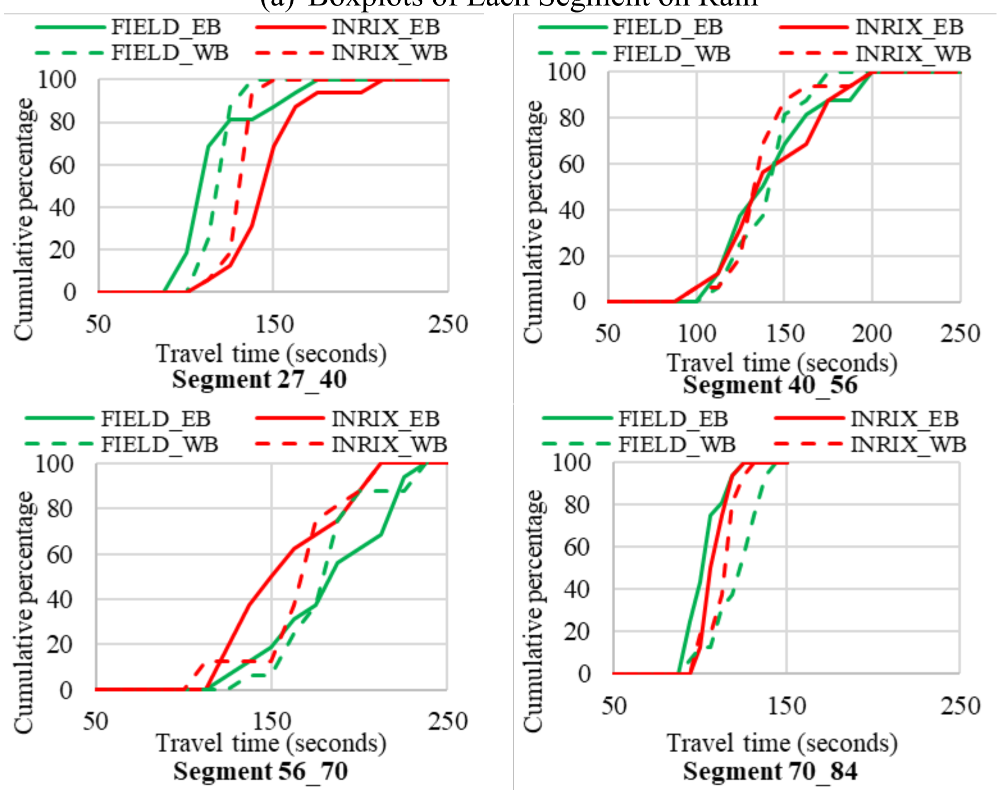
5.2.1.3 Measures of Dispersion

Figure 5.5 shows standard boxplots and CDF of TTD of the four segments during rainy conditions for EB and WB traffic from field and INRIX sources. These boxplots and CDF charts visually show the distribution characteristics of the travel time.

The shape of the CDFs provides a rough idea of whether the TTD from the field and INRIX data are similar or dissimilar. Among all the boxplots, segment 40_56 and 70_84 seem to have similar TTDs for field observation and INRIX. Furthermore, segment 56_70 seems to have more variations in the TTD.



(a) Boxplots of Each Segment on Rain



(b) CDF of Each Segment on Rain

Figure 5.5 Boxplot and CDF of travel time during rainy condition

Table 5.2 lists the measure of dispersion of the TTD quantitatively: it includes standard deviation and interquartile ranges of field and INRIX travel time data for both the EB and WB directions.

Table 5.2 Measures of dispersion of travel time of four segment during rainy condition

	Segment 27_40		Segment 40_56		Segment 56_70		Segment 70_84	
	EB	WB	EB	WB	EB	WB	EB	WB
	Standard deviation (seconds)							
Field	22.0	8.5	27.0	17.5	34.6	26.1	9.5	13.9
INRIX	23.7	6.9	28.3	20.0	30.9	28.0	6.9	8.4
% Difference	7.5	-19.0	5.0	14.1	-10.7	7.3	-27.0	-39.1
Avg % Difference	16.0		8.8		-2.9		-45.6	
	Interquartile range (seconds)							
Field	18.2	11.2	33.8	19.0	53.4	19.7	12.7	17.9
INRIX	22.2	5.2	43.7	11.4	50.1	16.7	9.2	7.5
% Difference	21.8	-53.2	29.2	-40.0	-6.2	-15.4	-27.9	-58.2
	1.7		-17.3		-3.4		-44.8	

Table 5.2 shows that the standard deviation of travel time for segment 27_40, 40_56, 56_70, and 70_84 for the EB direction from field observation was 22.0, 27.0, 34.6, and 9.5 seconds, respectively. In comparison, INRIX's standard deviation of travel time was 23.7, 28.3, 30.9, and 6.9 seconds, respectively, for these four segments. Therefore, the percentage difference of the standard deviation of travel time between field observation and INRIX was 7.5%, 5.0%, -10.7%, and -27.0%, respectively. For WB traffic, this percentage difference was -19.0%, 14.1%, 7.3%, and -39.1%, respectively.

Note that the average percentage difference (both directions combined) of the standard deviation of the travel time was found to be 16.0%, 8.8%, -2.9%, and -45.6%, respectively, for the four segments. Therefore, INRIX measured the standard deviation of travel time of the four segments within a range of -45.6% to 16.0%. Note that under normal weather conditions during the PM peak, this accuracy was -24.1% to 10.7%.

Table 5.2 also shows that INRIX measured the interquartile range of travel time of four segments with an accuracy of -44.8% to 1.7%. Under normal conditions during the PM peak period, this accuracy ranged from -20.2% to 7.0%.

From the observations above, it seems that INRIX measured the measure of dispersion less accurately under rainy conditions compared to that of normal PM peak hours.

5.2.1.4 Travel Time Reliability Index

Table 5.3 analyzes and compares the TTR metric for four segments during rainy conditions from field and INRIX data sources. Table 5.3 shows that the TTI metric obtained from field observation for EB traffic was 1.37, 1.95, 2.25, and 1.41, respectively, for the four segments. The INRIX value of the TTI metric was 1.70, 1.98, 1.93, and 1.49, respectively. Therefore, INRIX measured the TTI metric with an accuracy of 24.7%, 1.7%, -14.5%, and 5.7%, respectively, compared to the field observation for EB traffic. Considering both directions of traffic, the accuracy of INRIX-produced TTI metric for the four segments was 16.5%, -0.5%, -11.4%, and -0.5%, respectively. Note that for normal weather during PM peak periods, INRIX accuracy for these four segments was 7.6%, -2.5%, -10.9% and -3.9%, respectively.

For the PTI metric, during rainy conditions, the INRIX accuracy was 11.1%, 3.7%, -12.4%, and -8.0%, respectively, for the four segments. The corresponding value under normal weather during PM periods was 11.1%, 0.3%, -4.5%, and -6.9%, respectively. For the LOTTR metric, during rainy conditions, the INRIX accuracy was 1.8%, 8.4%, -1.5%, and -8.0% for the four segments, respectively. The corresponding INRIX accuracy under normal weather during PM periods was -0.6%, -1.7%, -1.2%, and 1.9%, respectively.

Table 5.3 Measures of travel time reliability metrics (unitless) of four segments during rainy condition

	Segment 27_40		Segment 40_56		Segment 56_70		Segment 70_84	
	EB	WB	EB	WB	EB	WB	EB	WB
	Travel time index (TTI)							
Field	1.37	1.39	1.95	1.94	2.25	2.22	1.41	1.67
INRIX	1.70	1.51	1.98	1.89	1.93	2.03	1.49	1.57
% Difference	24.7	8.4	1.7	-2.8	-14.5	-8.3	5.7	-5.8
Avg % Difference	16.5		-0.5		-11.4		-0.5	
	Planning time index (PTI)							
Field	1.85	1.51	2.66	2.32	2.77	2.86	1.63	1.89
INRIX	2.15	1.62	2.59	2.26	2.50	2.50	1.63	1.74
% Difference	16.7	7.1	-2.6	-2.7	-9.8	-12.4	0.1	-8.2
Avg % Difference	11.1		3.7		-12.4		-8.0	
	Level of travel time reliability (LOTTR)							
Field	1.12	1.03	1.13	1.06	1.20	1.04	1.07	1.08
INRIX	1.09	1.02	1.28	1.06	1.26	1.11	1.06	1.02
% Difference	-2.2	-0.8	12.8	-0.1	5.7	6.9	-1.2	-5.8
Avg % Difference	1.8		8.4		-1.5		-8.0	
	Buffer index (BI)							
Field	0.35	0.08	0.36	0.19	0.23	0.29	0.16	0.13
INRIX	0.26	0.07	0.30	0.19	0.30	0.23	0.10	0.11
% Difference	-24.7	-16.3	-16.1	0.8	29.0	-19.9	-38.6	-21.4
Avg % Difference	-21.8		19.1		-4.9		-41.2	
	Coefficient of variation (COV)							
Field	0.19	0.07	0.19	0.13	0.19	0.14	0.09	0.12
INRIX	0.16	0.05	0.20	0.15	0.20	0.17	0.06	0.07
% Difference	-13.8	-25.3	3.2	17.4	4.4	17.1	-30.9	-35.3
Avg % Difference	-0.5		9.4		9.6		-45.3	

For the BI metric, the accuracy of INRIX during rainy conditions was -21.8%, 19.1%, -4.9%, and -41.2%, and during normal weather for PM peak periods was 22.7%, 11.6%, 23.8%, and -17.9%, respectively, for the four segments.

For the COV metric, the accuracy of INRIX during rainy conditions was –0.5%, 9.4%, 9.6%, and -45.3% and during normal weather for PM peak periods was 3.0%, 4.8%, 15.3%, and -21.0%, respectively, for the four segments.

It can be seen from the information above that during rainy conditions the accuracy of INRIX for TTI, PTI, LOTTR, BI, and COV was within a range of -0.5% to 16.5%, -12.4 % to 11.1%, -8.0% to 8.4%, -41.2% to 19.1%, and -45.3% to 9.6%, respectively, for the four segments. Therefore, the LOTTR metric was best captured by the INRIX source compared to field observation during rainy conditions for the Highway 2 testbed, and INRIX was less accurate for BI and COV for the same conditions.

From the results above it can be concluded that the accuracy of INRIX was better in normal weather. However, rainy conditions had the least impact on the accuracy of the TTI, PTI, and LOTTR metrics compared to the BI and COV metrics. In other words, the accuracy difference between normal and rainy conditions was higher for the BI and COV metrics.

5.2.2 Incremental Segment-wise Analysis Under Rain Condition

This section analyzes and compares travel time statistics as segment length increases. Segment 27_40, 27_56, 27_70, and 27_84, which have incremental lengths of 1.18, 2.27, 3.51, and 4.71 miles, respectively, were analyzed during rainy conditions. As mentioned previously, the biggest segment 27_84 analysis is over the entire corridor under rainy conditions.

Table 5.4 shows the mean and median values of the incremental segment for EB and WB traffic and the average value from both directions obtained from field observation and the INRIX data source. It is expected the travel time increases from segment 27_40 to 27_84, as the length of the segment gets longer. This factual increase in travel time over different incremental segments is well captured by both field and INRIX sources.

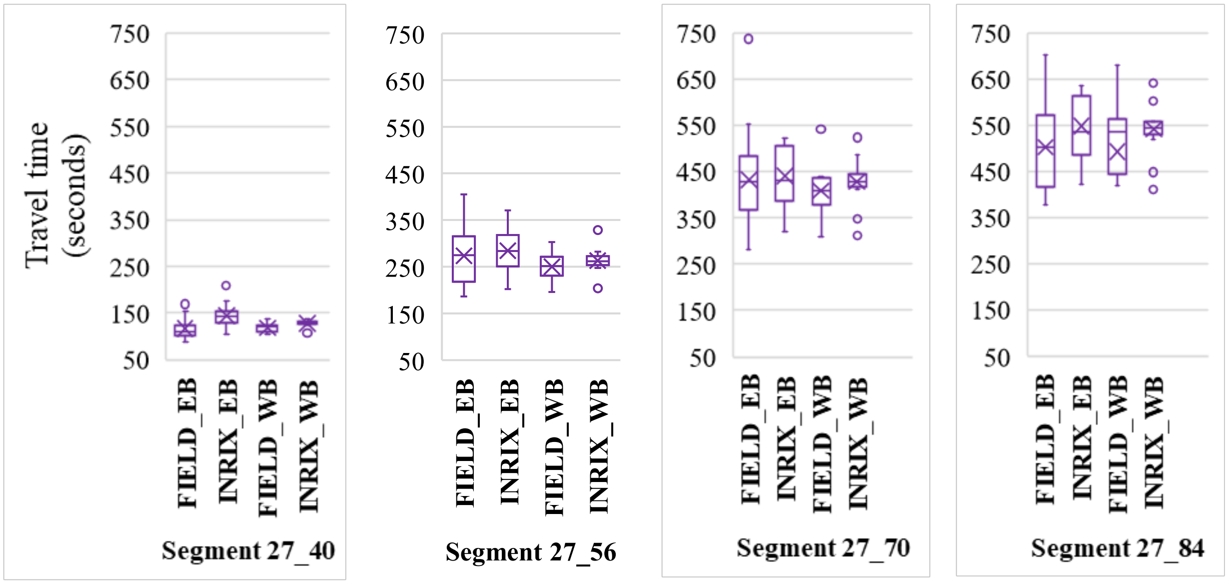
Table 5.4 Measures of central tendency of travel time of incremental segment during rainy condition

	Segment 27_40		Segment 27_56		Segment 27_70		Segment 27_84	
	EB	WB	EB	WB	EB	WB	EB	WB
	Mean (seconds)							
Field	116.1	118.3	273.7	250.2	432.9	409.0	502.1	531.1
Avg Field	117.2		262.0		421.7		515.1	
INRIX	144.8	128.3	284.6	263.0	441.2	427.8	548.2	541.1
Avg INRIX	136.5		273.8		434.5		544.7	
% Difference	24.7	8.4	4.0	5.1	1.9	4.6	9.2	1.9
Avg % Difference	16.5		4.5		3.0		5.7	
	Median (seconds)							
Field	110.5	120.4	275.0	251.3	428.0	409.6	501.8	536.6
Avg Field	113.7		257.9		414.3		530.8	
INRIX	142.5	129.3	283.5	261.9	429.9	427.2	537.0	543.6
Avg INRIX	130.5		263.7		427.2		541.8	
% Difference	29.0	7.4	3.1	4.2	0.5	4.3	7.0	1.3
Avg % Difference	14.8		1.5		3.1		2.1	

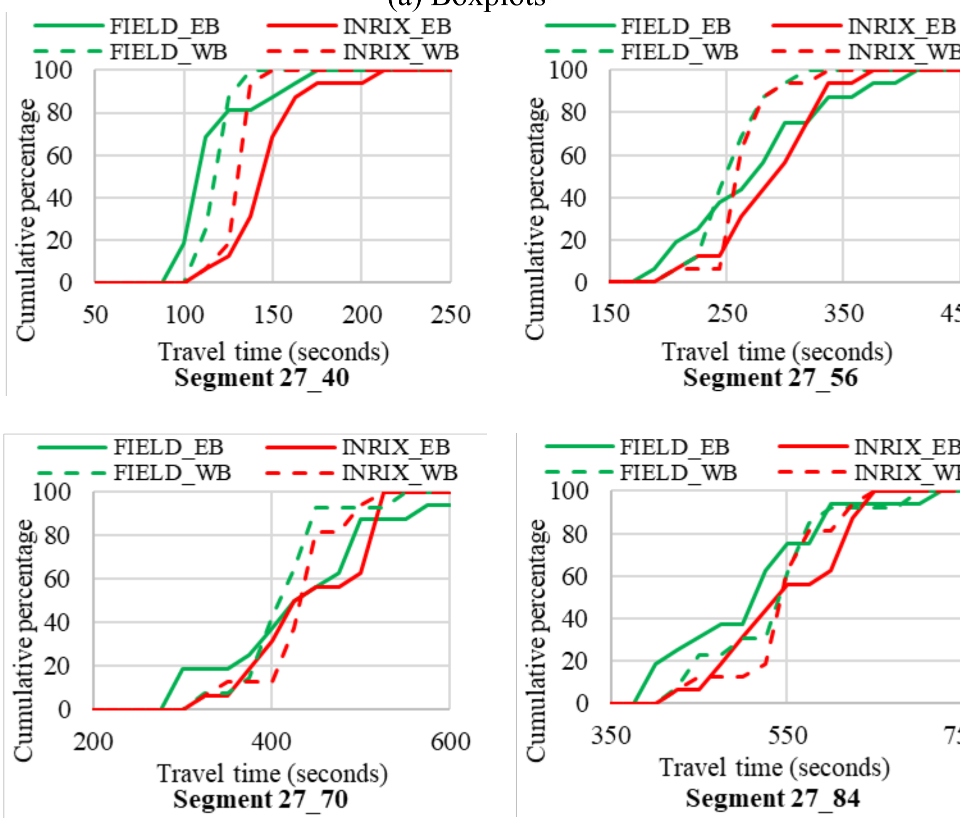
Table 5.4 shows that the mean travel time for segments 27_40, 27_56, 27_70 and 27_84 in the EB direction obtained from field observation was 116.1, 273.7, 432.9, and 502.1 seconds, respectively. In comparison, INRIX travel time was 144.8, 284.6, 441.2, and 548.2 seconds, respectively, for the four EB segments. Therefore, the percentage difference between field observation and INRIX travel time was 24.7%, 4.0%, 1.9%, and 9.2%, respectively for EB traffic. The percentage difference for WB traffic was 8.4%, 5.1%, 4.6%, and 1.9%, respectively. If the average travel time of both directions is considered, then the average percentage difference was found to be 16.5%, 4.5%, 3.0%, and 5.7%, respectively. Note that for normal weather during PM peak periods, the average percentage difference was 10.7%, 2.5%, 3.0%, and 2.6%, respectively for segment 27_40, 27_56, 27_70, and 27_84. Similarly, the average percentage difference for median travel time was 14.8%, 1.5%, 3.1%, and 2.1%, respectively, for the four

incremental segments during rainy conditions. For normal weather during PM peak periods, the average percentage difference was 9.2%, 4.0%, -5.7%, and 3.8%, respectively. Therefore, during rainy conditions, INRIX measured both mean and median values of travel time for the four incremental segments within an accuracy of 1.5% to 16.5%. Note that for individual segments, this accuracy was -11.4% to 16.5%, during rainy conditions.

Figure 5.6 shows standard boxplots and CDF charts of the travel time distribution for the four incremental segments during rainy conditions. As expected, boxplots shifted to higher positions in their respective y-axes as the length of the segment increases from segment 27_40 to 27_84. Similarly, the CDFs from segment 27_56 to 27_84 shifted to the right on the x-axis to indicate the increase of travel time with incremental segment length.



(a) Boxplots



(b) CDF

Figure 5.6 Boxplot and CDF of travel time of incremental segment during rainy condition

Table 5.5 lists quantitative information on the travel time measures of dispersion for the incremental segment. It shows that the travel time standard deviation for segments 27_40, 27_56, 27_70, and 27_84 for WB from field observation were 8.5, 27.6, 52.8, and 71.2 seconds, respectively. Note that as the length of segment increased, so did the standard deviation values in the field observation. Similarly, INRIX's measurement of standard deviation increased with segment length, which was 6.9, 24.7, 49.1, and 54.7, respectively, for WB traffic. Therefore, the percentage difference between field observation and INRIX standard deviation was -19.0%, -10.6%, -7.1%, and -23.2%, respectively. In this case, INRIX underestimated the standard deviation within an accuracy of -7.1% to -23.2% compared to field observation.

When both directions are considered, the average percentage difference of INRIX's standard deviation measurement was within -16.9% to 24.9% for the four incremental segments under rainy conditions. Note that, when the individual segments were analyzed, this range was -45.6% to 16.0%.

Note that under normal weather during PM peak periods, the accuracy of INRIX to measure standard deviation was -6.4% to 10.7% for the incremental segments. For rainy conditions it was -16.9% to 24.9%.

Table 5.5 Measures of dispersion of travel time of incremental segment during rainy condition

	Segment 27_40		Segment 27_56		Segment 27_70		Segment 27_84	
	EB	WB	EB	WB	EB	WB	EB	WB
	Standard deviation (seconds)							
Field	22.0	8.5	63.1	27.6	113.5	52.8	91.2	71.2
Avg Field	16.5		49.3		89.8		82.8	
INRIX	23.7	6.9	43.9	24.7	66.1	49.1	69.3	54.7
Avg INRIX	19.1		36.7		57.7		61.5	
% Difference	7.5	-19.0	-30.4	-10.6	-41.8	-7.1	-24.1	-23.2
Avg % Difference	24.9		-25.6		-35.8		-25.7	
	Interquartile range (seconds)							
Field	18.2	11.2	75.6	32.7	106.0	51.2	123.9	65.6
Avg Field	14.5		48.0		83.8		112.0	
INRIX	22.2	5.2	61.2	15.6	116.1	19.8	120.0	21.3
Avg INRIX	14.7		34.4		76.4		85.1	
% Difference	21.8	-53.2	-19.0	-52.2	9.5	-61.3	-3.1	-67.5
Avg % Difference	1.7		-28.4		-8.9		-24.1	

Similar to the pattern of standard deviation, Table 5.5 shows the interquartile range found from both field observation and INRIX increased as the length of segment increased. The average percentage difference of INRIX's interquartile range was within -28.4% to 1.7% for the four incremental segments compared to the field observation. Note that for individual segment analysis, this range of accuracy for INRIX was -44.8% to 1.7%.

Under normal weather during PM peak periods, the accuracy of INRIX to measure the interquartile range was -5.7% to 15.1% for the incremental segments. For rainy conditions, the range was -28.4% to 1.7%, as shown in Table 5.5.

Table 5.6 lists different TTR metrics of the four incremental segments during rainy conditions. Out of the five TTR metrics measured, the value of TTI, PTI, and LOTTR (measured by both field observation and INRIX source) increased gradually from segment 27_40 to 27_56 and from segment 27_56 to 27_70 as the length of segments increased. For example, the average field-measured value of the TTI metric was 1.38, 1.68, and 1.78 for segment 27_40, 27_56, and 27_70, respectively. The average INRIX value for the TTI metric was 1.61, 1.76 and 1.83, respectively, for the three segments. In this case, INRIX measured the TTI metric with an accuracy of 16.5%, 4.5%, and 3.0%, respectively. For the PTI metrics, INRIX's accuracy was 11.1%, -5.1%, and -5.2%, respectively, for the three incremental segments. In the case of the LOTTR metric, INRIX's accuracy was even higher—in the order of 1.8%, 4.0%, and 1.5%, respectively. Therefore, according to the metrics of TTI, PTI, and LOTTR obtained from both field observation and INRIX, the reliability of the segment decreased as the length of the segment increased up to segment 27_70.

