Analytical Methods for Work Zone Travel Time Reliability

Final Report
June 2018

SWZDI
Smart Work Zone Deployment Initiative

Sponsored by
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About SWZDI

Iowa, Kansas, Missouri, and Nebraska created the Midwest States Smart Work Zone Deployment Initiative (SWZDI) in 1999 and Wisconsin joined in 2001. Through this pooled-fund study, researchers investigate better ways of controlling traffic through work zones. Their goal is to improve the safety and efficiency of traffic operations and highway work.

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16. Abstract

Travel time reliability studies have garnered interest in recent years with researchers and practitioners recognizing reliability as a trait of significant importance to commuters. Presence of work zones can significantly impact the capacity and speeds at the location and consequently impact travel time reliability.

This study built a framework for studying impacts of work zone on travel time reliability. The framework covers aspects of work zone selection, evaluation of work zones, derivation of travel time distributions for each work zone, and developing a predictive model for work zone impact on travel time reliability.

Work zone and travel time data were collected from 19 freeway and highway work zones across the state of Wisconsin. Supporting hourly traffic counts were collected for the work zones where available. Average travel time trends through a day, travel time distribution, and reliability metrics were studied at each candidate location individually to observe the impacts of the work zone. Reliability measures from across all work zones were combined to study discernible relationships between the change in reliability measures caused due to the work zone and a variety of work zone properties, and predictive regression models were developed to estimate work zone impact on reliability. Due to limitations in the quality and quantity of data available, the regression modeling yielded moderate goodness of fits. A larger dataset and/or availability of detailed work zone information might result in better travel time reliability models.

The report presents limitations and findings from the study and informs on quality of data that needs to be collected for future studies on work zone travel time reliability.

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ANALYTICAL METHODS FOR WORK ZONE TRAVEL TIME RELIABILITY

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This research was conducted under the Smart Work Zone Deployment Initiative (SWZDI) and Federal Highway Administration (FHWA) Pooled Fund Study TPF-5(295), involving the following state departments of transportation:

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EXECUTIVE SUMMARY

Background and Objective

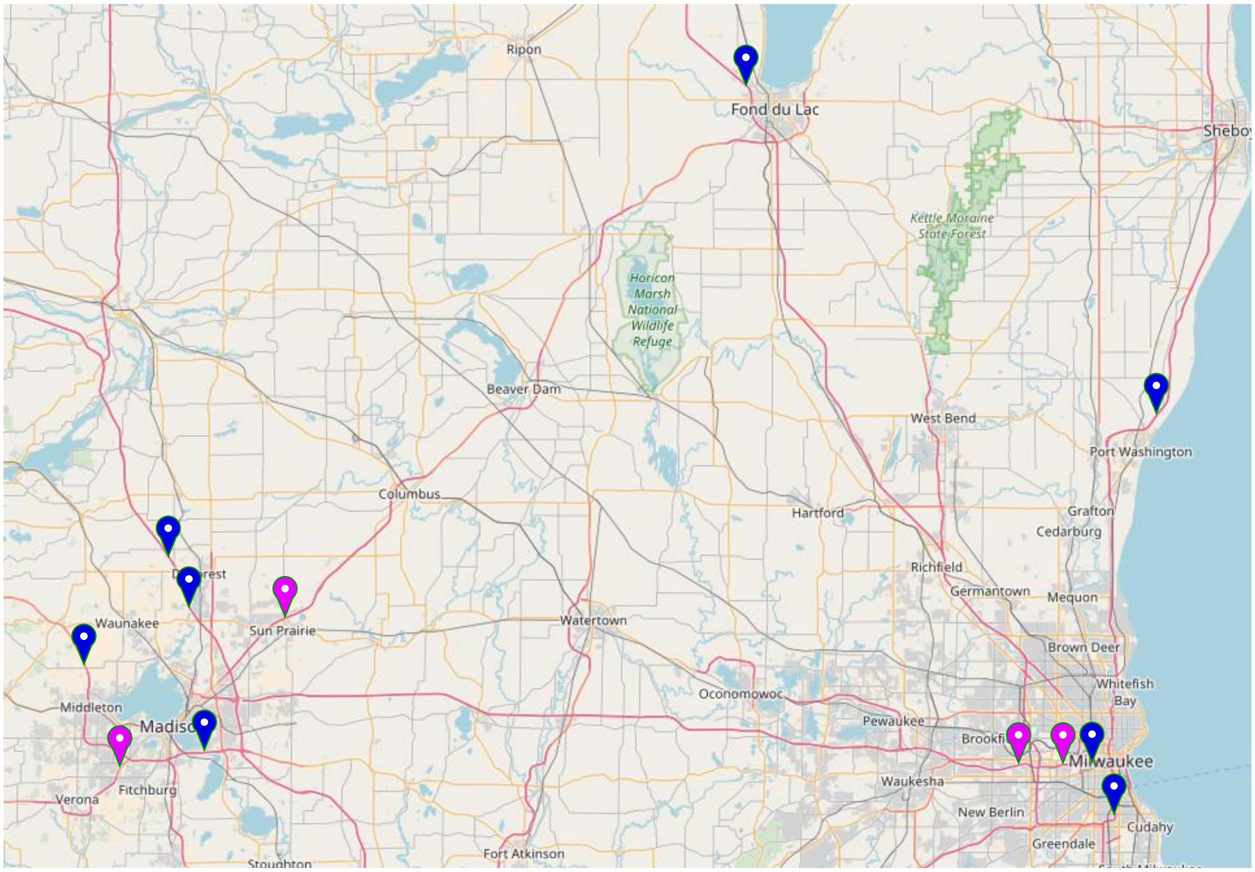
Researchers and practitioners have identified in the past years that travel time reliability is of significant importance to commuters, especially for time sensitive trips such as work commute, medical appointments, and trips to the airport. Commuters are often interested in knowing, for example, how much buffer time to plan ahead to ensure that they reach their destinations on time, in addition to shortest possible, or average expected travel time. The presence of work zones on the roadway can not only increase delays by inducing or exacerbating congestion, but also significantly impact travel time reliability. Nevertheless, there is a limited understanding of the impacts of work zones on travel time reliability.

Existing studies have focused on either modeling travel time reliability measures for a general environment, or the impacts of work zones on performance measures such as capacity and free-flow speed. Very limited studies have tried to assess the impact of work zones on travel time reliability, and such studies have used privately acquired data, which may limit the transferability of their models and results to a wider spectrum of practice based on accessibility to similar type of data source. More importantly, these studies have modeled daily aggregate travel time reliability measure due to lack of access to higher resolution traffic counts.

The main objective of this study is to provide a framework for developing analytical methods for estimating work zone travel time reliability, considering various factors such as traffic volume, work zone configuration, and work zone intensity. The framework covers aspects of work zone selection for the model, evaluating each work zone individually and deriving travel time distributions and reliability measures for each work zone, and developing a general predictive model for work zone travel time reliability.

Data Collection

The Wisconsin Lane Closure System (WisLCS) was used as the source of archived data on work zones across Wisconsin. WisLCS records details of each work zone in the state, with information on the location of the work zone (freeway, county, start and end locations), date and time ranges when the work zone was active, and the impact on lane-configuration (number of lanes closed). Where available, Wisconsin Transportation Management Plans (WisTMP) system was refered to for details of the work zone project. However, this was not available consistently for all work zones considered, and thus not used for modeling efforts in the study. A total of 19 work zones (out of over 30,000 candidate work zones considered) were identified across the state based on a list of predetermined selection criteria; see Figure 1 for their locations.