Table 5.6 Measures of travel time reliability metrics (unitless) of incremental segment during rainy condition

	Segment 27_40		Segment 27_56		Segment 27_70		Segment 27_84	
	EB	WB	EB	WB	EB	WB	EB	WB
	Travel time index (TTI)							
Field	1.37	1.39	1.76	1.61	1.83	1.73	1.63	1.72
Avg Field	1.38		1.68		1.78		1.67	
INRIX	1.70	1.51	1.83	1.69	1.86	1.80	1.78	1.76
Avg INRIX	1.61		1.76		1.83		1.77	
% Difference	24.7	8.4	4.0	5.1	1.9	4.6	9.2	1.9
Avg % Difference	16.5		4.5		3.0		5.7	
	Planning time index (PTI)							
Field	1.85	1.51	2.43	1.85	2.52	2.00	2.02	2.04
Avg Field	1.75		2.24		2.31		2.10	
INRIX	2.15	1.62	2.21	1.89	2.18	2.09	2.05	2.00
Avg INRIX	1.95		2.13		2.19		2.06	
% Difference	16.7	7.1	-9.4	2.0	-13.4	4.2	1.6	-2.1
Avg % Difference	11.1		-5.1		-5.2		-2.0	
	Level of travel time reliability (LOTTR)							
Field	1.12	1.03	1.17	1.09	1.13	1.07	1.16	1.06
Avg Field	1.09		1.13		1.15		1.08	
INRIX	1.09	1.02	1.13	1.05	1.18	1.05	1.14	1.03
Avg INRIX	1.11		1.17		1.17		1.12	
% Difference	-2.2	-0.8	-3.2	-3.9	3.8	-1.6	-1.2	-2.8
Avg % Difference	1.8		4.0		1.5		3.7	
	Buffer index (BI)							
Field	0.35	0.08	0.38	0.15	0.38	0.16	0.24	0.18
Avg Field	0.27		0.33		0.30		0.26	
INRIX	0.26	0.07	0.21	0.12	0.17	0.16	0.15	0.14
Avg INRIX	0.21		0.21		0.19		0.16	
% Difference	-24.7	-16.3	-46.3	-22.9	-54.5	-3.1	-35.9	-25.1
Avg % Difference	-21.8		-36.9		-34.7		-36.0	
	Coefficient of variation (COV)							
Field	0.19	0.07	0.23	0.11	0.26	0.13	0.18	0.13
Avg Field	0.14		0.19		0.21		0.16	
INRIX	0.16	0.05	0.15	0.09	0.15	0.11	0.13	0.10
Avg INRIX	0.14		0.13		0.13		0.11	
% Difference	-13.8	-25.3	-33.0	-15.0	-42.9	-11.2	-30.5	-24.6
Avg % Difference	-0.5		-28.9		-37.7		-29.7	

When the last segment 70_84 is considered under segment 27_84, the value of all five TTR metrics was lower than segment 27_70. This indicates that the rising trend of the TTR metric value was disrupted when segment 70_84 was taken into account. Note that in between 70th Street and 84th Street (i.e., segment 70_84), there is no signalized intersection. On the other hand, there are signalized intersections between 27th and 40th Street, 40th and 56th Street, and 56th and 70th Street, along the Highway 2 testbed as discussed in Chapter 3. It can be hypothesized that the presence of signalized intersections within each segment of 27_40, 40_56, and 56_70 contributed to the increased variability of the travel time. Therefore, for each incremental segment of 27_40, 27_56, and 27_70, the TTR metric values increased. When segment 70_84 was added, there was variability in travel time, potentially due to the absence of signalized intersections. This reduced the overall TTR metric of segment 27_84. Note that a similar observation was also made under normal weather conditions during PM peak hour periods. This example demonstrates that segment length and its characteristics may impact the TTR metric, as hypothesized when the incremental segment was considered for analysis.

Note that, for incremental segments in rainy conditions, the TTI, PTI, and LOTTR metrics derived from INRIX travel time data were accurate within -5.2% to 16.1%. Among these three metrics, INRIX measured the LOTTR metric most accurately. In comparison, BI and COV values from INRIX were less accurate. The average percentage difference from INRIX data for BI ranged from -21.8% to -36.0%, and for COV it ranged from -0.5% to -37.7%, compared to the field observation, during rainy conditions. Note that both BI and COV metrics underestimated the values, which means that the INRIX source would suggest better reliability for these four incremental segments than field observation.

Note that for incremental segment analysis, for both normal weather during PM peak hours and rainy conditions, INRIX captured the LOTTR metric most accurately and BI was measured with the least accuracy.

Note that segment 27_84 represents the entirety of the Highway 2 testbed (i.e., corridor 27_84). It was found that, under rainy conditions, INRIX was able to measure the mean, median, standard deviation, and interquartile range of observed travel time with an accuracy of 5.7%, 2.1%, -25.7%, and -24.1%, respectively. Note that during normal weather conditions for PM peak periods, these accuracies were 2.6%, 3.8%, 0.9%, and 3.9%, respectively. Therefore, it shows that during normal weather conditions, INRIX captured the measure of dispersion more accurately than during rainy conditions for the entire corridor.

During rainy conditions, for corridor 27_84, INRIX measured the PTI, TTI, LOTTR, BI, and COV metric as 1.77, 2.06, 1.12, 0.16, and 0.11 against the field observed values of 1.67, 2.10, 1.08, 0.26 and 0.16. Therefore, the accuracy of INRIX to measure the five TTR metrics becomes 5.7%, -2.0%, 3.7%, -36.0%, and -29.7%, respectively. Therefore, the accuracy of INRIX for PTI, TTI, and LOTTR remains higher and similar for rainy conditions. Similar to the previous observations, BI and COV were least accurately measured by INRIX for rainy conditions in corridor 27_84.

5.3 Analysis and Validation of Travel Time Reliability Under Snow Condition

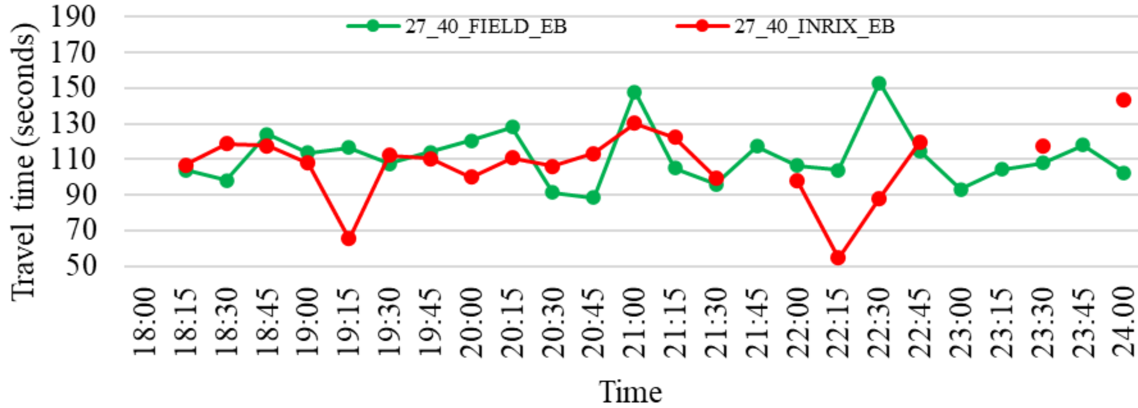
The goal of this section is to compare the travel time from both field and INRIX sources with comparison charts, measuring statistics, and reliability metrics during snowy conditions.

5.3.1 Segment-wise Analysis Under Snow Condition

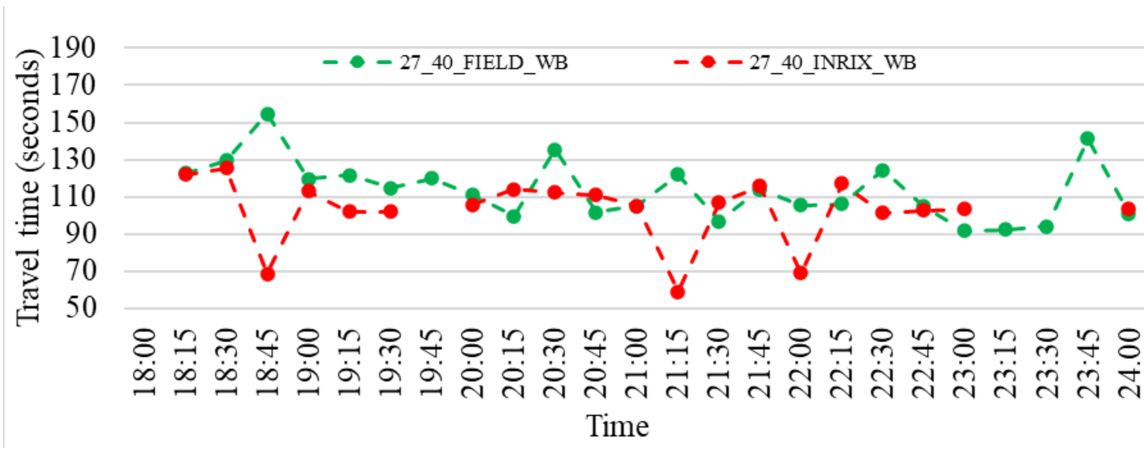
The segment-wise analysis refers to the analysis of each segment. However, as previously mentioned, the video camera located at 56th Street on Highway 2 malfunctioned during snowy conditions and did not record any footage or collect MAC addresses. Therefore, for segment-wise analysis, segments 27_40 and 70_84 were analyzed. The comparison charts, measures of central tendency, dispersion, and reliability metrics for these two segments during snowy conditions are presented below.

5.3.1.1 Comparison Charts

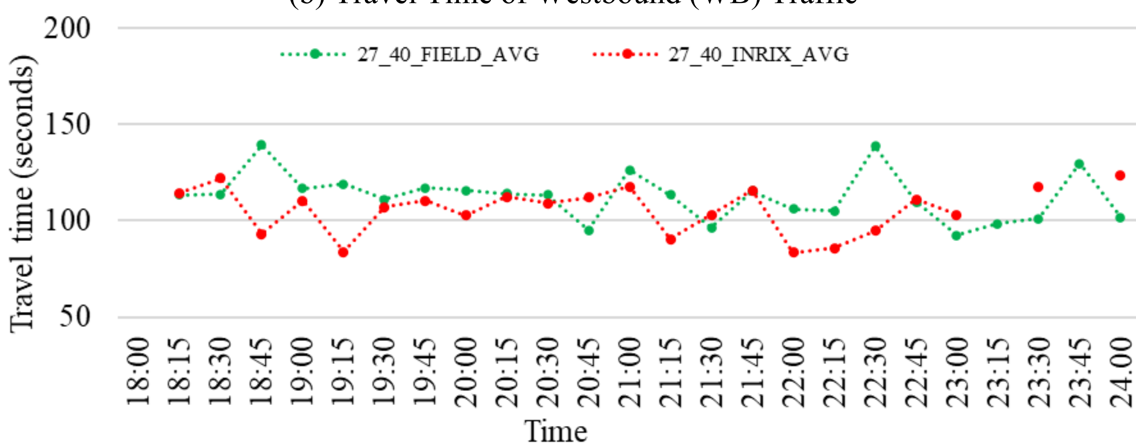
Figures 5.7 and 5.8 show the travel time during snowy conditions for segment 27_40 and 70_84 for EB, WB, and both directions combined from field and INRIX data sources. Note that there was missing data for a few 15 minutes intervals, which were not plotted in the charts.



(a) Travel Time from Eastbound (EB) Traffic

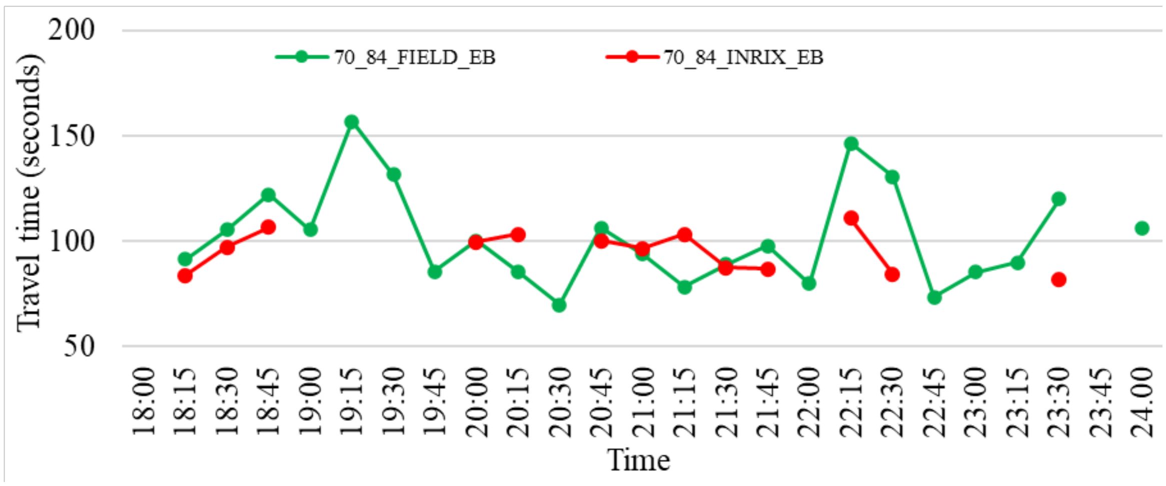


(b) Travel Time of Westbound (WB) Traffic

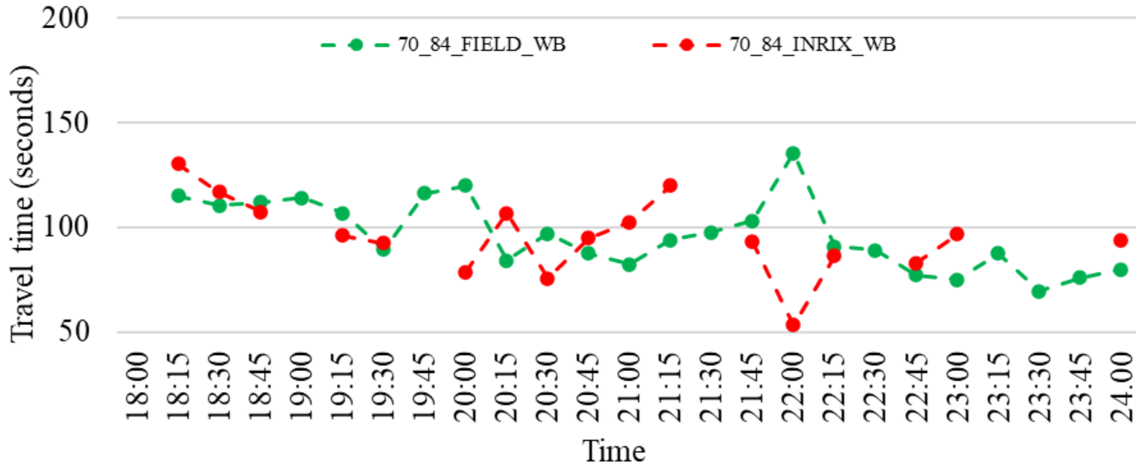


(c) Average Travel Time of EB and WB Traffic

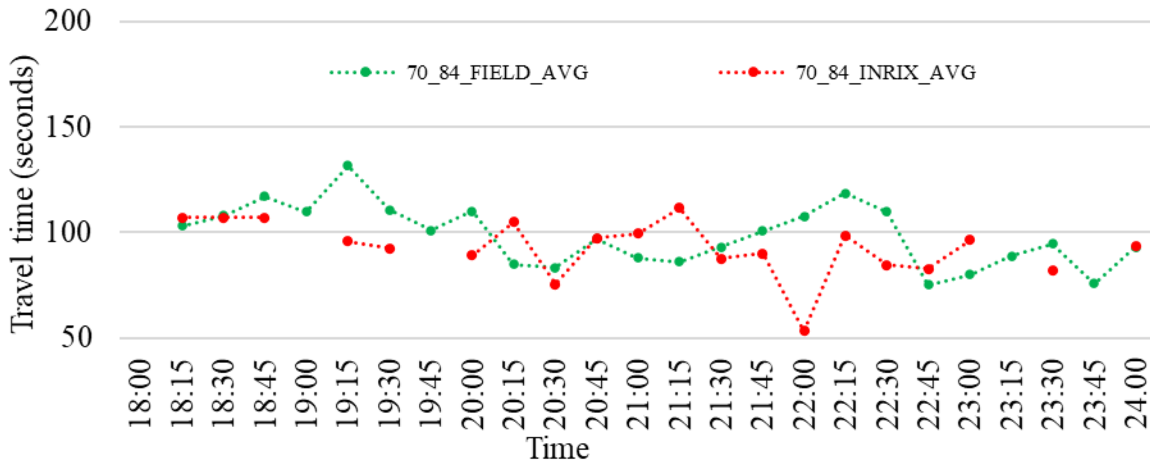
Figure 5.7 Comparisons of travel time for Segment 27_40 during snowy condition



(a) Travel Time from Eastbound (EB) Traffic



(b) Travel Time of Westbound (WB) Traffic



(c) Average Travel Time of EB and WB Traffic

Figure 5.8 Comparisons of travel time for Segment 70_84 during snowy condition

Figures 5.7 and 5.8 shows that, overall, INRIX's travel time follows the pattern of field observation for EB, WB, and combined directions of traffic. However, for a few 15-minute intervals, data from two sources did not match accurately. The following sections discuss and compare the statistics and reliability metrics related to travel time during snowy conditions.

5.3.1.2 Measures of Central Tendency

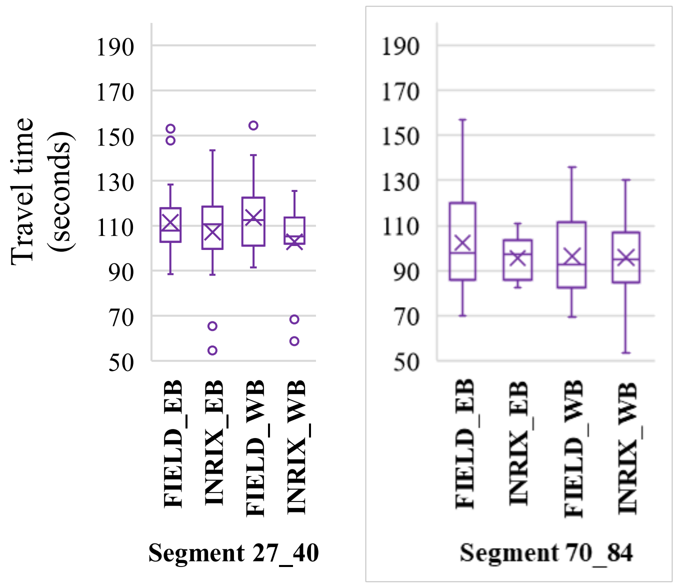
Table 5.7 lists the measures of central tendency, which are the mean and median, for each segment for both directions of traffic on segment 27_40 and 70_84. The table shows that INRIX measured the mean value of travel time for segment 27_40 and 70_84 with an accuracy of -6.8% and -3.6%, respectively, compared to the field observation. Similarly, for the median, INRIX captured the values with an accuracy of -1.9% and 2.4%, respectively.

Table 5.7 Measures of central tendency of travel time of two segments during snowy condition

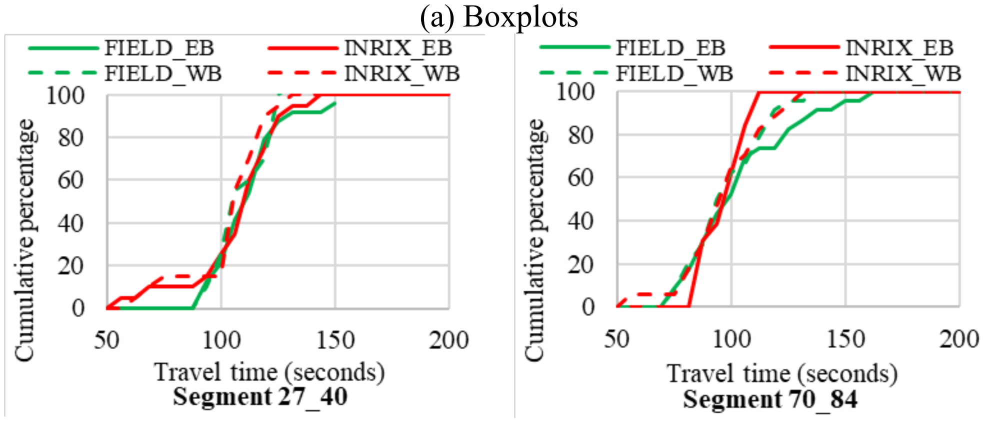
	Segment 27_40		Segment 70_84	
	EB	WB	EB	WB
	Mean (seconds)			
Field	111.6	113.7	102.3	96.3
INRIX	107.2	102.9	95.6	95.7
% Difference	-4.0	-9.5	-6.5	-0.6
Avg % Difference	-6.8		-3.6	
	Median (seconds)			
Field	107.8	112.5	98.0	92.5
INRIX	110.7	105.3	97.2	94.8
% Difference	2.7	-6.4	-0.8	2.5
Avg % Difference	-1.9		2.4	

5.3.1.3 Measures of Dispersion

Figure 5.9 shows standard boxplots and the CDF of the travel time distribution for EB and WB traffic in two segments during snowy conditions obtained from field and INRIX sources. These boxplots and CDF charts visually show the distribution characteristics of the travel time.



(a) Boxplots



(b) CDF

Figure 5.9 Boxplot and CDF of travel time during snowy condition

Table 5.8 lists the measure of dispersion of the travel time distribution quantitatively. It shows that the standard deviation of travel time in the WB direction for segment 27_40 and 70_84 obtained from field observation was 16.1 and 17.0 seconds, respectively. In comparison, INRIX's standard deviation of travel time was 17.6 and 18.2 seconds, respectively, for these two segments in the EB direction. Therefore, the percentage difference in the standard deviation of travel time between field observation and INRIX was 9.5% and 7.3%, respectively. INRIX's accuracy was lower for EB traffic: 27.9% and -58.6%, respectively, for segment 27_40 and

70_84. Combining both directions, the average percentage difference was 19.1% and -26.4%, respectively, for the two segments.

Table 5.8 Measures of dispersion of travel time of two segments during snowy condition

	Segment 27_40		Segment 70_84	
	EB	WB	EB	WB
	Standard deviation (seconds)			
Field	15.8	16.1	23.0	17.0
INRIX	20.2	17.6	9.5	18.2
% Difference	27.9	9.5	-58.6	7.3
Avg % Difference	19.1		-26.4	
	Interquartile range (seconds)			
Field	13.8	20.7	27.4	27.2
INRIX	17.9	11.1	16.2	20.4
% Difference	29.6	-46.4	-40.9	-25.1
Avg % Difference	-24.0		-35.1	

Table 5.8 also shows that INRIX measured the interquartile range of travel time for the two segments with an accuracy of -24.0% and -35.1% during snowy conditions. Therefore, during snowy conditions, INRIX captured the central tendency of TTD more precisely than the measure of dispersion.

Note that, mostly, we did not compare the snow condition with the normal weather condition analyzed in Chapter 4. This is because the peak hour periods during normal weather were from 7:00 a.m. to 10:00 a.m. and from 4:00 p.m. to 7:00 p.m. for a given day. On the other hand, the snow occurred from 6:00 p.m. to 12:00 a.m. There is a natural difference in traffic demand between peak and non-peak hour periods. The rainy condition analyzed occurred from 3:00 p.m. to 7:00 p.m. Therefore, comparing the snow conditions from 6:00 p.m. to 12:00 a.m.

with other times mentioned may not be appropriate. This is why the focus of the analysis is on the observed values of TTD and the accuracy of INRIX within the snow periods.

5.3.1.4 Travel Time Reliability Index

Table 5.9 compares the TTR metrics for segments 27_40 and 70_84 during snowy conditions for field and INRIX data sources. The INRIX accuracy when measuring the TTI, PTI, and LOTTR metrics was -6.8% to -3.6%, -13.7% to -11.7%, and -9.3% to -2.0%, respectively, compared to the field observation for both directions combined. However, the accuracy of INRIX in measuring the BI and COV metrics was comparatively lower. The average percentage difference of INRIX's measurement of BI measurement was -32.8% and -32.4%, respectively, for segments 27_40 and 70_84. For COV, the average percentage difference was 27.8% and -23.7%, respectively. Therefore, TTI metrics are best captured by the INRIX source compared to the field observation during the snowy condition for the two segments on the Highway 2 testbed. Note that BI and COV being the least accurate metrics to be measured by INRIX were observed across other conditions (i.e., normal weather, rain) as well.

Table 5.9 Measures of travel time reliability metrics (unitless) of travel time of two segments during snowy condition

	Segment 27_40		Segment 70_84	
	EB	WB	EB	WB
	Travel time index (TTI)			
Field	1.31	1.34	1.30	1.23
INRIX	1.26	1.21	1.22	1.22
% Difference	-4.0	-9.5	-6.5	-0.6
Avg % Difference	-6.8		-3.6	
	Planning time index (PTI)			
Field	1.71	1.65	1.85	1.52
INRIX	1.54	1.44	1.38	1.55
% Difference	-9.7	-13.1	-25.2	2.2
Avg % Difference	-13.7		-11.7	
	Level of travel time reliability (LOTTR)			
Field	1.10	1.10	1.24	1.22
INRIX	1.07	1.09	1.06	1.13
% Difference	-2.7	-1.0	-14.3	-7.1
Avg % Difference	-2.0		-9.3	
	Buffer index (BI)			
Field	0.30	0.24	0.42	0.24
INRIX	0.22	0.19	0.13	0.28
% Difference	-25.9	-21.1	-67.8	14.3
Avg % Difference	-32.8		-32.4	
	Coefficient of variation (COV)			
Field	0.14	0.14	0.23	0.18
INRIX	0.19	0.17	0.10	0.19
% Difference	33.2	21.0	-55.7	7.9
Avg % Difference	27.8		-23.7	

5.3.2 Incremental Segment-wise Analysis Under Snow Condition

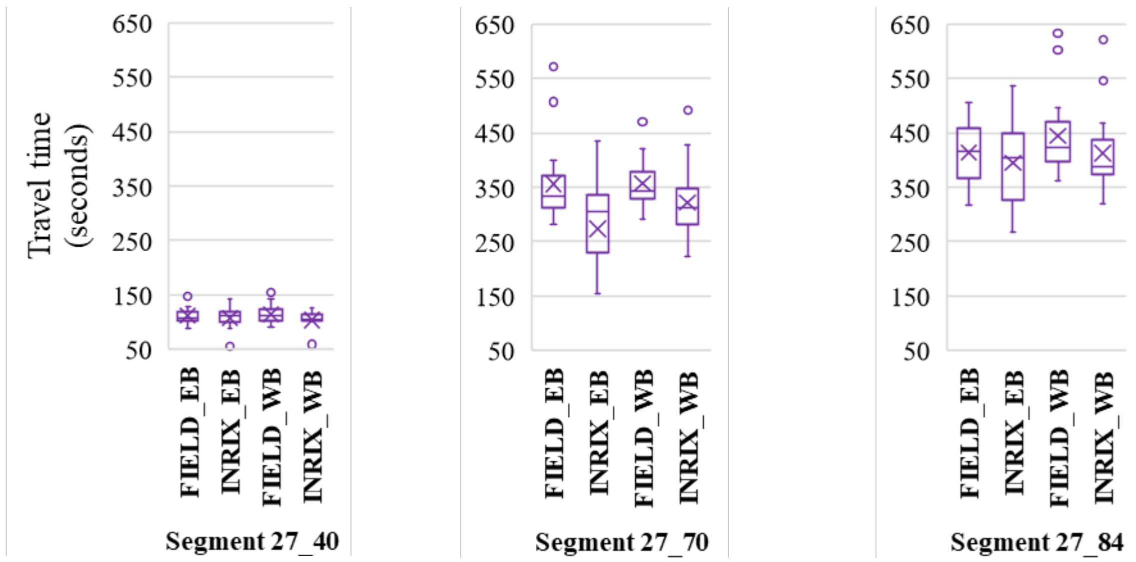
This section analyzes travel time statistics when the segment length increases. As noted earlier, under snow conditions, the video data of 56th Street on Highway 2 was missing. For this reason, segments of 27_40, 27_70, and 27_84, which have the incremental length of 1.18, 3.51, and 4.71 miles, respectively, were analyzed. The biggest segment 27_84 analysis covers the entire corridor under snowy conditions.

Table 5.10 Measures of central tendency of travel time of incremental segment during snowy condition

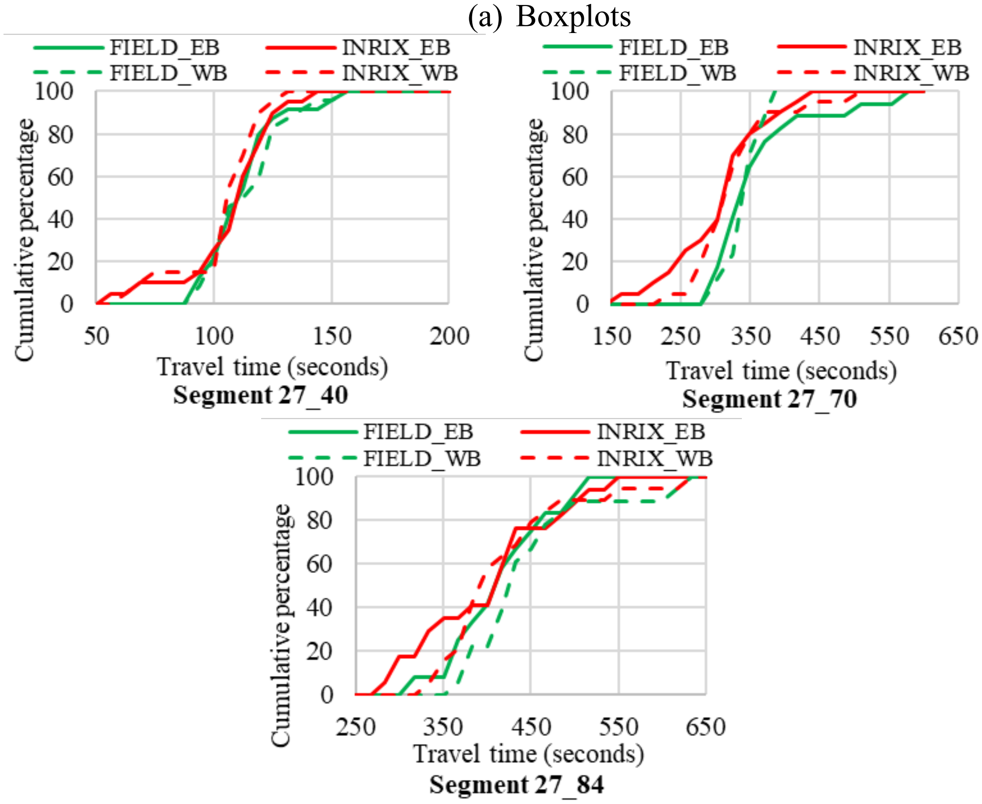
	Segment 27_40		Segment 27_70		Segment 27_84	
	EB	WB	EB	WB	EB	WB
	Mean (seconds)					
Field	111.6	113.7	355.4	357.0	413.5	444.2
Avg Field	112.6		356.3		431.9	
INRIX	107.2	102.9	301.2	321.8	394.4	412.6
Avg INRIX	105.0		311.5		404.0	
% Difference	-4.0	-9.5	-24.5	-13.8	-4.6	-7.1
Avg % Difference	-6.8		-12.6		-6.4	
	Median (seconds)					
Field	107.8	112.5	334.4	343.0	415.5	424.0
Avg Field	109.5		340.7		420.5	
INRIX	110.7	105.3	306.6	311.4	405.0	388.2
Avg INRIX	107.4		307.5		400.8	
% Difference	2.7	-6.4	-8.3	-9.2	-2.5	-8.4
Avg % Difference	-1.9		-9.7		-4.7	

Table 5.10 shows that, as expected, the mean and median travel time for the incremental segment increased as the segment size got larger for both data sources. The mean field-observed travel time for segment 27_40, 27_70, and 27_84 for both directions was 112.6, 356.3, and 431.9 seconds, respectively. In comparison, INRIX's mean travel time was 105.0, 311.5, and 404.0 seconds, respectively, for these three segments. Therefore, the percentage difference between field observation and INRIX travel time was -6.8%, -12.6%, and -6.4%, respectively. In the case of the median, INRIX was able to capture the difference with more precision compared to its mean counterpart: -1.9%, -9.7%, and -4.7%, respectively for segment 27_40, 27_70, and 27_84.

Note that for both the mean and median, INRIX measured slightly lower travel times (i.e., negative percentage difference) for all combination except one compared to the field observation.



(a) Boxplots



(b) CDF

Figure 5.10 Boxplot and CDF of travel time of incremental segment during snowy condition

Figure 5.10 shows standard boxplots and CDF charts for the TTD of the three incremental segments during snowy conditions. As expected, boxplots shift to higher positions in their respective y-axis as the length of the segment increases from segment 27_40 to 27_84. Similarly, the CDFs from segment 27_40 to 27_84 shifted to the right with respect to the x-axis to indicate the increase of travel time with incremental segment length.

Table 5.11 lists quantitative information on the travel time's measures of dispersion for the incremental segment during snowy conditions. It shows that the average field travel time standard deviation for segments 27_40, 27_70 and 27_84 was 15.8, 63.0, and 68.2 seconds, respectively. Note that as the length of segment increased, so did the standard deviation values in the field observation. Similarly, INRIX's measurement of average standard deviation increased with segment length, which was 18.8, 65.1, and 75.9 seconds, respectively. To compare accuracy, the percentage difference between field observation and INRIX standard deviation was 19.1%, 3.3%, and 11.3%, respectively.

Similar to the pattern of standard deviation, the interquartile range found from both field observation and INRIX increased as the length of segment increased. The accuracy of INRIX measurements for the interquartile range varied from -24.0% to 9.9% across the three incremental segments.

Table 5.11 Measures of dispersion of travel time of incremental segment during snowy condition

	Segment 27_40		Segment 27_70		Segment 27_84	
	EB	WB	EB	WB	EB	WB
	Standard deviation (seconds)					
Field	15.8	16.1	77.3	50.5	56.9	73.7
Avg Field	15.8		63.0		68.2	
INRIX	20.2	17.6	70.4	59.3	80.6	72.6
Avg INRIX	18.8		65.1		75.9	
% Difference	27.9	9.5	-9.0	17.4	41.7	-1.6
Avg % Difference	19.1		3.3		11.3	
	Interquartile range (seconds)					
Field	13.8	20.7	55.2	47.0	73.0	59.0
Avg Field	18.8		58.6		76.4	
INRIX	17.9	11.1	71.6	61.8	96.0	59.7
Avg INRIX	14.3		64.4		77.6	
% Difference	29.6	-46.4	29.6	31.5	31.5	1.1
Avg % Difference	-24.0		9.9		1.5	

Table 5.12 lists the TTR metrics of three incremental segments. The field measurement shows that all five TTR metrics except LOTTR increased as the segment length increased from 27_40 to 27_70. For the INRIX measurements, the value of all five TTR metrics increased from segment 27_40 to 27_70. To be specific, from segment 27_40 to segment 27_70, the average value of field measured TTI, PTI, LOTTR, BI, and COV changed from 1.33 to 1.50, 1.71 to 2.06, 1.12 to 1.11, 0.29 to 0.37, and 0.14 to 0.18, respectively. For INRIX, from segment 27_40 to segment 27_70, these changes were 1.24 to 1.31, 1.48 to 1.81, 1.09 to 1.13, 0.20 to 0.38, and 0.18 to 0.21, respectively.

Table 5.12 Measures of travel time reliability metrics (unitless) of incremental segment during snowy condition

	Segment 27_40		Segment 27_70		Segment 27_84	
	EB	WB	EB	WB	EB	WB
	Travel time index (TTI)					
Field	1.31	1.34	1.50	1.51	1.34	1.44
Avg Field	1.33		1.50		1.40	
INRIX	1.26	1.21	1.27	1.36	1.28	1.34
Avg INRIX	1.24		1.31		1.31	
% Difference	-4.0	-9.5	-15.2	-9.9	-4.6	-7.1
Avg % Difference	-6.8		-12.6		-6.4	
	Planning time index (PTI)					
Field	1.71	1.65	2.19	1.98	1.61	1.97
Avg Field	1.71		2.06		1.81	
INRIX	1.54	1.44	1.73	1.82	1.69	1.80
Avg INRIX	1.48		1.81		1.75	
% Difference	-9.7	-13.1	-21.1	-8.1	4.5	-8.9
Avg % Difference	-13.7		-12.1		-3.6	
	Level of travel time reliability (LOTTR)					
Field	1.10	1.10	1.12	1.10	1.11	1.12
Avg Field	1.12		1.11		1.11	
INRIX	1.07	1.09	1.14	1.12	1.14	1.14
Avg INRIX	1.09		1.13		1.12	
% Difference	-2.7	-1.0	1.7	1.3	3.2	1.9
Avg % Difference	-2.0		2.1		0.7	
	Buffer Index (BI)					
Field	0.30	0.24	0.46	0.31	0.20	0.37
Avg Field	0.29		0.37		0.29	
INRIX	0.22	0.19	0.36	0.34	0.32	0.34
Avg INRIX	0.20		0.38		0.33	
% Difference	-25.9	-21.1	-21.7	8.2	56.2	-7.1
Avg % Difference	-32.8		2.2		13.6	
	Coefficient of Variation (COV)					
Field	0.14	0.14	0.22	0.14	0.14	0.17
Avg Field	0.14		0.18		0.16	
INRIX	0.19	0.17	0.23	0.18	0.20	0.18
Avg INRIX	0.18		0.21		0.19	
% Difference	33.2	21.0	7.4	30.2	48.5	5.9
Avg % Difference	27.8		18.2		19.0	

Compared to the field observation, the accuracy of INRIX's measurement for segment 27_40 and 27_70 was -6.8% and -12.6%, -13.7% and -12.1%, -2.0% and 2.1%, -32.8% and 2.2%, and 27.8% and 18.2%, respectively, for the TTI, PTI, LOTTR, BI, and COV metrics. Therefore, among these five TTR metrics, INRIX measured LOTTR most accurately.

When the last segment 70_84 is considered under segment 27_84, all five TTR metric's values in segment 27_84 was lower than segment 27_70. This indicates that the trend of rising TTR metrics values was disrupted when segment 70_84 was taken into account. Similar to the rain condition and normal condition during PM peak hour periods, it can be hypothesized that the presence of signalized intersections within each segment of 27_40, 40_56, and 56_70 contributed to the increased variability of the travel time. Therefore, for the incremental segment of 27_70, the values of TTR metrics increased compared to 27_40. When segment 70_84 was added, the overall TTR metric was reduced for the full corridor segment 27_84.

Note that segment 27_84 represents the entirety of the Highway 2 testbed (i.e., corridor 27_84). It was found that, under snowy conditions, INRIX was able to measure the mean, median, standard deviation, and interquartile range of observed travel time with an accuracy of -6.4%, -4.7%, 11.3%, and 1.5%, respectively. Note that during rainy conditions, these accuracies were 5.7%, 2.1%, -25.7%, and -24.1%, respectively. These quantitative measures may mean that INRIX captured the dispersion characteristics of TTD better in snowy conditions than in rain. However, due to the potential traffic demand differences during the rain and snow periods such deduction may not be appropriate.

During rainy conditions for corridor 27_84, INRIX measured the PTI, TTI, LOTTR, BI, and COV metrics as 1.31, 1.75, 1.12, 0.33, and 0.19, against field observed values of 1.40, 1.81, 1.11, 0.29, and 0.16, respectively. Therefore, INRIX's accuracy when measuring the five TTR metrics was -6.4%, -3.6%, 0.7%, 13.6%, and 19.0%, respectively. The accuracy of INRIX for PTI, TTI, and LOTTR was higher, with LOTTR being the most accurately measured metric. Similar to the previous observations, BI and COV were least accurately measured by INRIX for snowy conditions in corridor 27_84.

5.4 Concluding Remarks

This chapter analyzed and compared statistics and TTR metrics found from field observed and INRIX travel time data for rain and snow conditions. Some of the key findings from this chapter are listed below.

1. For four individual segments, during rainy conditions, the accuracy of INRIX's measurement was -0.5% to 16.5% and -9.9% to 14.8% for mean and median of travel time, respectively.

2. For four individual segments, the accuracy of INRIX's measurement for standard deviation and interquartile ranged from -45.6% to 16.0% and from -44.8% to 1.7%, respectively. Overall, INRIX captured the central tendency of TTD with higher accuracy compared to the measure of dispersion characteristics during rainy conditions. Rain occurred from 4:00 p.m. to 7:00 p.m. during the PM peak period. Compared with the PM peak during normal weather conditions, INRIX measured the dispersion of travel time with less accuracy under rainy conditions. However, it is important to note normal conditions had 32 hours of data to use for analysis while rainy conditions only occurred for three hours.

3. Based on the analysis of the four individual segments during rainy conditions, INRIX the LOTTR metric was the most accurately captured metric and the BI and COV metrics were the least accurately captured. The TTI and PTI metrics did not see a big difference in accuracy

when measured by INRIX. Overall, all metrics were captured less accurately during rainy conditions than normal conditions.

4. As the length of the segment increased, in general, the value of standard deviation and interquartile range of travel time increased under rainy conditions. A similar observation was made for normal weather during the PM peak.

5. As the length of the segment increased, for rainy conditions, from segment 27_40 to 27_70, in general, the value of all five TTR metrics increased (for both data sources). This may be explained by the presence of several signalized intersections between 27th and 70th Street along the testbed, which increased the variability of travel time.

6. For incremental segment analysis, for both rainy and normal weather (PM peak), INRIX captured the LOTTR metric most accurately, and BI was measured with the least accuracy.

7. Regardless of individual or incremental segments during rainy conditions, in general, INRIX captured the PTI, TTI, and LOTTR metrics with the most precision, whereas, BI and COV were captured with less precision.

8. Considering both data sources and both directions of traffic during rainy conditions, the value of the PTI, TTI, and LOTTR metrics of the four individual segments ranged from 1.37 to 2.25, 1.51 to 2.86, and 1.02 to 1.28, respectively.

9. For corridor 27_84, considering both data sources and both directions of traffic during rainy conditions, the value of the PTI, TTI, and LOTTR metrics of the four individual segments ranged from 1.63 to 1.78, 2.00 to 2.04, and 1.03 to 1.14, respectively.

10. Due to malfunction during snowy conditions, video data from 56th Street in the testbed was not recorded. Therefore, segments 27_40 and 70_84 were analyzed. For the

incremental segment, segments 27_70 and 27_84 were analyzed. Snow occurred from 6:00 p.m. to 12:00 a.m. Therefore, comparing the snowy condition with normal weather (AM or PM peak) or the rainy condition (duration of 3:00 p.m. – 7:00 p.m.) may not be appropriate.

11. For the two segments analyzed during snowy conditions, INRIX captured the central tendency of travel time better than the measure of dispersion.

12. For the individual or incremental segment, during snowy conditions, INRIX captured PTI, TTI, and LOTTR with higher accuracy, whereas BI and COV were measured with lower accuracy. This pattern is predominantly present in other comparisons discussed above.

13. For corridor 27_84, considering both data sources and both directions of traffic during snowy conditions, the value of the PTI, TTI, and LOTTR metrics of the four individual segments ranged from 1.28 to 1.44, 1.61 to 1.97, and 1.11 to 1.14, respectively.

Chapter 6 Performance Reliability and Safety Index

This chapter discusses travel time reliability under conditions that potentially impact traffic safety such as adverse weather and global events—like the COVID-19 pandemic—for Region VII highways. Changes in major traffic demand on a given roadway may arise as a result of a complete shift in land use or a change in travel mode choice. However, such changes in land use or mode choice do not occur in a short period. Similarly, changes in accident rate or frequency for highway facilities require years of observation. However, restrictions imposed during the COVID-19 pandemic suddenly impacted traffic conditions in the US, bringing an unforeseeable opportunity to study driver behavior and highway safety. Therefore, COVID-19 presented an opportunity to study its impact on travel time reliability.

On the other hand, it is well known that adverse weather disrupts the transportation system. Apart from catastrophic disasters such as floods, tornadoes, and hurricanes, which can be devastating, more typical weather such as rain, snow, and ice can also have significant detrimental effects on the transportation system. These effects include reduced travel demand, limitation of physical capacity to drive safely, and overall deterioration in traffic safety and reliability. Therefore, analyzing travel time characteristics under rainy conditions can reveal the intriguing relationship between traffic safety and reliability, especially compared to normal weather conditions.

This chapter has two main sections. Section 6.1 includes three studies regarding the impact of COVID-19 on travel time reliability. The first study presented was conducted by Rilett et al. (2021) regarding travel time reliability and COVID-19 using testbeds from Lincoln, Nebraska located near the Highway 2 testbed. Second, we studied the impact of COVID-19 on the Highway 2 testbed used for INRIX validation in Chapters 4 and 5. Third, the findings of a study conducted by Tufuor and Rilett (2022) regarding the impact of COVID-19 on interstate highways are presented. Section 6.2 includes the travel time reliability impacts during the normal and rainy conditions for the Highway 2 testbed.

6.1 COVID-19 and Travel Time and Driving Behavior

The COVID-19 pandemic caused reductions in worldwide travel volumes across all modes of travel, resulting in trip reductions up to 50% (e.g., Beck and Hensher, 2020; de Haas et al., 2020; Lee at al., 2023). Consequently, average distance traveled daily was reduced by around 90% in the US (Glanz et al., 2020). NDOT (2020) reported that average volumes on all state highways decreased around 29% compared with the previous three-year average. Even though daily trips and average distance travelled reduced significantly, the freight traffic for essential supplies did not reduce for obvious reasons (Hendrickson and Rilett 2020). Most importantly, despite less traffic during the pandemic year and a smaller number of traffic accidents, the severity of accidents and risky driving behavior increased (Yasin et al., 2021, Gong et al., 2023; Shaik and Ahmed, 2022). The National Highway Traffic and Safety Administration reported that the fatality rate per 100 million vehicle miles travelled (VMT) was projected to increase from 1.06 in the first half of 2019 to 1.25 in the same period during the COVID-19 pandemic (NHTSA 2020).

As a result, the changes in traffic present an opportunity to analyze TTR performance measurements for different transportation facilities caused by the COVID-19 pandemic. In other words, how do the safer roads (in terms of accident rates) due to less traffic demand impact the TTR metrics? Furthermore, it will be important to find which TTR metric among the wide range of metrics best captures these traffic changes.

6.1.1 COVID-19 and Safety Impacts on Travel Time Reliability on Dodge Street, O Street, Superior Street, and 84th Street

Rilett et al. (2021) investigated the impact of COVID-19 preventive measures on the travel time reliability on arterial roads located in Region VII. They conducted a comparative analysis to assess the average travel time distributions (TTD) and the corresponding travel time reliability metrics before and during the COVID-19 pandemic.

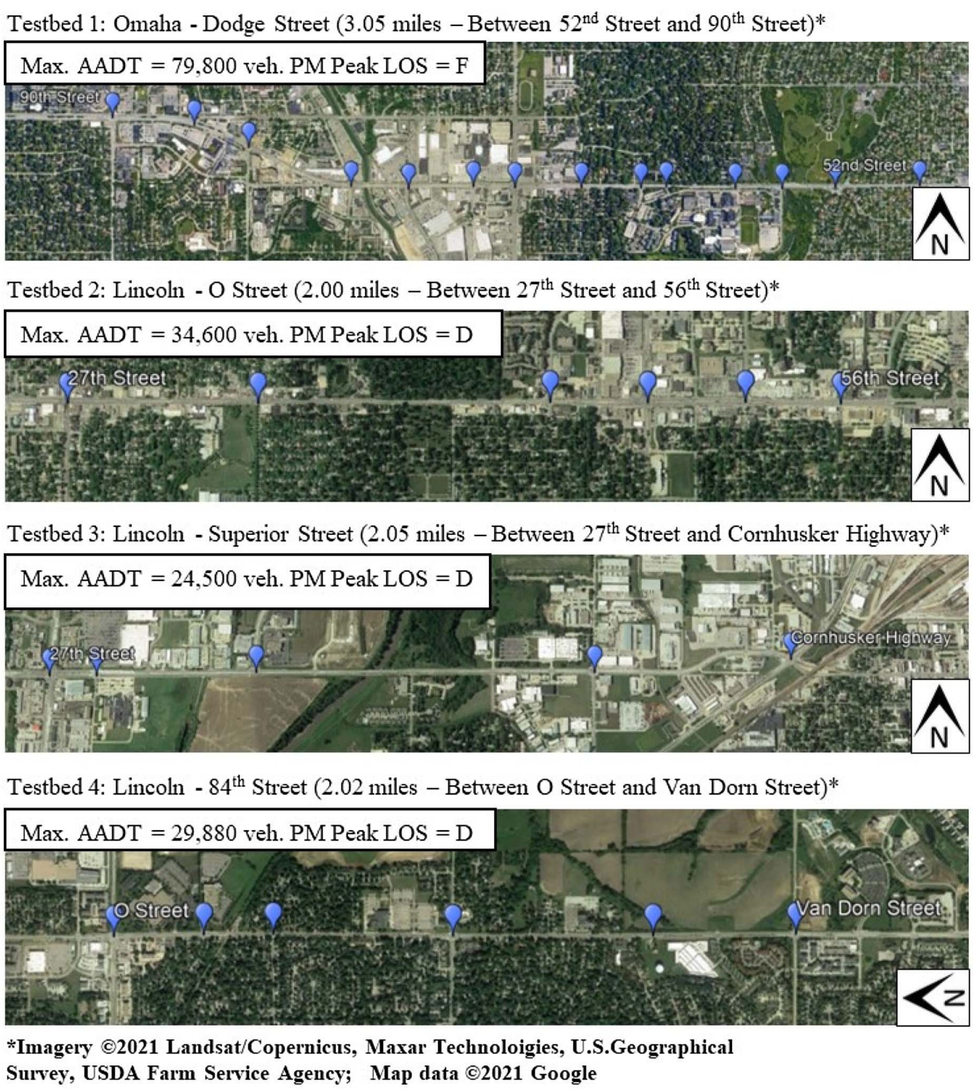


Figure 6.1 Four testbeds at Lincoln and Omaha (Rilett et al., 2021)

Figure 6.1 shows aerial views of the four corridors studied. The corridors ranged in length from 2.0 to 3.1 miles, experienced AADT values of 24,500–79,800 vehicles, and had levels of service as defined by the HCM that ranged from D to F. Testbed 1 was located in Omaha, Nebraska (Dodge Street, from 52nd street to 90th street). Testbeds 2, 3, and 4 were O Street (between 27th Street and 56th Street), Superior Street (between 27th Street and Cornhusker Highway), and 84th Street (between O Street and Van Dorn Street), respectively.

This study used INRIX data from March 1, 2020, to May 31, 2020. This period was chosen to capture the initial effects of COVID-19-related restrictions (e.g., closing of business, stay-at-home protocols, and so forth) that impacted travel in Nebraska.

For comparison, INRIX data for the same March-May period in 2018 and 2019 were also obtained. The analysis focused on the AM peak (7–10 a.m.) and PM peak (4–7 p.m.) periods. Because these periods typically experience the highest traffic volumes and congestion. Each peak period was further divided into 15-minute subperiods to identify and analyze any dynamic changes in travel time. Note that only weekdays were considered for the analysis. Therefore, 16 (2*2*4) scenarios were analyzed in this study: two for AM and PM peak periods, two directions of traffic, and four testbeds.

Rilett et al. (2021) measured the central tendency (i.e., mean and median) and dispersion (i.e., standard deviation, interquartile range, and skewness) of the 16 scenarios of travel time distributions of four testbeds during the COVID-19 pandemic (i.e., 2020), 2018, and 2019. It was found that in 2020, the average mean and standard deviation values for all 16 scenarios were reduced by an average of 14.0% and 43.4%, respectively, compared to the corresponding values from 2018 and 2019.

Table 6.1 lists the TTR metrics as TTI, PTI, LOTTR, BI, and COV during and before the COVID-19 pandemic.

Table 6.1 Measures of travel time reliability metrics of four testbeds during the COVID-19 pandemic (Rilett et al., 2021)

	Dodge Street				O Street				Superior Street				84th Street			
	EB		WB		EB		WB		EB		WB		NB		SB	
Year	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
Travel time index (TTI)																
2018	1.47	1.93	1.63	1.92	1.37	1.51	1.38	1.63	1.33	1.42	1.4	1.4	1.16	1.19	1.14	1.14
2019	1.50	1.82	1.6	1.92	1.31	1.47	1.33	1.51	1.32	1.38	1.41	1.44	1.21	1.24	1.14	1.17
2020	1.15	1.57	1.35	1.47	1.15	1.25	1.12	1.23	1.23	1.24	1.26	1.29	1.06	1.08	1.05	1.06
Percentage difference (negative %)																
%Δ[a]	23.0	16.2	16.7	23.2	13.7	16.3	16.9	21.7	7.1	11.6	10.0	9.3	10.7	11.3	7.7	8.6
Planning time index (PTI)																
2018	1.94	2.56	2.10	2.66	1.71	2.05	1.82	2.15	1.59	1.88	1.73	1.64	1.34	1.41	1.30	1.27
2019	1.81	2.40	1.93	2.89	1.56	1.85	1.73	1.89	1.5	1.63	1.64	1.69	1.4	1.49	1.30	1.36
2020	1.32	1.83	1.60	1.84	1.33	1.44	1.31	1.51	1.4	1.43	1.50	1.50	1.17	1.17	1.15	1.13
Percentage difference (negative %)																
%Δ[a]	29.7	26.3	20.4	33.7	18.5	26.2	26.2	25.2	9.2	18.5	10.9	10.2	14.5	19.5	11.6	13.9
Level of travel time reliability (LOTTR)																
2018	1.16	1.15	1.13	1.20	1.12	1.17	1.15	1.16	1.10	1.13	1.08	1.06	1.06	1.08	1.06	1.05
2019	1.10	1.14	1.10	1.33	1.09	1.12	1.09	1.13	1.06	1.06	1.08	1.09	1.08	1.10	1.06	1.07
2020	1.08	1.09	1.09	1.11	1.07	1.06	1.09	1.08	1.07	1.07	1.09	1.08	1.04	1.04	1.04	1.03
Percentage difference (negative %)																
%Δ[a]	5.0	5.0	2.4	12.6	3.1	7.4	2.7	5.2	0.4	2.4	*0.5*	*0.5*	2.5	4.7	1.5	2.8
Buffer index (BI)																
2018	0.32	0.33	0.29	0.38	0.25	0.36	0.32	0.32	0.20	0.32	0.23	0.17	0.15	0.18	0.14	0.11
2019	0.20	0.32	0.2	0.51	0.19	0.26	0.30	0.25	0.13	0.18	0.16	0.18	0.16	0.21	0.14	0.16
2020	0.15	0.16	0.19	0.25	0.15	0.15	0.16	0.23	0.14	0.15	0.18	0.16	0.1	0.08	0.09	0.07
Percentage difference (negative %)																
%Δ[a]	42.6	49.6	22.4	44.4	30.1	50	47.1	19.3	15.9	38.9	6.2	6.4	32.6	56.5	34.1	46.9
Coefficient of variation (COV)																
2018	0.18	0.18	0.16	0.22	0.14	0.17	0.2	0.17	0.11	0.17	0.13	0.09	0.11	0.10	0.09	0.10
2019	0.22	0.17	0.11	0.28	0.10	0.13	0.16	0.14	0.09	0.11	0.10	0.11	0.10	0.15	0.08	0.09
2020	0.08	0.09	0.10	0.17	0.08	0.08	0.10	0.12	0.08	0.09	0.1	0.09	0.06	0.09	0.05	0.04
Percentage difference (negative %)																
%Δ[a]	60.3	45.0	24.0	30.0	33.1	44.4	44.3	20.5	21.4	38.7	11.1	7.8	46.4	24.6	39.8	56.9

Note: EB = eastbound; WB = westbound; NB = northbound; and SB = southbound. [a]Estimated as quotient of (1) difference between 2020 value and average of 2018 and 2019 values, and (2) average of 2018 and 2019 values. Note that numbers in italics indicate a positive change.

Table 6.1 shows that the TTI, PTI, LOTTR, and BI metrics associated with these travel time distributions were reduced, on average, by 14.0%, 19.7%, 3.5%, and 35.0%, respectively. In general, Rilett and Tufuor (2021) found that out of the four testbeds, the two most congested testbeds (in terms of AADT), Dodge Street and O Street, experienced the most reduction for the TTI, PTI, and BI TTR metrics in the pandemic period compared to the non-pandemic year. However, the LOTTR metric remained insensitive to the high AADT of Dodge Street and O Street, hence, it showed similar changes in LOTTR during the pandemic period across all four testbeds.

Overall, it was found that all TTR metrics were reduced during the COVID-19 pandemic, and it demonstrated that the travel time reliability during the COVID-19 pandemic improved.

6.1.2 COVID-19 and Safety Impacts on Travel Time Reliability on Highway 2

Similar to the study described in Section 6.1.1, we measured the central tendency, dispersion, and TTR metrics for the testbed on Highway 2 using INRIX travel time data. Corridor 27_84 (between 27th Street and 84th Street on Highway 2) was analyzed from March to May (weekdays) for the years 2019 and 2020 for the AM peak (7:00 a.m. –10 a.m.) and PM peak (4:00–7:00 p.m.) periods. Note that 2018 values were not used in this analysis due to missing data.

Table 6.2 Measures of central tendency of travel time of Highway 2 during and before COVID-19 pandemic

	Highway 2			
	EB		WB	
Year	AM	PM	AM	PM
	Mean (min)			
2019	8.35	8.89	7.83	8.77
2020	8.23	7.23	7.32	8.84
	Percentage difference (negative %)			
%Δ[a]	1.50	18.68	6.52	*0.84*
	Median (min)			
2019	8.49	8.69	7.55	8.71
2020	8.43	7.04	7.17	8.70
	Percentage difference (negative %)			
%Δ[a]	0.71	18.94	5.03	0.11

Note: EB = eastbound; WB = westbound; [a]Estimated as quotient of (1) difference between 2020 and 2019 values, and (2) 2019 value. Note that numbers in italics indicate a positive change.

Table 6.2 shows the measure of central tendency (i.e., mean and median) of travel time distributions. This table also includes the percentage difference made by the COVID-19 pandemic year compared to 2019.

The median travel time for both directions observed from AM and PM traffic reduced during the COVID-19 pandemic period. This observation was also true for mean travel time except for the WB traffic from the PM period. Table 6.3 lists two standard measures of dispersion of the travel time distribution: the standard deviation, and the IQR.

Table 6.3 Measures of dispersion of travel time of Highway 2 during and before COVID-19 pandemic

	Highway 2			
	EB		WB	
Year	AM	PM	AM	PM
	Standard deviation (min)			
2019	1.14	1.42	1.22	1.21
2020	1.00	1.04	0.85	1.57
	Percentage difference (negative %)			
%Δ[a]	11.61	26.60	30.43	*29.68*
	Interquartile range (min)			
2019	1.66	1.69	1.66	1.15
2020	1.56	1.33	0.94	1.51
	Percentage difference (negative %)			
%Δ[a]	6.04	21.04	43.20	*31.37*

Note: EB = eastbound; WB = westbound; [a]Estimated as quotient of (1) difference between 2020 and 2019 values, and (2) 2019 value. Note that numbers in italics indicate a positive change.

Except for the PM period from WB traffic, all traffic scenarios during the pandemic period experienced lower standard deviation ranging from 11.61% to 30.43% and lower interquartile range ranging from 6.04% to 43.20% compared to the year 2019.

Table 6.4 lists the TTI, PTI, LOTTR, BI and COV TTR metrics during and before the COVID-19 pandemic.

Table 6.4 Measures of travel time reliability metrics of Highway 2 during and before COVID-19 pandemic

	Highway 2			
	EB		WB	
Year	AM	PM	AM	PM
Travel time index (TTI)				
2019	1.63	1.73	1.52	1.71
2020	1.60	1.41	1.42	1.72
Percentage difference (negative %)				
%Δ[a]	1.50	18.68	6.52	*0.84*
Planning time index (PTI)				
2019	1.94	2.28	1.99	2.09
2020	1.86	1.76	1.72	2.24
Percentage difference (negative %)				
%Δ[a]	3.96	22.83	13.47	*6.97*
Level of travel time reliability (LOTTR)				
2019	1.09	1.13	1.16	1.09
2020	1.08	1.14	1.09	1.12
Percentage difference (negative %)				
%Δ[a]	1.14	*0.94*	5.44	*2.61*
Buffer index (BI)				
2019	0.19	0.32	0.31	0.23
2020	0.16	0.25	0.21	0.30
Percentage difference (negative %)				
%Δ[a]	15.37	21.01	31.75	*32.85*
Coefficient of variation (COV)				
2019	0.14	0.16	0.16	0.14
2020	0.12	0.14	0.12	0.18
Percentage difference (negative %)				
%Δ[a]	10.27	9.73	25.58	*28.60*

Note: EB = eastbound; WB = westbound; [a]Estimated as quotient of (1) difference between 2020 and 2019 values, and (2) 2019 value. Note that numbers in italics indicate a positive change.

Table 6.4 shows that, except for the WB direction from the PM period for all TTR metrics and EB direction from PM for LOTTR, all other traffic scenarios experienced reduced measurement of travel time reliability metrics during the COVID-19 pandemic compared to the year 2019.

Furthermore, it can be observed from Table 6.6 that out of all the scenarios for TTR metrics that showed reduced values during the pandemic period, LOTTR relatively reduced at a smaller rate compared to other TTR metrics. Note that this observation was also true for the four testbeds studied by Rilett and Tufuor (2021) in Section 6.1.1.

Overall, travel became more reliable in the Highway 2 testbed during the COVID-19 pandemic period. This phenomenon can be attributed to the pandemic restrictions that resulted in reduced traffic demand.

6.1.3 COVID-19 and Safety Impacts on Travel Time Reliability on Interstate Highways

Tufuor and Rilett (2022) examined the effect of the COVID-19 pandemic on TTR performance on two high traffic volume interstate highway (i.e., freeway) corridors (I-90 and I-405) in the U.S.A. The TTD before (2018 and 2019) and after (2020) the pandemic was compared for the months of March to May. The Interstate 90 (I-90) corridor was from Chicago, Illinois to Rockford, Illinois, and the Interstate 405 (I-405) corridor was from Los Angeles, California to Mission Viejo, California. Note that the corridor of I-90 was closer to Region VII. These corridors were two of the top 15 most traveled corridors in the U.S.A. The 2019 AADT on I-90 and I-405 were 321,700 and 383,500, respectively. The length of the I-90 and I-405 corridors analyzed were 75 miles and 73 miles, respectively.

Tufuor and Rilett (2022) collected INRIX travel time data from two corridors, from morning peak (6:00 a.m. to 10:00 a.m.) and afternoon peak (3:00 p.m. to 7:00 p.m.), from two directions of traffic for three years. For this analysis, data aggregation levels of 5 minutes and 15 minutes were considered to find if there were any differences in TTR metric if different levels of aggregation were considered. Therefore, there were 48 TTD captured in total for the estimation of the five TTR metrics: TTI, PTI, LOTTR, BI, and COV.

Before the pandemic (during 2018 and 2019), Tufuor and Rilett (2022) found that for the I-405 California corridor, based on 15-minute data aggregation, the TTI, PTI, LOTTR, BI, and COV metrics ranged from 1.55 to 2.05, 1.54 to 2.72, 1.14 to 1.20, 0.26 to 0.32, and 0.17 to 0.20, respectively. For the I-90 Chicago corridor, these metrics ranged from 1.08 to 1.40, 1.07 to 1.83, 1.08 to 1.18, 0.17 to 0.30, and 0.10 to 0.17, respectively. Note that the TTR metrics from I-90 Chicago are more relevant than those from I-405 California for our project due to the proximity to Region VII.

While comparing the pandemic period (2020), Tufuor and Rilett (2022) found that the TTI values and the PTI values experienced an average reduction of 34% and 23%, respectively. The decrease in values ranged from 15% to 49% for the TTI and from 17% to 28% for the PTI. LOTTR only decreased, on average, by 3% during the COVID-19 pandemic. LOTTR had the lowest percentage reduction compared with the TTI and PTI metrics (the decrease for LOTTR ranged from 2% to 12%).

On the other hand, in 2020, the BI values ranged from 5% to 216% with an average of 89%. Similarly, the COV values increased by an average of 25% in 2020 (range of 4% to 78%). Therefore, unlike, PTI, TTI and LOTTR, the BI and COV metrics increased during pandemic indicating that the TTR reduced during the pandemic, which is a counterintuitive finding compared to the notion that reduced traffic demand during the pandemic would have increased the TTR. Tufuor and Rilett (2022) argued that such counterintuitive phenomena were observed because i) both BI and COV measured the ratio of change of dispersion characters of TTD and central tendency of TTD and during the pandemic the dispersion increased at a greater rate than the measure of central tendency, and ii) a higher percentage of truck traffic demand in the pandemic year, trucks travel slower than passenger cars, and trucks have less variability in travel time compared to passenger cars.

Tufuor and Rilett (2022) found no appreciable difference in the five TTR metrics whether the analyses were conducted using 5 minutes or 15 minutes data aggregation during the pre-pandemic years of 2018 and 2019. During the pandemic year, similar results were found for TTI, PTI, and LOTTR. However, there was on average a 13.8% and 6.1% increase in the BI values and the COV values, respectively, when the travel time data was aggregated at a 15-minute level compared with a 5-minute level.

Tufuor and Rilett (2022) conducted a spatial analysis with three selected segments based on different levels of congestion by AADT from the I-90 test corridor. This spatial analysis considered westbound evening peak traffic movement at the 15-minute aggregate scenario. The three segments denoted as SEG1, SEG2, and SEG3 are 6.7 miles, 7.0 miles, and 5.2 miles, respectively. SEG1 is located within the central business district of Chicago while the starts of SEG2 and SEG3 are located approximately 23 miles and 45 miles from the end of SEG1, respectively. The AADT volumes for SEG1, SEG2, and SEG3 were 195,800, 136,400, and 56,300, respectively (IDOT, AADT, 2021). Table 6.7 shows the descriptive statistics of TTD and the corresponding TTR metrics for three segments of the I-90 corridor during the analysis years.

Table 6.5 Travel time distribution statistics and travel time reliability metrics for three I-90 segments (Tufuor and Rilett, 2022)

Origin and destination intersections	Segment 1 (6.7 miles) Exit 50 to I-90/I-94 W split SEG1	Segment 2 (7.0 miles) IL-53 to Barrington Road SEG2	Segment 3 (5.2 miles) IL-47 to US-20 SEG3
Mean (minutes)			
2018	20.55	7.28	4.85
2019	18.56	7.86	4.86
2020	6.46	6.50	4.56
Percentage difference (negative %Δ*)	67.0	14.1	6.1
Standard Deviation (minutes)			
2018	7.83	2.41	0.16
2019	7.36	3.10	0.38
2020	2.79	1.22	0.15
Percentage difference (negative %Δ*)	63.3	55.7	44.4
95th percentile (minutes)			
2018	33.19	11.70	5.07
2019	30.80	12.15	5.78
2020	12.39	7.59	4.90
Percentage difference (negative %Δ*)	61.3	36.4	9.7
Travel time index (unitless)			
2018	2.71	1.07	1.05
2019	2.45	1.16	1.06
2020	0.85	0.96	0.99
Percentage difference (negative %Δ*)	67.1	13.9	6.2
Planning time index (unitless)			
2018	4.38	1.72	1.10
2019	4.06	1.79	1.26
2020	1.63	1.12	1.07
Percentage difference (negative %Δ*)	61.4	36.2	9.3
Level of travel time reliability (unitless)			
2018	1.35	1.32	1.02
2019	1.32	1.39	1.04
2020	1.14	1.23	1.02
Percentage difference (negative %Δ*)	14.6	9.2	1.0
Buffer index (unitless)			
2018	0.62	0.61	0.05
2019	0.66	0.55	0.19
2020	0.92	0.17	0.07
Percentage difference (negative %Δ*)	*43.8*	70.7	41.7
Coefficient of variance (unitless)			
2018	0.38	0.33	0.03
2019	0.40	0.39	0.08
2020	0.43	0.19	0.03
Percentage difference (negative %Δ*)	*10.3*	47.2	45.5

Note: *The percentage change is estimated as the quotient of (i) the difference between the 2020 value and the average of the 2018 and 2019 values, and (ii) the average of the 2018 and 2019 values. All positive changes are italicized.

Table 6.5 shows that, before the COVID-19 pandemic, the more congested segments tended to have longer travel times. As expected, the segments that experienced the highest pre-pandemic congestion levels also had a greater decrease in the mean travel time (i.e., 67%, 14%, and 6% for SEG1, SEG2, and SEG3) and measure of dispersion (i.e., 63%, 56%, and 44% for SEG1, SEG2, and SEG3) during the pandemic, all else being equal.

Table 6.5 shows that TTI, PTI, and LOTTR metrics, reduced during the pandemic period, and these reductions were greater in the segments that were most congested during the pre-pandemic time. However, for SEG1 (i.e., the most congested segment), the BI and COV metrics increased, meaning that the TTR during the pandemic period was reduced. Tufuor and Rilett (2022) noted that understanding how choosing different TTR metrics impacts TTR differently for a given situation requires a deep understanding of how the measures of central tendency and measures of dispersion are changing.

6.2 Rain and Safety Impacts on Travel Time Reliability on Highway 2

Inclement weather conditions such as rain can be considered the most common natural event that may impact normal traffic state and driver behaviors. Previous studies listed adverse impacts of rain on travel demand, traffic flow, physical capacity of driving, and overall traffic safety (e.g., Pang et al., 2017; Jackson et al., 2016; Maurice et al., 2015; Edwards et al., 1998; Jaroszweski et al., 2014). Adverse weather is more likely to impact the 80^{th} or 95^{th} percentile travel time than the mean travel time, meaning the travel time reliability is likely to be impacted (Zhang et al., 2019).

In this section, we study the travel time reliability under rainy conditions for the Highway 2 testbed. Note that Chapter 4 discussed the validation of travel time reliability during rain and snow conditions. In this chapter, the travel time reliability during rainy conditions is compared to the normal conditions that prevailed just a week before on the same day and same period.

Travel time data during the rainy conditions in 2022 along the Highway 2 testbed were collected using INRIX. From historical weather data, month, day, and duration of rain were confirmed and selected for analysis. Note that weekdays were considered for the analysis. The month and day selected for analysis traffic during rain are as follows: March 18 (12:00 a.m. - 2:00 a.m.), April 29 (6:30 p.m. - 7:00 a.m.), May 25 (7:00 p.m. - 10:00 p.m.), June 17 (1:00 a.m. - 2:00 a.m.), July 7 (9:00 p.m. - 10:00 p.m.). Also, a normal day without rain was considered for comparison purposes. Normal days were selected as the same day of a week (7 days before the rainy day) during the same time period of rain. Therefore, March 11 (12:00 a.m. to 2:00 a.m.), April 22 (6:30 a.m. - 7:00 a.m.), May 18 (7:00 p.m. - 10:00 p.m.), June 10 (1:00 a.m. - 2:00 a.m.), and June 30 (9:00 p.m. - 10:00 p.m.). The goal was to select days and times so that traffic demand remains similar except for the rain condition for a meaningful comparison. In the analysis, travel time data (in minutes) were aggregated into 15-minute intervals for both directions of traffic to catch the dynamic changes.

Tables 6.6, 6.7, and 6.8 list the comparative analysis of the measure of central tendency, dispersion characteristics, and travel time reliability metrics, respectively, for normal and rainy weather conditions.

Table 6.6 Measures of central tendency of travel time of Highway 2 during rain and normal conditions

	Highway 2			
Condition	EB	WB	EB	WB
	Mean (min)		Median (min)	
Rain	7.21	6.74	7.02	6.61
Normal	6.72	6.62	6.59	6.39
Percentage difference (negative %)				
%Δ[a]	6.76	1.87	6.13	3.33

Note: EB = eastbound; WB = westbound; [a]Estimated as quotient of (1) difference between Normal and Rain conditions' values, and (2) Rain condition'. Note that numbers in italics indicate a positive change.

Table 6.6 shows that for both EB and WB directions of traffic, the mean and median value of travel time during rainy conditions was higher compared to normal weather conditions.

Table 6.7 Measures of dispersion of travel time of Highway 2 during rain and normal conditions

	Highway 2			
Condition	EB	WB	EB	WB
	Standard deviation (min)		Interquartile range (min)	
Rain	0.93	0.70	1.09	0.75
Normal	0.70	0.73	0.81	0.63
Percentage difference (negative %)				
%Δ[a]	24.86	*4.13*	25.69	15.44

Note: EB = eastbound; WB = westbound; [a]Estimated as quotient of (1) difference between Normal and Rain conditions' values, and (2) Rain condition'. Note that numbers in italics indicate a positive change.

Table 6.7 shows that the standard deviation for WB traffic during rainy conditions was smaller than the rainy condition (i.e., 4.13%). However, standard deviation of travel time during rain for EB was higher (i.e., 24.86%) compared to the normal conditions.

The interquartile range for both directions of traffic was higher (i.e., 25.69% for EB and 15.44% for WB) for rainy conditions compared to normal weather.

Table 6.8 Measures of travel time reliability metrics of Highway 2 during rain and normal conditions

	Highway 2									
Condition	EB	WB	EB	WB	EB	WB	EB	WB	EB	WB
	Travel time index (TTI)		Planning time index (PTI)		Level of travel time reliability (LOTTR)		Buffer index (BI)		Coefficient of variation (COV)	
Rain	1.40	1.31	1.67	1.52	1.14	1.10	0.19	0.16	0.13	0.10
Normal	1.31	1.29	1.53	1.50	1.11	1.09	0.17	0.16	0.10	0.11
	Percentage difference (negative %)									
%Δ[a]	6.76	1.87	8.70	1.69	3.30	0.71	12.79	*1.34*	19.41	*6.12*

Note: EB = eastbound; WB = westbound; [a]Estimated as quotient of (1) difference between Normal and Rain conditions' values, and (2) Rain condition'. Note that numbers in italics indicate a positive change.

The TTR metrics for TTI, PTI, and LOTTR during rainy conditions were higher compared to the normal condition for both directions of traffic for the Highway 2 testbed. For WB traffic, only the BI and COV metrics were less for rainy conditions compared to normal weather. Therefore, in general, we found that the travel was less reliable during the rainy conditions compared to the normal condition for the Highway 2 testbed.

6.3 Concluding Remarks

From all the studies conducted in this section, it was found that events like COVID-19 had a significant impact on the travel time reliability in Region VII highways. Furthermore, inclement weather such as rain can negatively impact reliability as well.

Most of the TTR metrics used were able to capture the impact of COVID-19 or rain for the testbed examined. However, different TTR metrics produced different rates of change and in a few cases the change of reliability pattern showed opposite results depending on which TTR metrics were used. In general, TTI and PTI metrics were able to capture the increased reliability on the COVID-19 pandemic period and reduced reliability during adverse weather. LOTTR did the same on a lesser degree. BI and COV metrics produced mixed results for different testbeds and different spatial and temporal characteristics of the study. Note that this pattern of performance for the TTR metrics is similar to the findings listed in Chapter 4 and Chapter 5.

The most remarkable finding from this project was that whether the transportation system's reliability increased or decreased or to what extent the reliability changed depended on which metric was used to measure it. Therefore, engineers and transportation agencies require a deeper understanding of the travel time related statistics and transportation system's characteristics to understand the actual changes that occur in travel time reliability.

Chapter 7 Conclusions and Recommendations

Roadway performance measures are used for operating, planning, and design purposes to improve services for road users. However, simple statistics of the performance metrics such as measures of central tendency (e.g., mean, median), while useful, are not robust enough for transportation agencies to make all planning or operation decisions. Consequently, performance reliability measures, which attempt to capture the day-to-day variability in performance, have received considerable research interest over the past decade and have the potential to benefit the areas of operation, planning, and design.

As transportation agencies and researchers have access to more comprehensive travel information due to the advancement of modern technology through ITS, the reliability of performance measures can be measured and communicated to the public. However, travel time data from ITS need proper validation before they can be trusted to measure the system's reliability. One of the major goals of this project was to analyze and validate the ITS travel time data for Region VII highways for different traffic and weather conditions. Furthermore, this project aimed to quantify TTR metrics and find the most suitable of them appropriate for Region VII highways.

A 4.71-mile corridor of Highway 2 from 27th Street to 84th Street was selected to test the INRIX data quality and measure travel time statistics and corresponding reliability metrics. The INRIX data was compared to the field observed data from the Highway 2 testbed. The accuracy of INRIX data, compared to the field observed data, was analyzed with different segments from the testbed and for the entire testbed, under normal weather for AM and PM peak periods, rain, and snow conditions.

The Highway 2 testbed was further analyzed to measure the impact of COVID-19. In addition, other notable research conducted in the Region VII testbed location and Interstate highways regarding COVID-19 was incorporated into this project report.

In brief, the major findings from this project are as follows.

1. INRIX captured the central tendency of travel time distribution with higher accuracy compared to the measure of dispersion characteristics.

2. The increase in the length of segment did not impact the accuracy of INRIX's measurements of central tendency of travel time distribution for either the AM or PM peak. However, the precision of dispersion measured by INRIX was higher during the PM peak compared to the AM peak, as the length of the segment increased.

3. Out of the five TTR metrics, in general, INRIX measured the TTI, PTI, and LOTTR metrics with the most accuracy. In most cases, LOTTR was most accurately measured by INRIX. On the other hand, INRIX measured BI and COV with the least accuracy, compared to the ground truth data.

7. Considering both data sources (INRIX and ground truth), both peak periods, and both directions of traffic, the value of the PTI, TTI, and LOTTR metrics of the four individual segments in the Highway 2 testbed ranged from 1.44 to 2.14, 1.61 to 3.20, and 1.05 to 1.22, respectively.

8. For the entire Highway 2 testbed corridor, considering both data sources, both peak periods, and both directions of traffic, the value of the PTI, TTI, and LOTTR metrics of the four individual segments ranged from 1.50 to 1.75, 1.78 to 2.29, and 1.07 to 1.15, respectively.

9. For the entire Highway 2 corridor, regardless of the data sources, all TTR metrics' values except for LOTTR were higher in the PM peak periods than the AM peak periods. Therefore, based on all metrics except LOTTR, travel is less reliable for the PM peak period.

10. Inclement weather, such as rain, negatively impacted the reliability of the Highway 2 testbed.

11. It was found that events like COVID-19 had a significant impact on the travel time reliability on Region VII highways. During the pandemic period, potentially due to less traffic demand, Region VII highways were more reliable. This observation was more appropriate for relatively high AADT highways.

12. Most of the TTR metrics used were able to capture the impact of COVID-19 or rain for all the testbeds examined in this report. However, different TTR metrics produced different rates of change and in a few cases the change of reliability pattern showed opposite results depending on which TTR metrics were used.

In general, TTI and PTI metrics were able to capture the increased reliability during the COVID-19 pandemic period and reduced reliability during adverse weather. LOTTR did the same on a lesser degree. BI and COV metrics produced mixed results for different testbeds and different spatial and temporal characteristics of the study.

13. For the testbed used in this project, INRIX measured the PTI, TTI, and LOTTR metrics with greater accuracy. These three metrics were more consistent in estimating the reliability of testbeds used in this project. Therefore, TTI, PTI, and LOTTR metrics can be recommended to identify how the highway system is performing on a real-time and historical basis.

The most remarkable finding from this project was that whether the transportation system's reliability increased or decreased or to what extent the reliability changed depended on which metric was used to measure it. Therefore, engineers and transportation agencies require a deeper understanding of the travel time related statistics and transportation system's characteristics to understand the actual changes that occur in travel time reliability.

For the testbed used in this project, in the majority of the scenarios, INRIX most accurately measured the LOTTR metric. Note that LOTTR is used as one of the key mobility indicators recommended in the MAP-21 Act and the FAST Act to assess the performance of national highways in the US. Therefore, the ability of INRIX to accurately measure the LOTTR metric under the testbed used in this project is a positive finding. However, all the testbeds presented in this report showed that, compared to the TTI and PTI metrics, the value of the LOTTR metric was lower. This means that LOTTR was not found to be highly susceptible to capturing the change of reliability characteristics as opposed to the ability of TTI and PTI metrics. Therefore, the LOTTR metric has the potential to report a transportation system more reliable than it actually is. This is problematic because LOTTR is one of the codified measures of TTR performance listed in the U.S. Code of Federal Relations (e.g., 23 CFR § 490.511) (NHS, Metrics, 2018). Therefore, the LOTTR metric should be used with caution. Future research is needed to address this issue.

TTR metrics are impacted by several factors including AADT, type of highways, time of day, etc. Therefore, ranges of value for the TTR metric are presented in this report.

While analyzing travel time data, seldomly, INRIX reported inappropriate travel time samples (e.g., reported travel time can only be true if the travel speed is 150 mph in a 55-mph speed limit segment) or missing data, especially during off-peak hours. While such occurrence of improper travel speed samples or missing data is rare, it can lead to inaccurate estimation of TTR metrics.

In this report, the results of the INRIX capability to capture ground truth observations are based on the Highway 2 testbed. Therefore, the accuracy reported in this report may not be applicable to other locations. Furthermore, while the quantitative values of TTR metrics reported in this project are based on several testbeds in Nebraska and may be applicable for Region VII highways, other locations may replicate the methodology used in this report to find appropriate TTR metrics.

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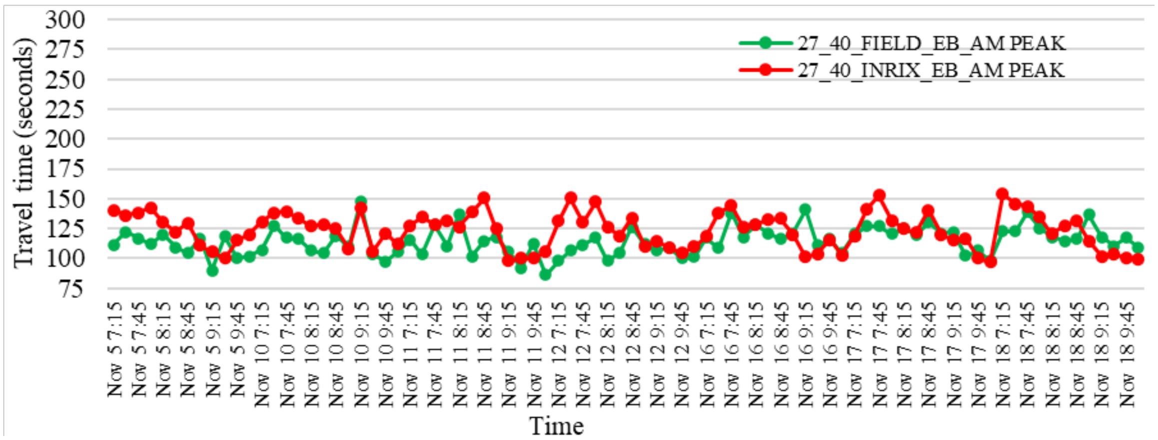
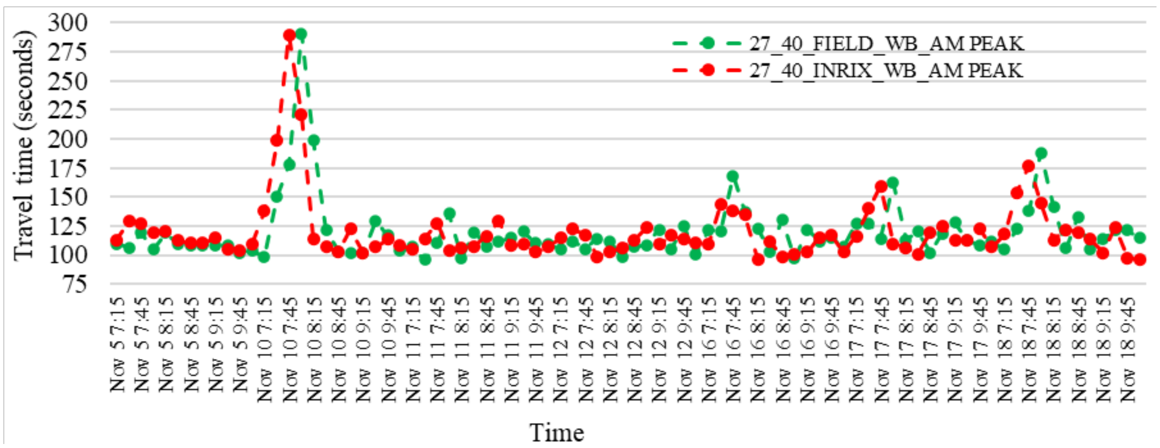
Appendix A

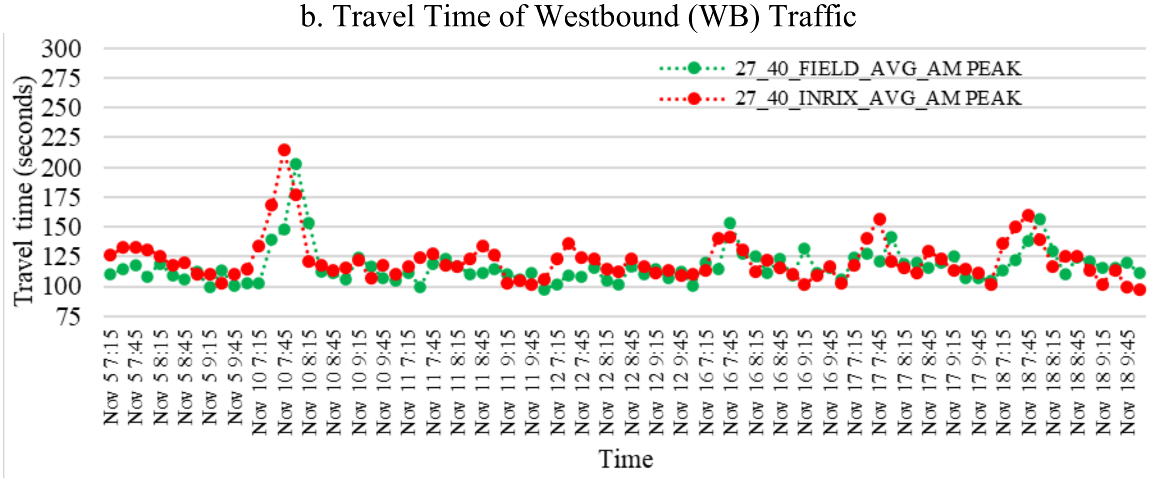
<u>A.1 Comparison Charts of Travel Time for Incremental Segment During Weekdays AM Peak Hour Periods</u>



a. Travel Time from Eastbound (EB) Traffic

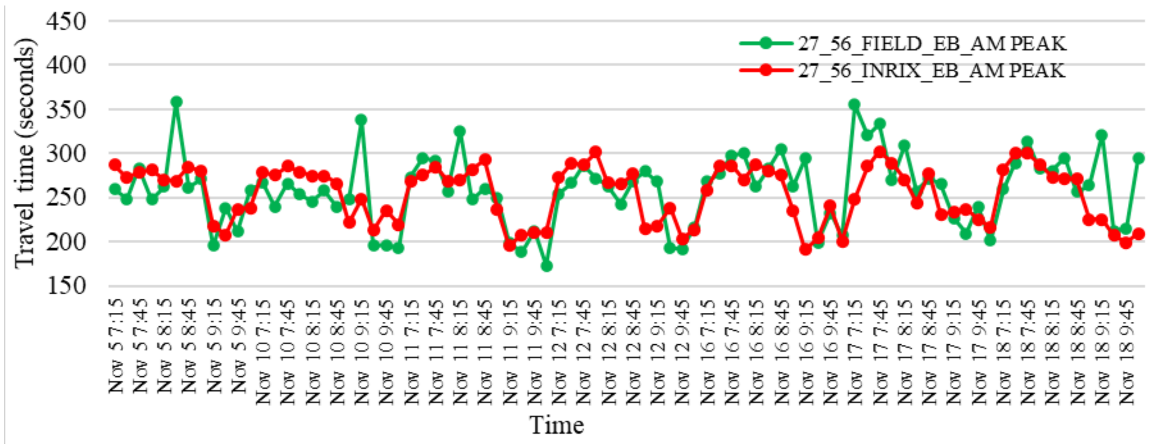


b. Travel Time of Westbound (WB) Traffic

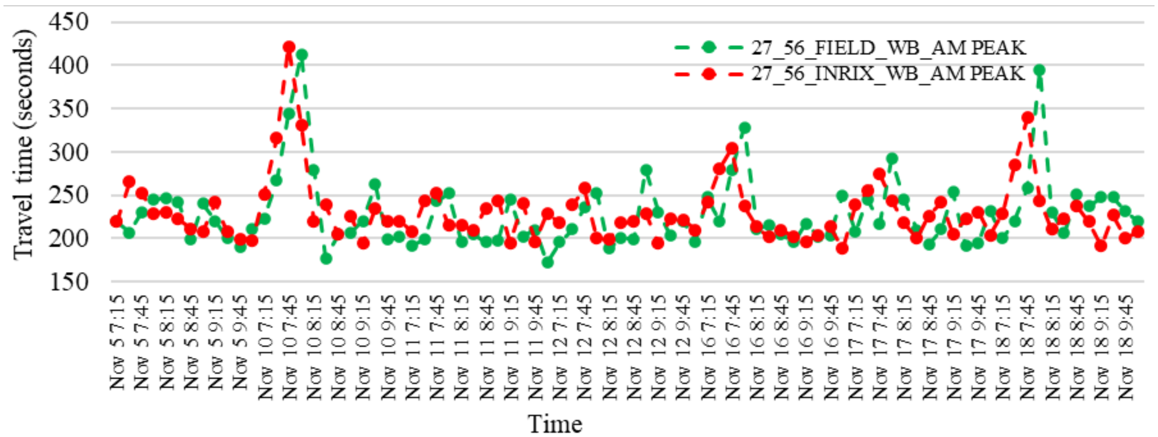


c. Average Travel Time of EB and WB Traffic

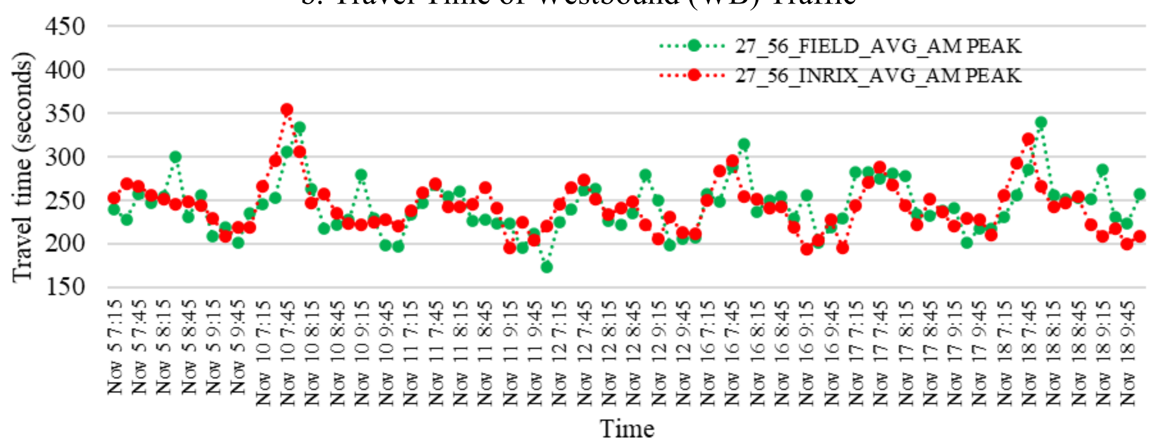
Figure A.1 Comparisons of travel time for Segment 27_40 during weekday AM peak hours



a. Travel Time from Eastbound (EB) Traffic

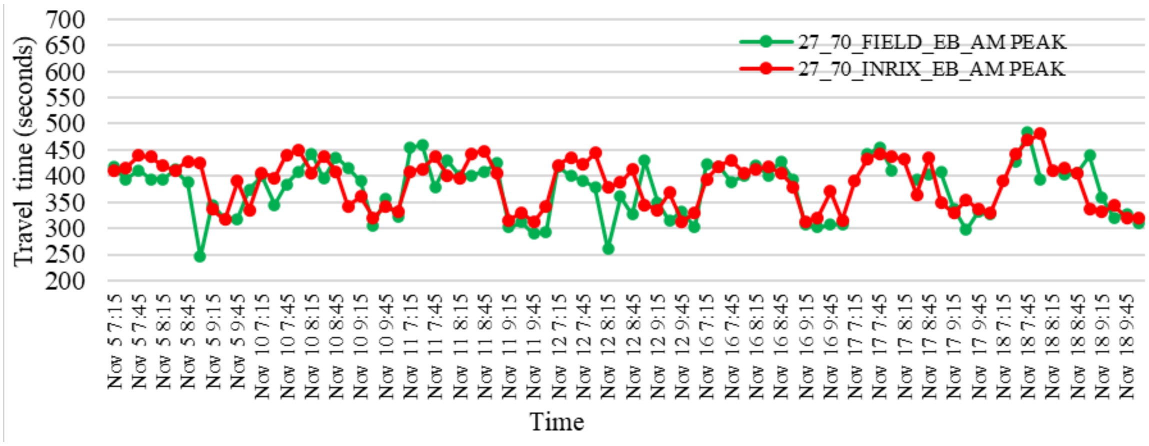


b. Travel Time of Westbound (WB) Traffic

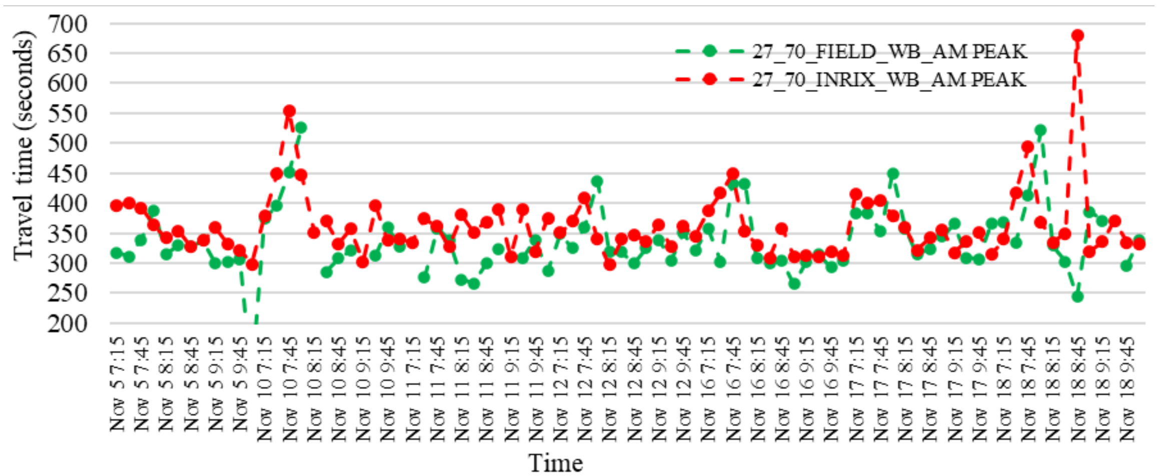


c. Average Travel Time of EB and WB Traffic

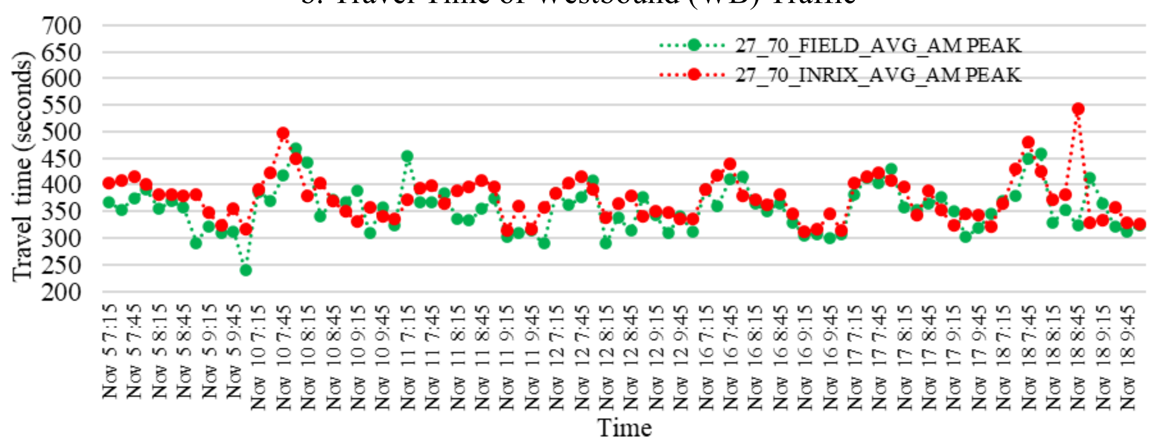
Figure A.2 Comparisons of travel time for Segment 27_56 during weekday AM peak hours



a. Travel Time from Eastbound (EB) Traffic

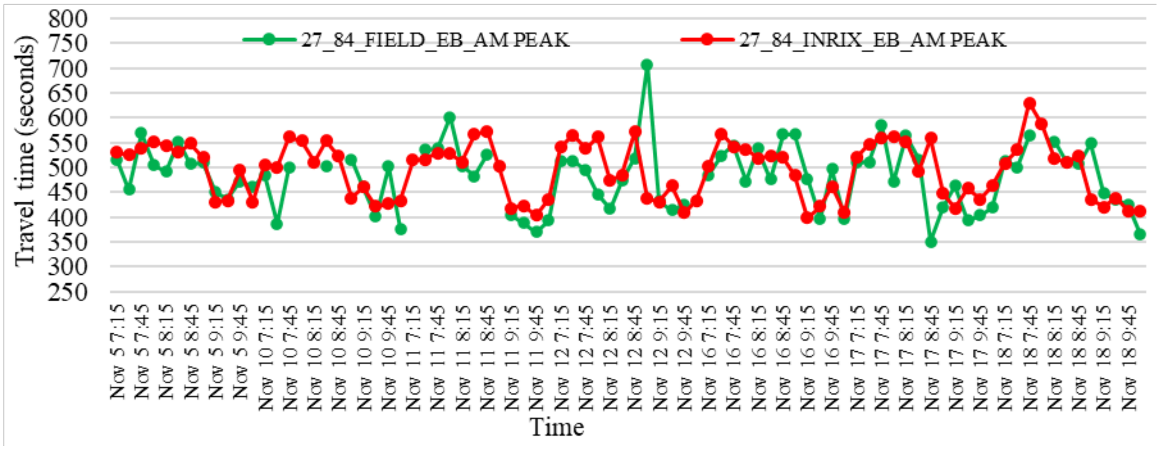


b. Travel Time of Westbound (WB) Traffic

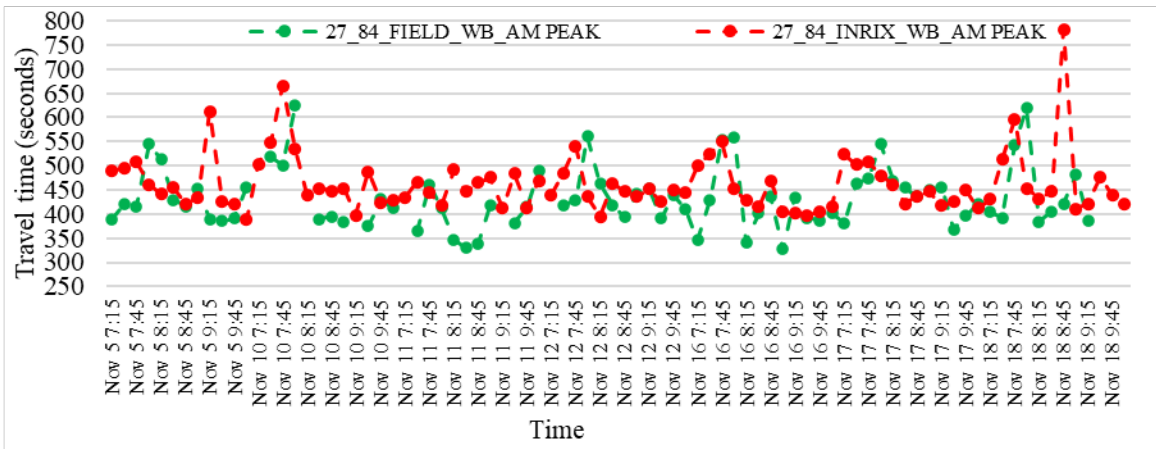


c. Average Travel Time of EB and WB Traffic

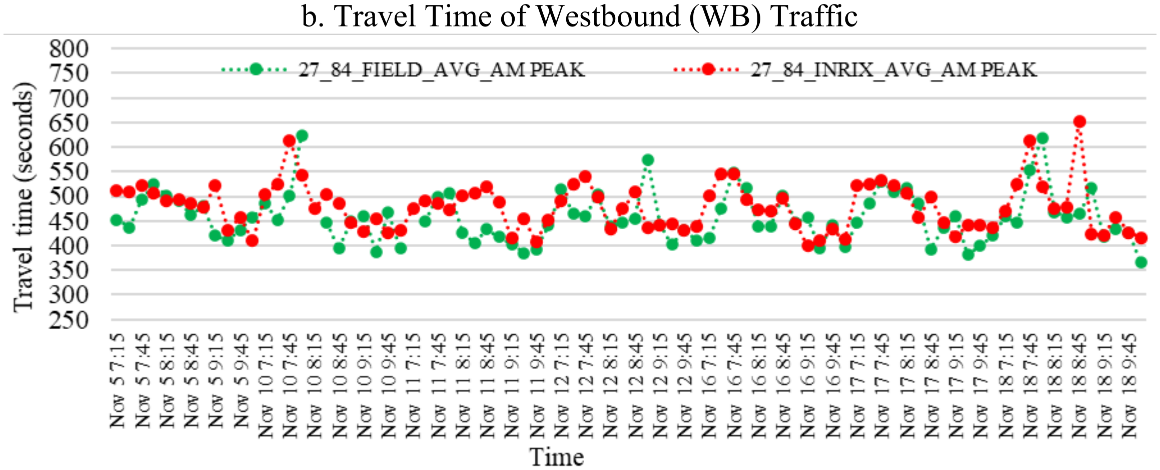
Figure A.3 Comparisons of travel time for Segment 27_70 during weekday AM peak hours



a. Travel Time from Eastbound (EB) Traffic



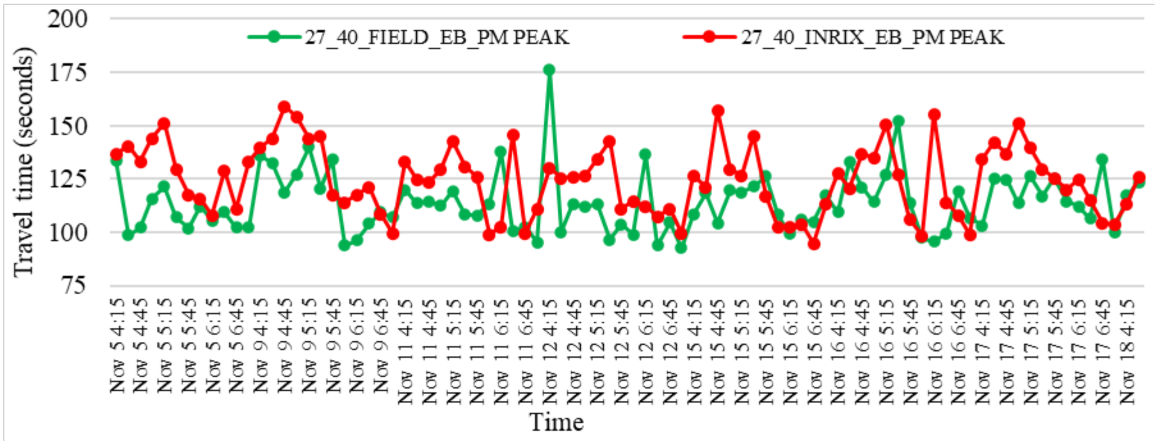
b. Travel Time of Westbound (WB) Traffic



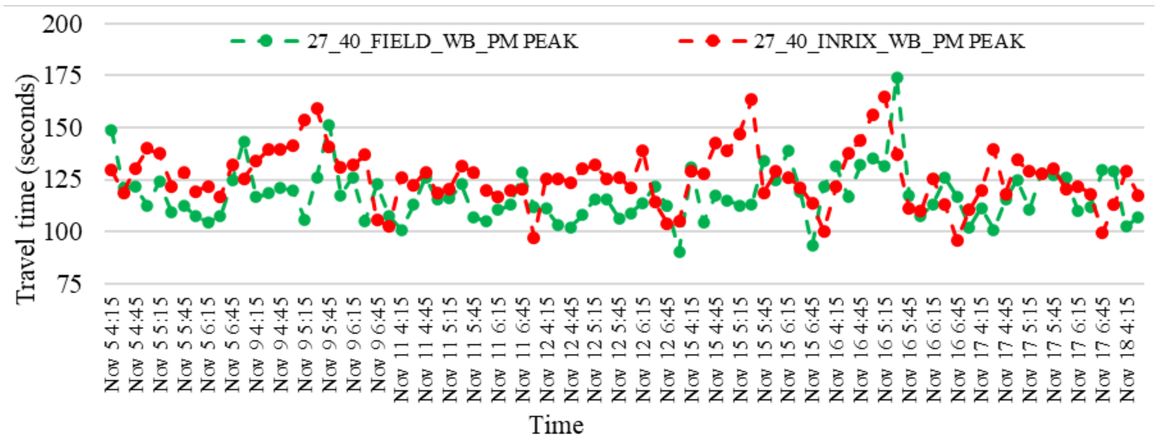
c. Average Travel Time of EB and WB Traffic

Figure A.4 Comparisons of travel time for Segment 27_84 during weekday AM peak hours

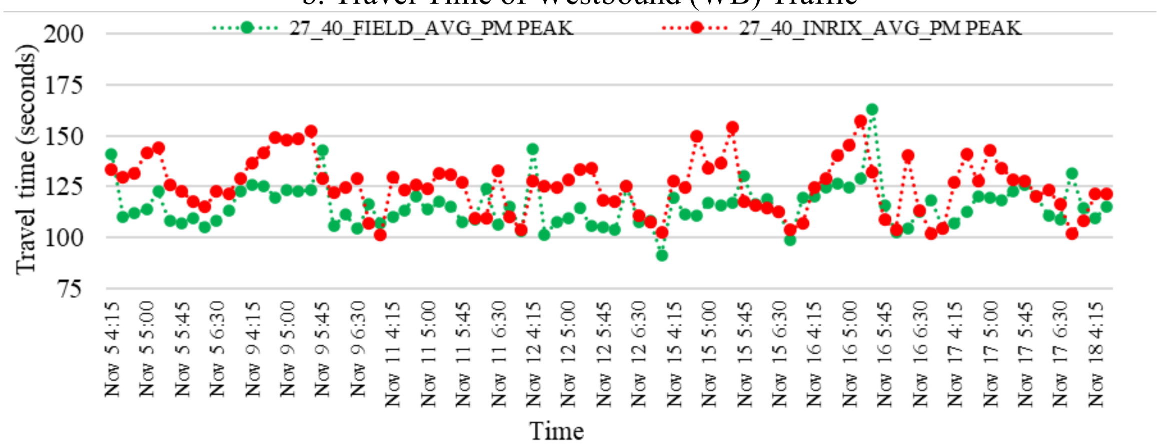
A.2 Comparison Charts of Travel Time for Incremental Segment During Weekdays PM Peak Hour Periods



a. Travel Time from Eastbound (EB) Traffic

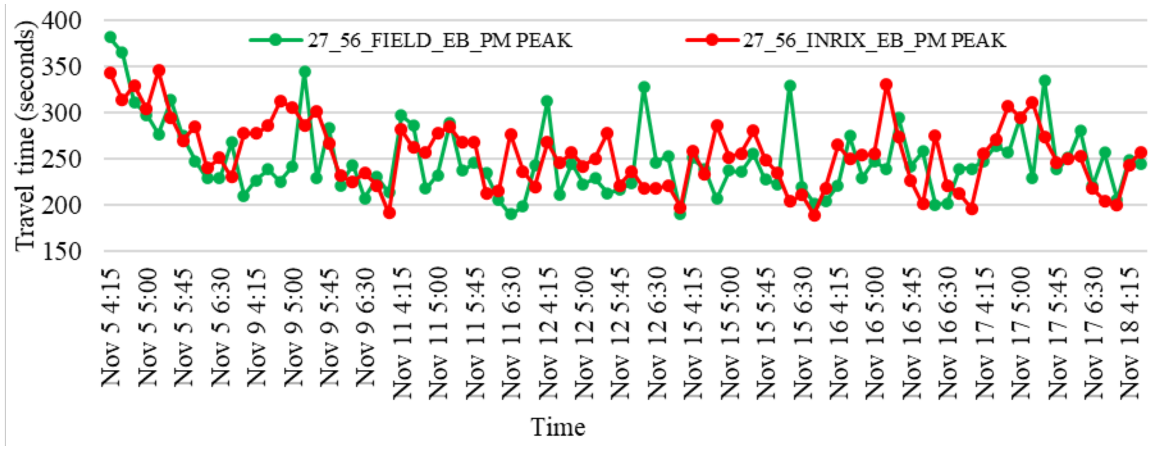


b. Travel Time of Westbound (WB) Traffic

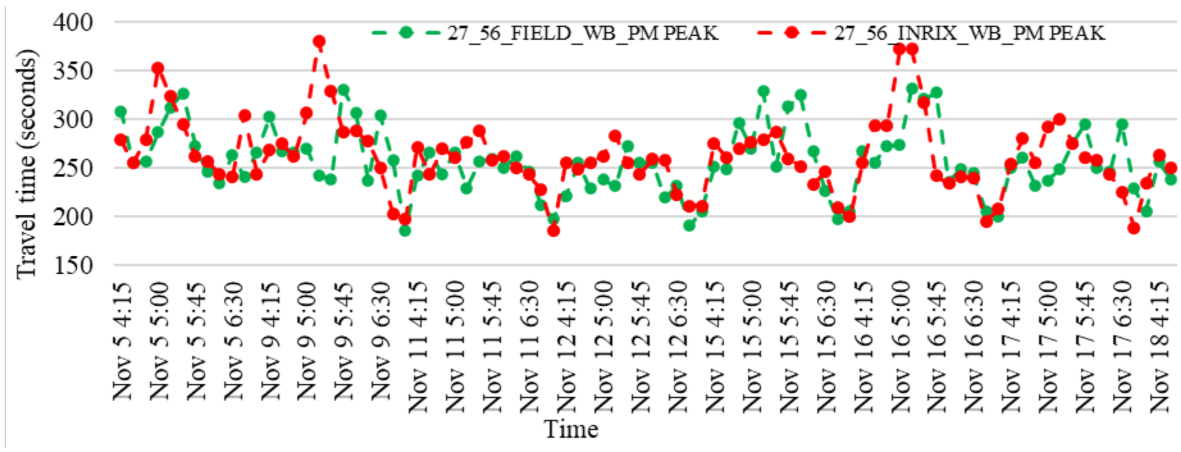


c. Average Travel Time of EB and WB Traffic

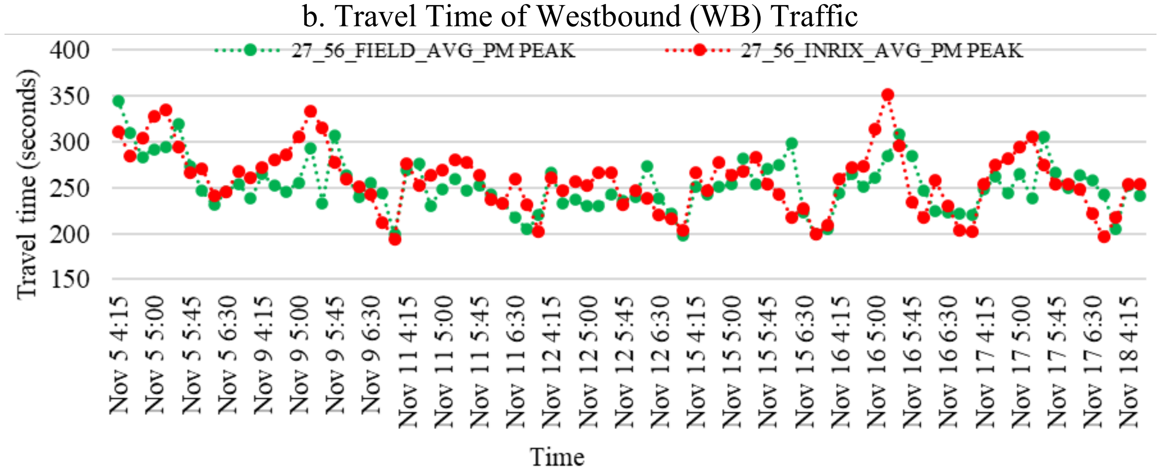
Figure A.5 Comparisons of travel time for Segment 27_40 during weekday PM peak hours



a. Travel Time from Eastbound (EB) Traffic

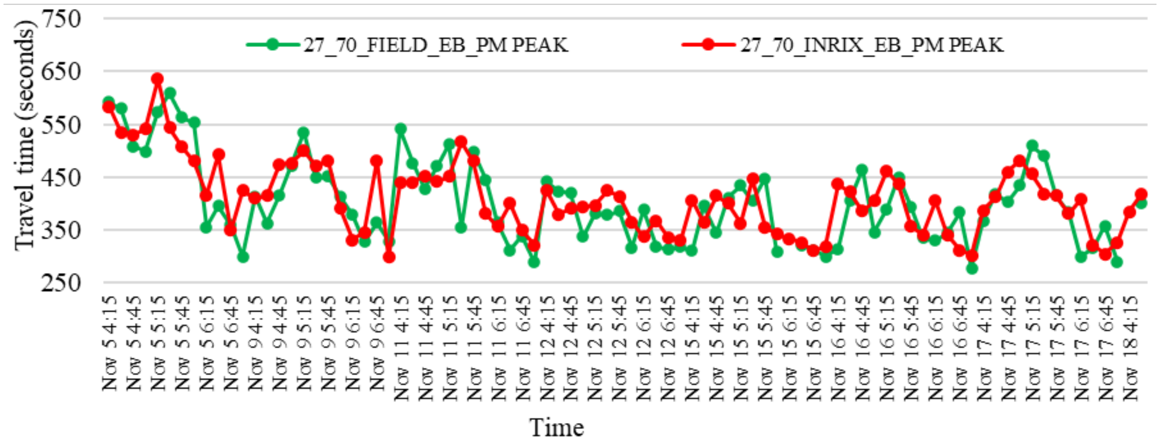


b. Travel Time of Westbound (WB) Traffic

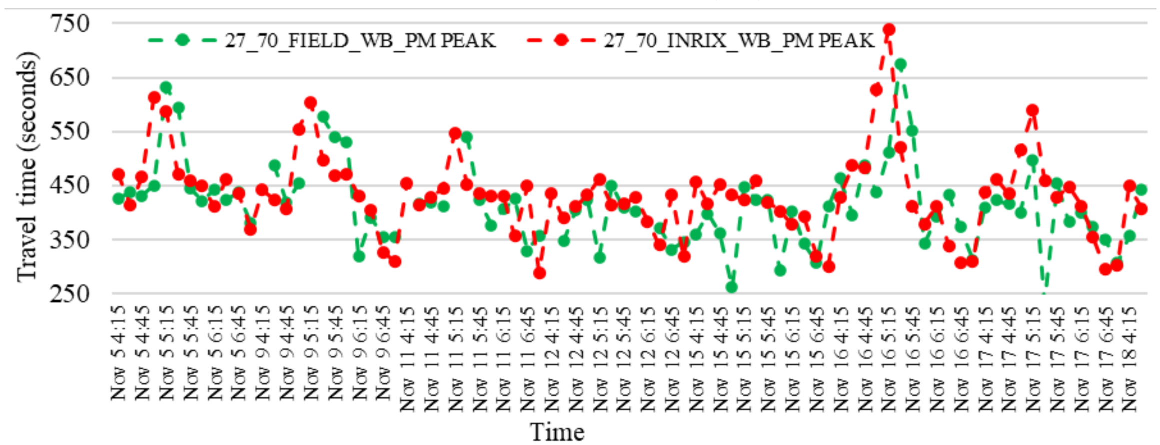


c. Average Travel Time of EB and WB Traffic

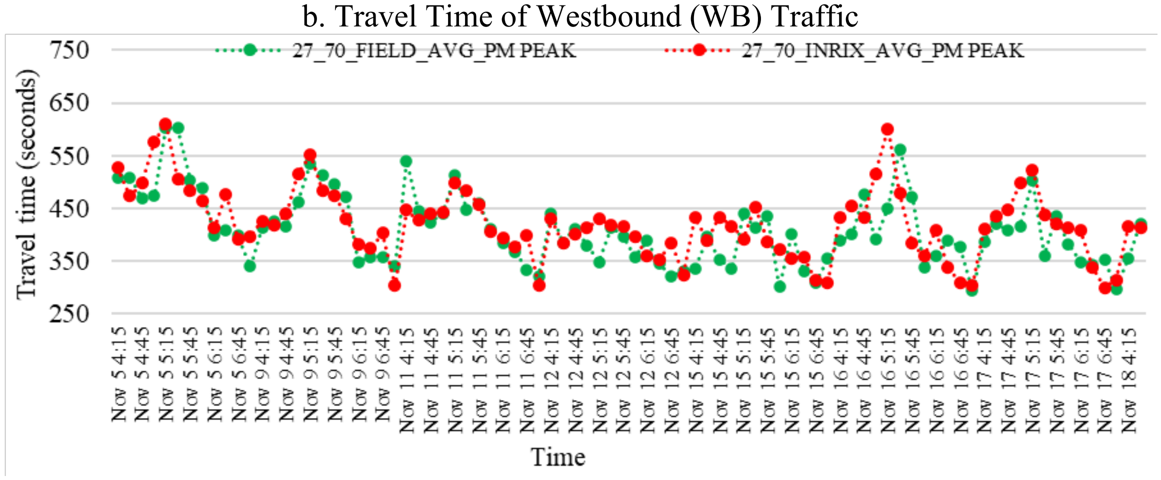
Figure A.6 Comparisons of travel time for Segment 27_56 during weekday PM peak hours



a. Travel Time from Eastbound (EB) Traffic

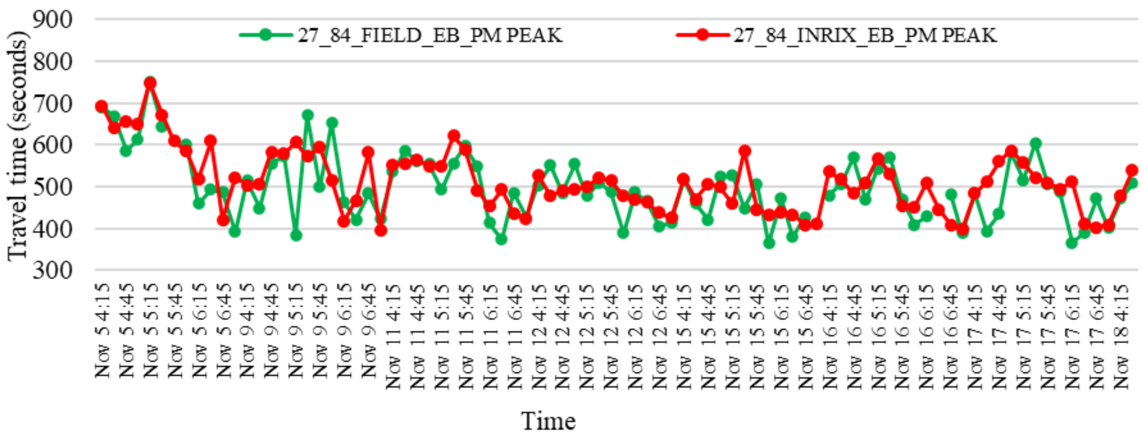


b. Travel Time of Westbound (WB) Traffic

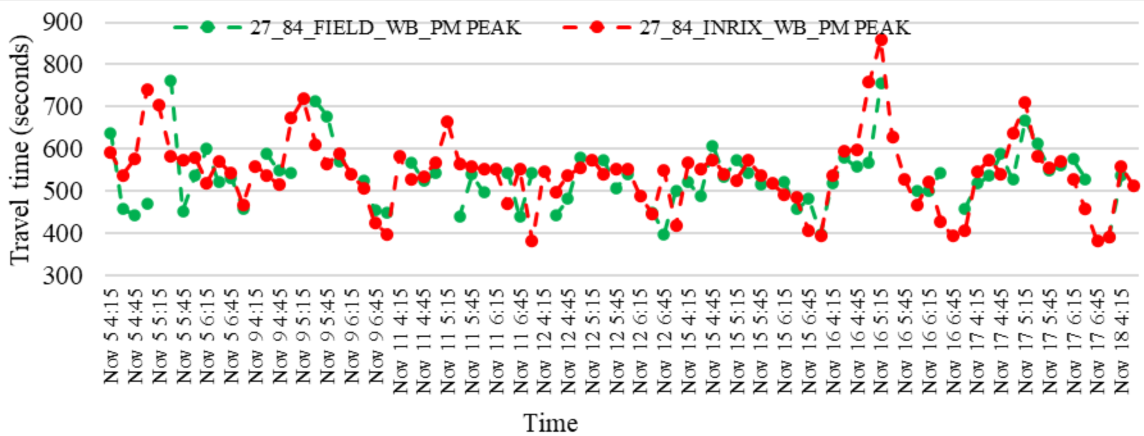


c. Average Travel Time of EB and WB Traffic

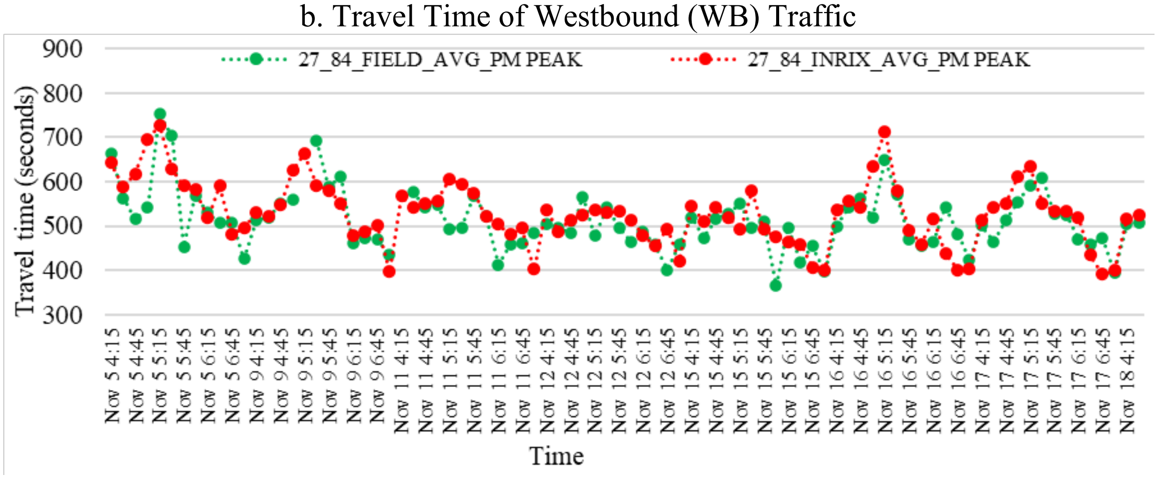
Figure A.7 Comparisons of travel time for Segment 27_70 during weekday PM peak hours



a. Travel Time from Eastbound (EB) Traffic



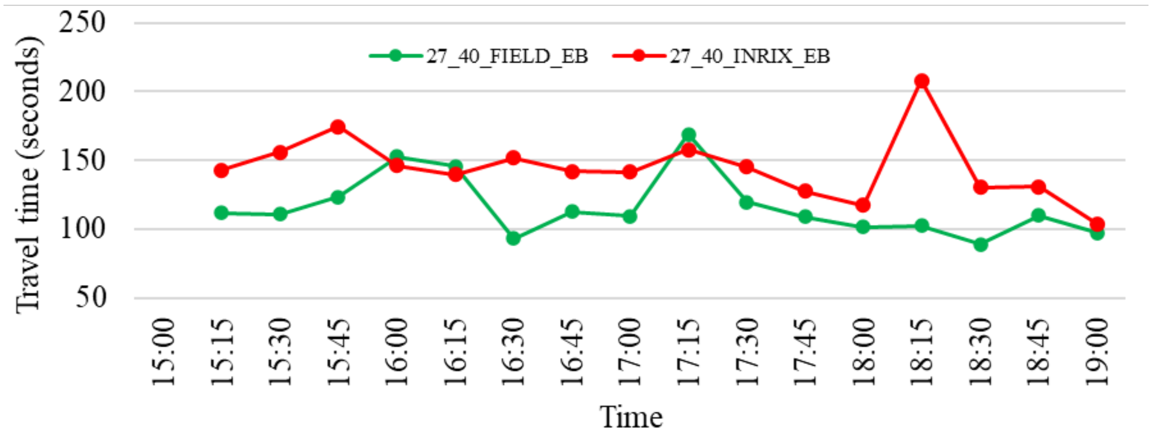
b. Travel Time of Westbound (WB) Traffic



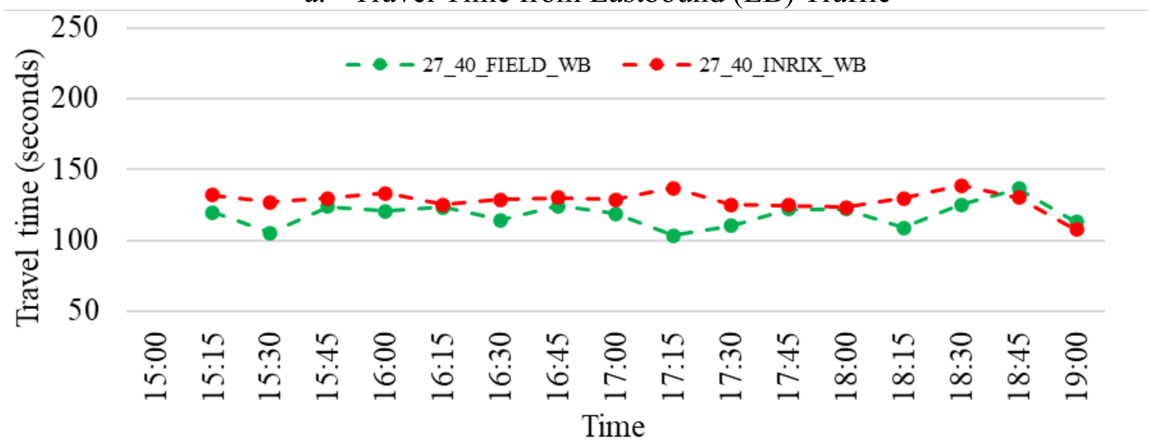
c. Average Travel Time of EB and WB Traffic

Figure A.8 Comparisons of travel time for Segment 27_84 during weekday PM peak hours

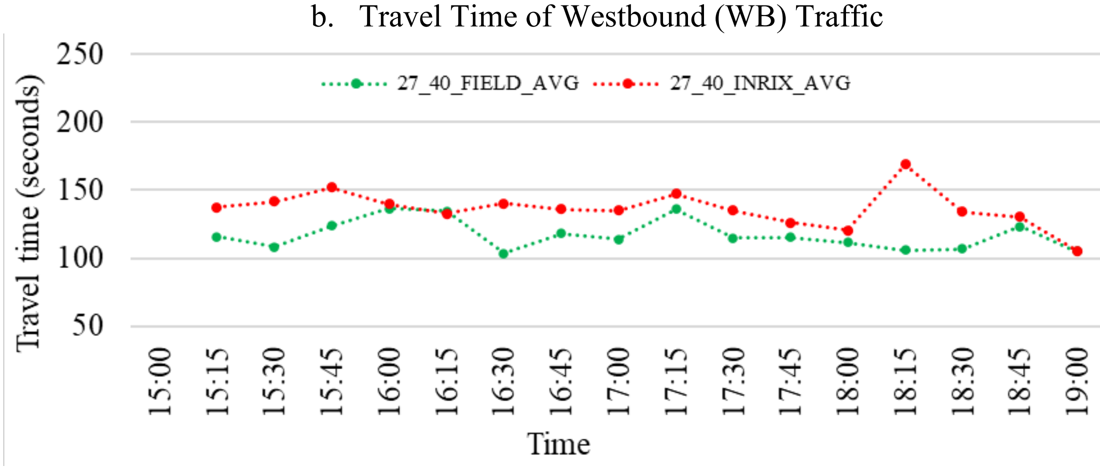
A.3 Comparison Charts of Travel Time for Incremental Segment During Rainy Condition



a. Travel Time from Eastbound (EB) Traffic

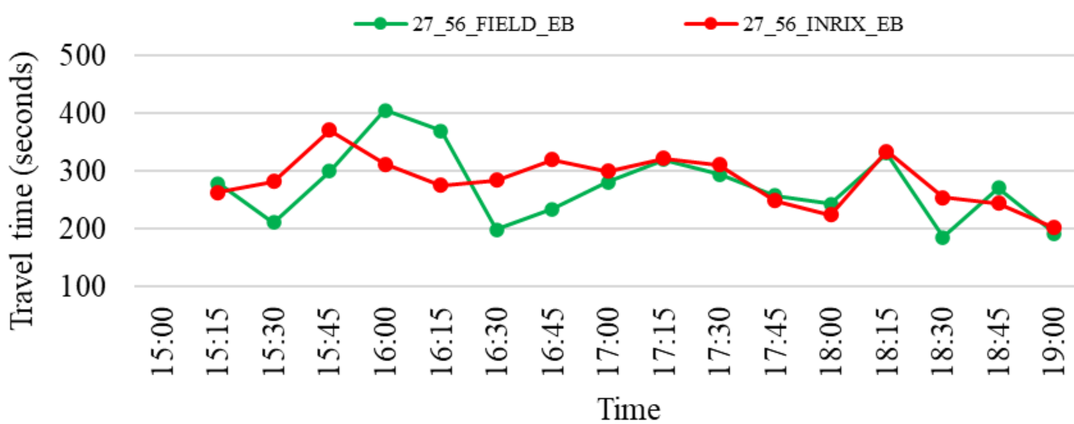


b. Travel Time of Westbound (WB) Traffic

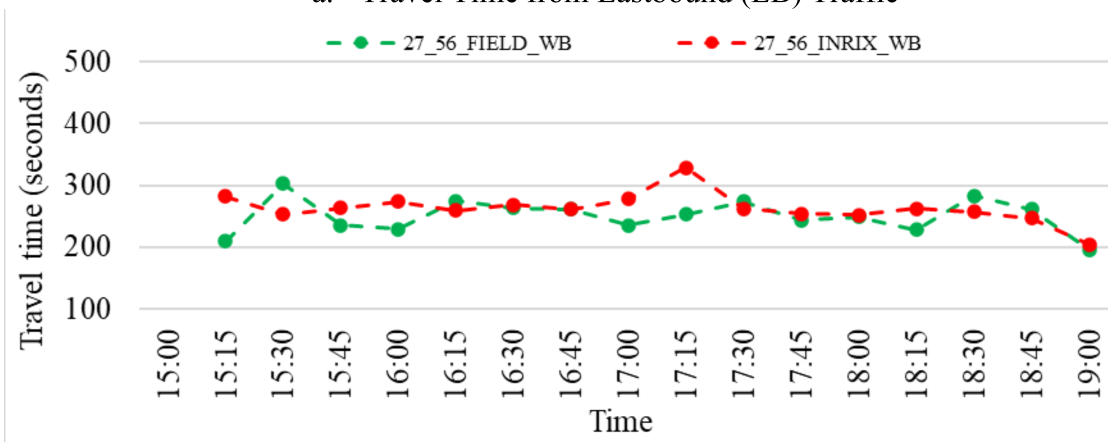


c. Average Travel Time of EB and WB Traffic

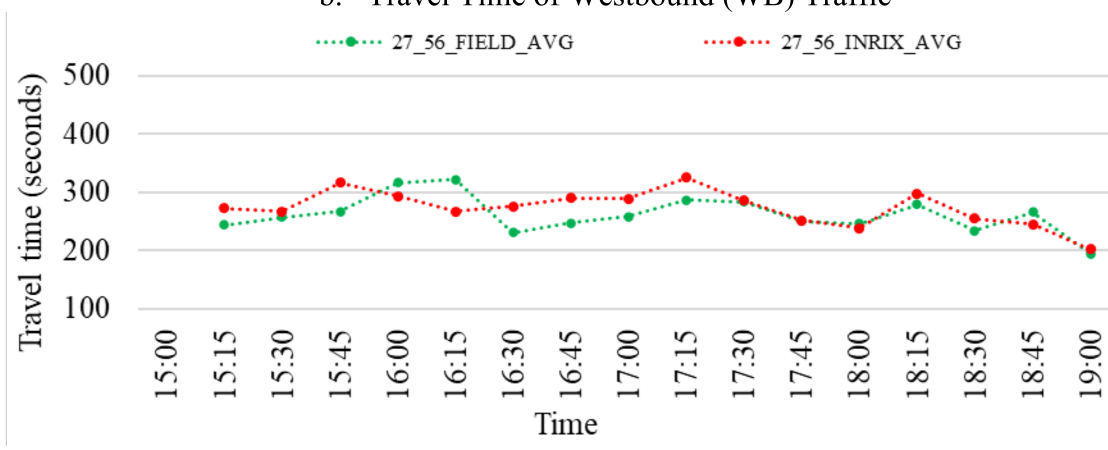
Figure A.9 Comparisons of travel time for Segment 27_40 during rainy condition



a. Travel Time from Eastbound (EB) Traffic

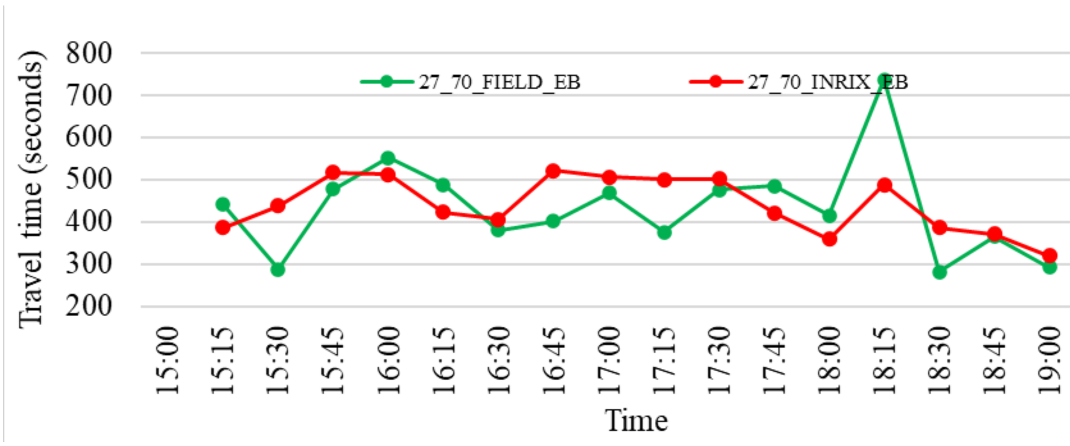


b. Travel Time of Westbound (WB) Traffic

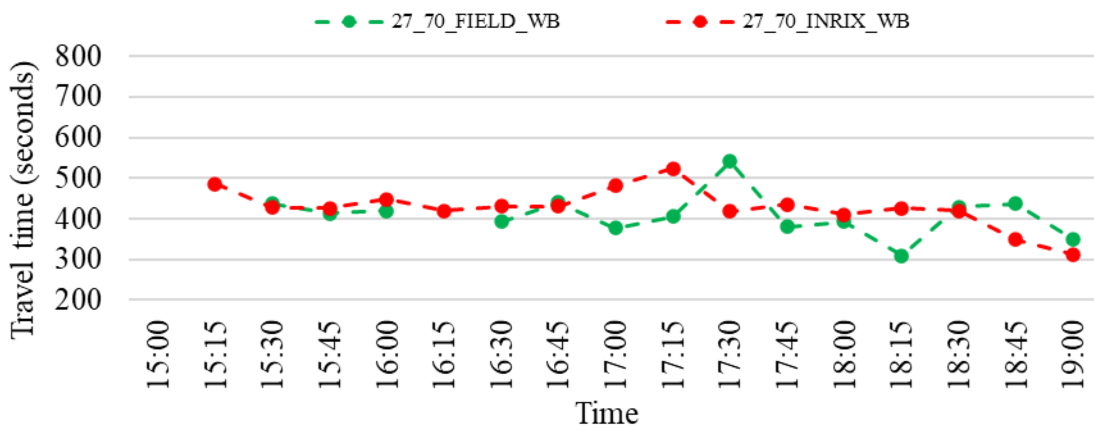


c. Average Travel Time of EB and WB Traffic

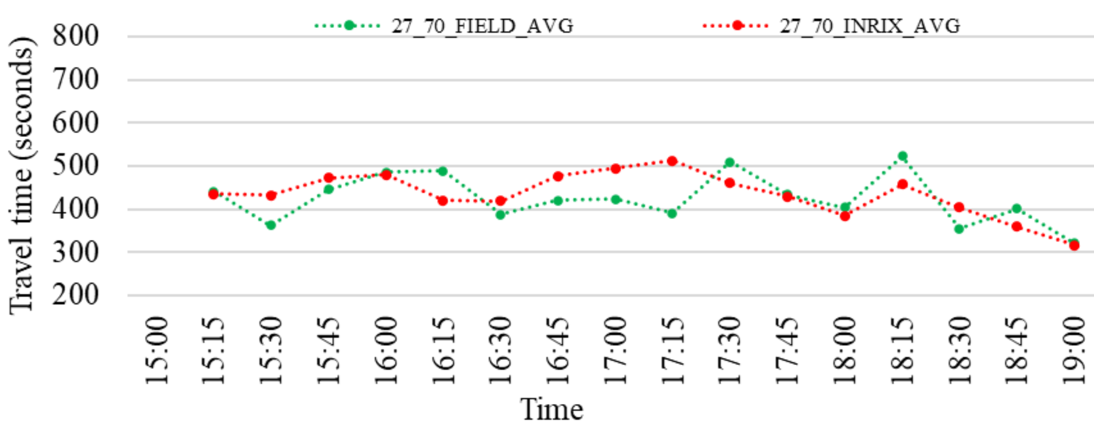
Figure A.10 Comparisons of travel time for Segment 27_56 during rainy condition



a. Travel Time from Eastbound (EB) Traffic

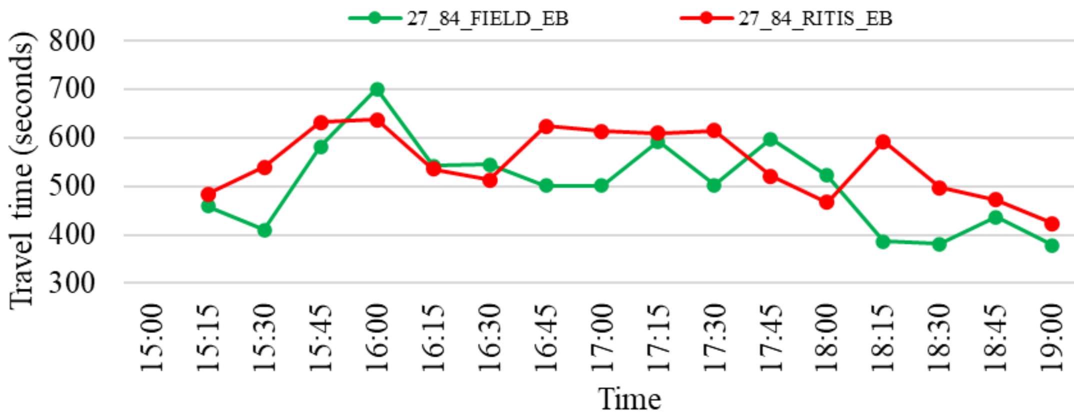


b. Travel Time of Westbound (WB) Traffic

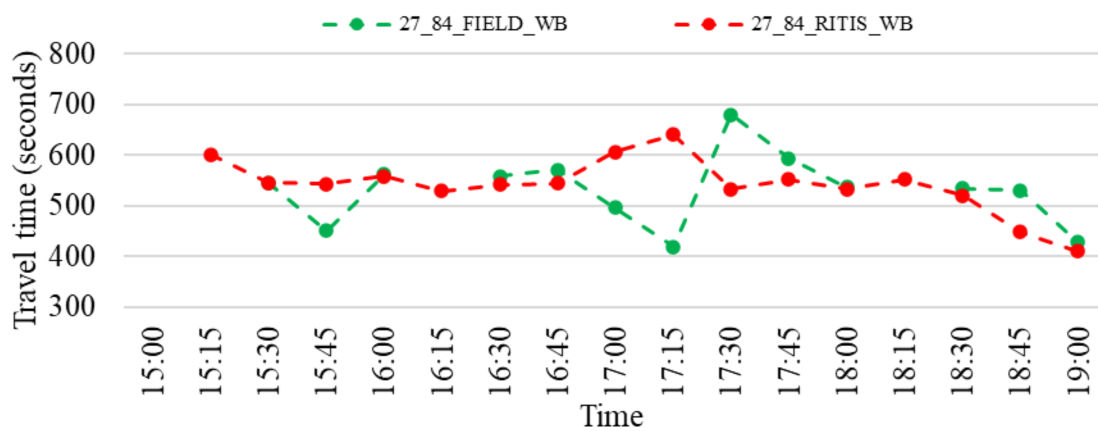


c. Average Travel Time of EB and WB Traffic

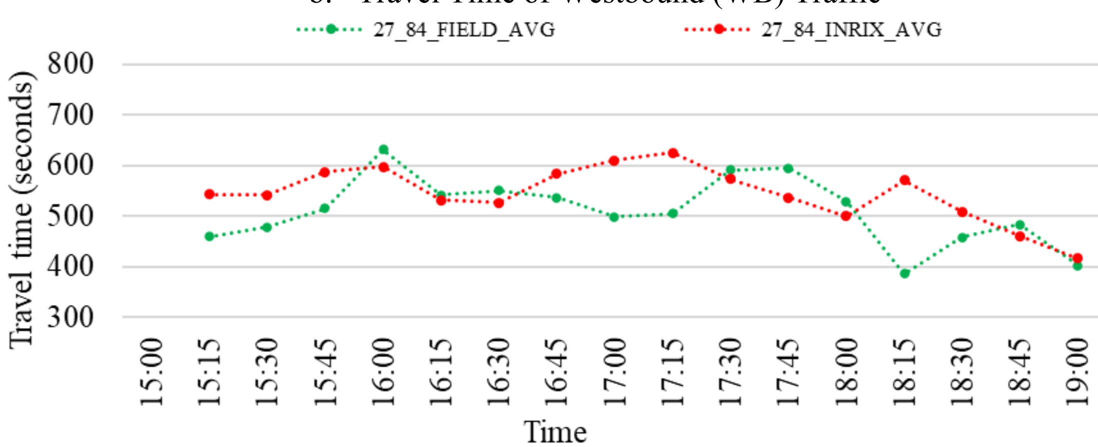
Figure A.11 Comparisons of travel time for Segment 27_70 during rainy condition



a. Travel Time from Eastbound (EB) Traffic



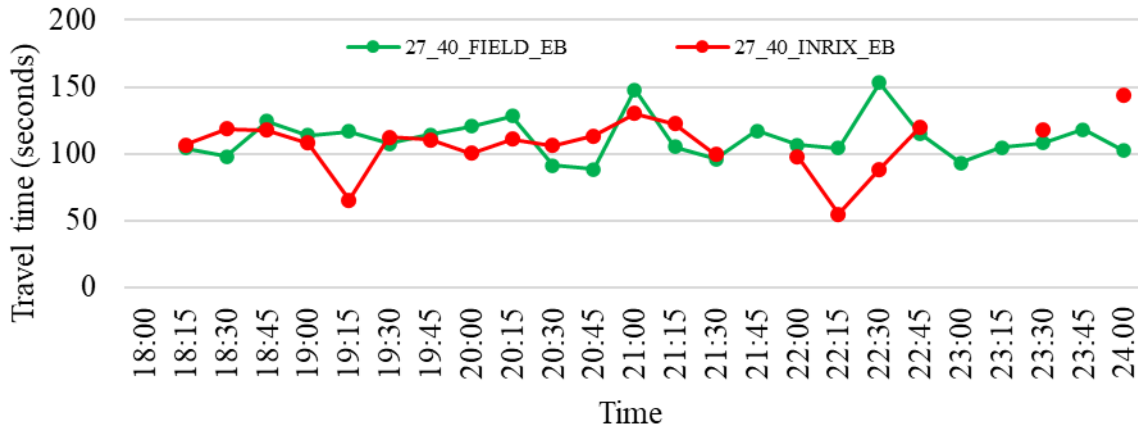
b. Travel Time of Westbound (WB) Traffic



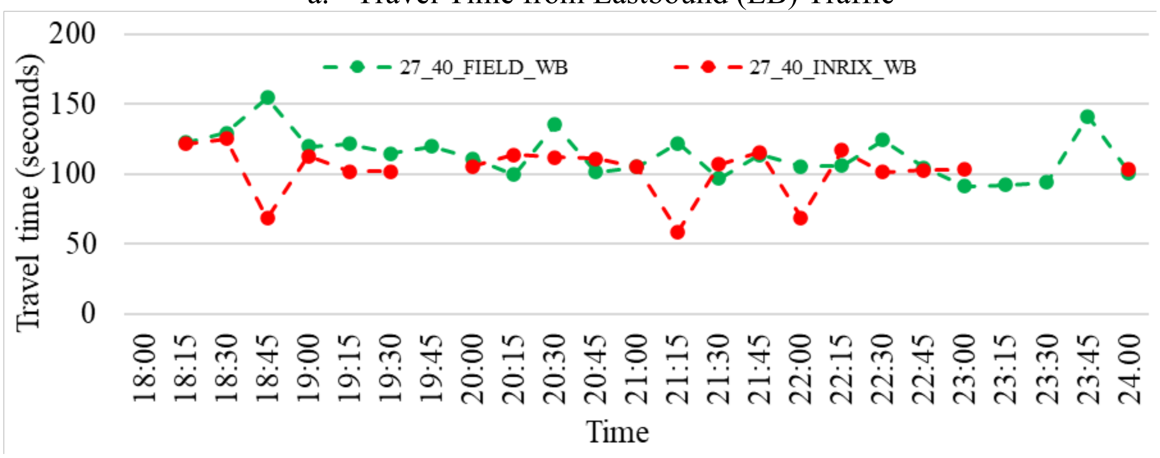
c. Average Travel Time of EB and WB Traffic

Figure A.12 Comparisons of travel time for Segment 27_84 during rainy condition

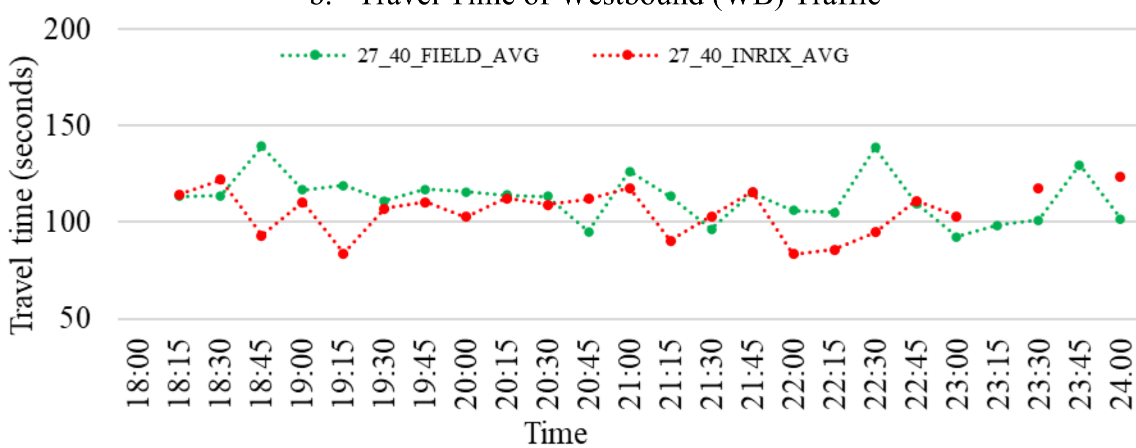
A.4 Comparison Charts of Travel Time for Incremental Segment During Snowy Condition



a. Travel Time from Eastbound (EB) Traffic

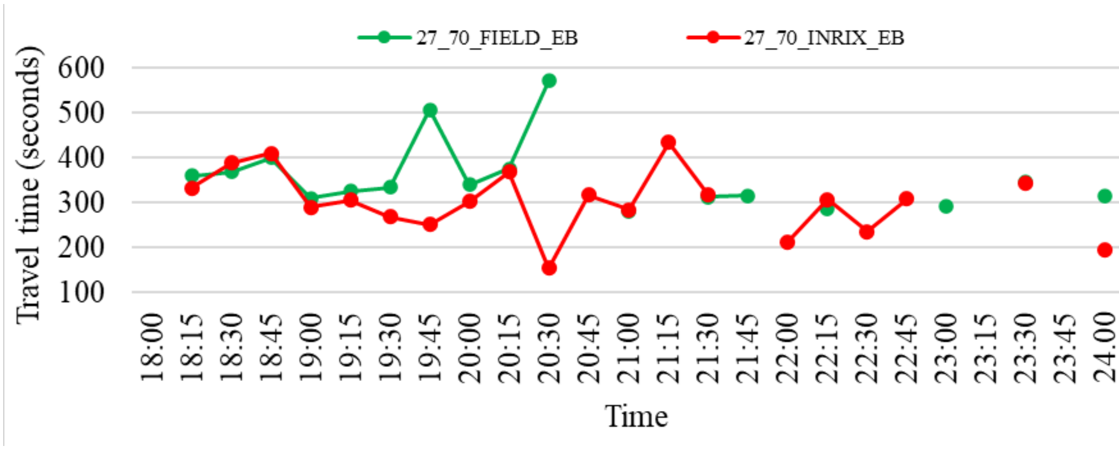


b. Travel Time of Westbound (WB) Traffic

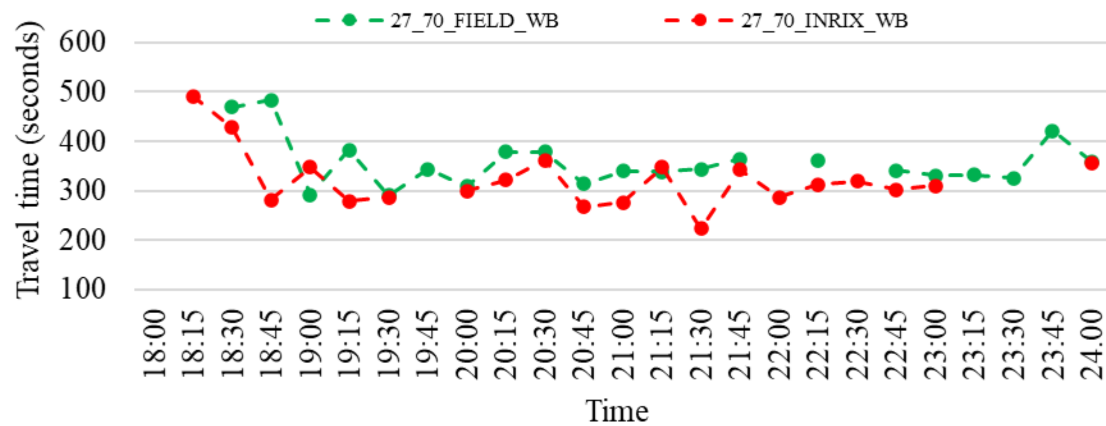


c. Average Travel Time of EB and WB Traffic

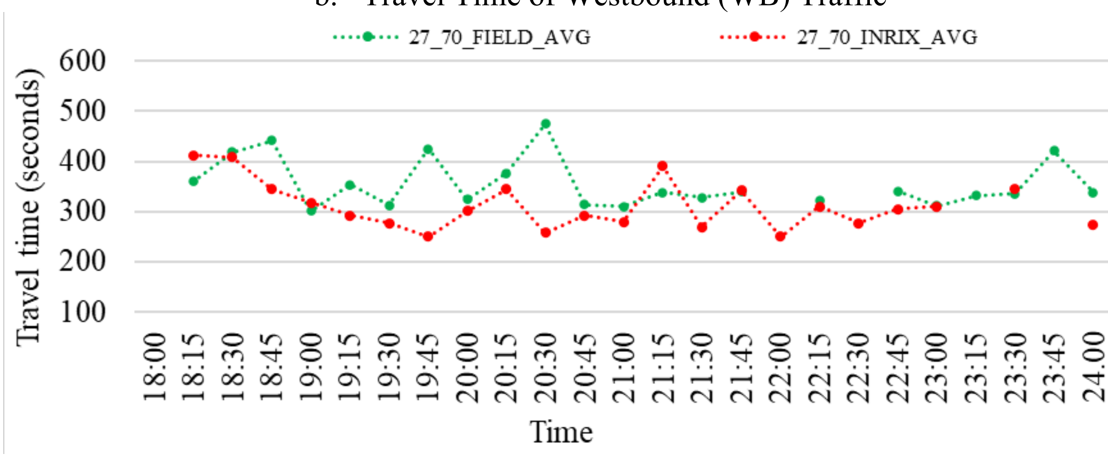
Figure A.13 Comparisons of travel time for Segment 27_40 during snowy condition



a. Travel Time from Eastbound (EB) Traffic

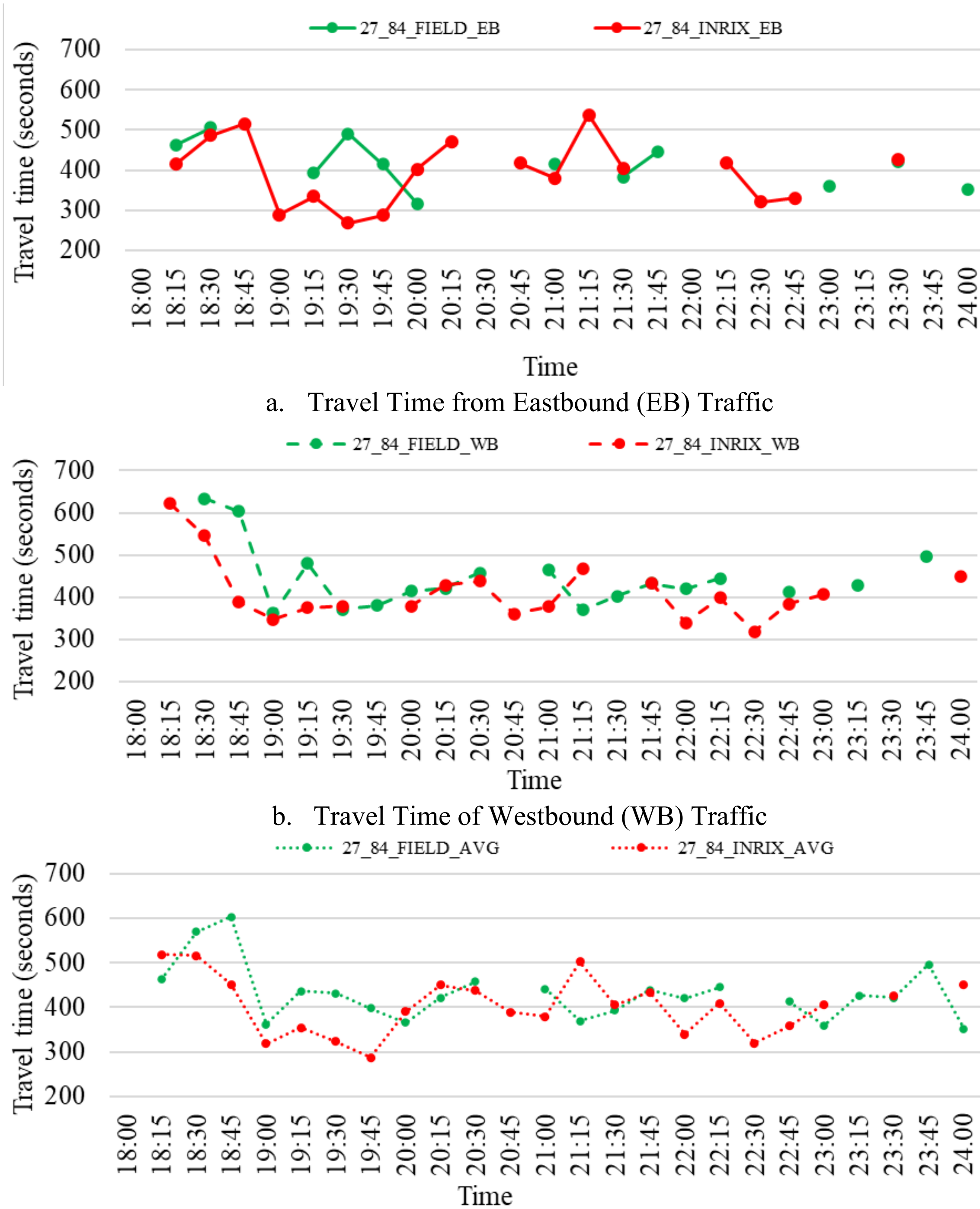


b. Travel Time of Westbound (WB) Traffic



c. Average Travel Time of EB and WB Traffic

Figure A.14 Comparisons of travel time for Segment 27_70 during snowy condition



a. Travel Time from Eastbound (EB) Traffic

b. Travel Time of Westbound (WB) Traffic

c. Average Travel Time of EB and WB Traffic

Figure A.15 Comparisons of travel time for Segment 27_84 during snowy condition