Blue markers represent locations with good traffic count information, purple markers indicate locations where traffic count was not available for part of the period studied
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Figure 1. Locations of work zones used in the study

The filtering criteria were identified to ensure that: (1) all relevant data are available, (2) both uncongested and congested traffic patterns are observed, (3) work zones demonstrated consistent traffic patterns across all work zone days, (4) winter months were excluded in the study period, (5) work zones were not in close vicinity of major interchanges, ramps or signals which can drastically affect traffic stability and can cause changes in traffic demand at the location, and (6) the work zone involved lane or shoulder closures on the mainline facility and not closures on the ramps with the ramp demands unaffected and all delay impacts of the work zone measurable (ramp travel times are not available).

Hourly travel time data from the National Performance Management Research Data Set (NPMRDS) and traffic volume data from the Wisconsin Automatic Traffic Recorder repositories were extracted corresponding to the study period for each work zone, to complete the data collection efforts.

Modeling

The time series plot of average travel times by hour, aggregated across all days in baseline period and work zone period respectively, was first constructed for each site (Figure 2 shows a representative plot for one work zone). The plot was used to identify general trends of variation in travel time through a typical average day and how they change due to the work zone.

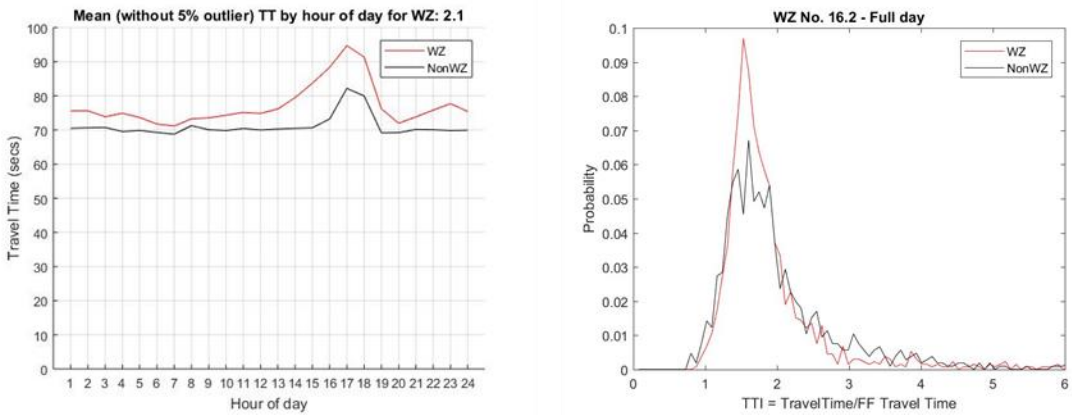


Figure 2. Time-of-day average travel time plot for work zone 2.1 (left), and travel time distribution for work zone 16.2 (right)

Next, the travel time distribution was obtained for each site using travel times observed across all study days (see Figure 2). Various well-known travel time reliability measures (such as buffer time, misery time, etc.) were also measured for each site along with the change in the measure due to the work zone.

Following the analysis of each work zone, work zone data and the corresponding reliability measures were combined across all study sites to study any discernable relationship between the change in reliability measure caused by the work zone and various work zone properties such as traffic demand and work zone lane configuration. This was done to understand if there are any relationships between the attributes, and if there are, what functional form(s) they might follow.

Finally, predictive models were developed using regression modeling to estimate work zone reliability measures based on the baseline reliability, and the work zone attributes considered. Due to limitations in the quality and quantity of data available, the regression modeling yielded moderate goodness of fits. A larger dataset and/or availability of detailed work zone information might result in better travel time reliability models.

Key Findings and Limitations

As expected, travel times increased during peak periods at most sites when work zones were active. However, an unexpected feature during the analysis was that some locations showed a reduction in travel time with a work zone during a peak period. While in most cases the reduction in travel time was not substantial (<10% change), this was not true in all cases, with three sites seeing a larger reduction during the morning peak, and one during the evening peak.

The impact of the work zone on travel time reliability appears to be loosely related to traffic volumes but have no visibly derivable relationship with other parameters considered. As seen in Figure 3, higher traffic counts correspond to a higher spread in possible levels of impact of work zone on the mean travel time, while lower volumes correspond to a tighter range of impacts. As can be expected from this result, any regression model tried had poor goodness of fit due to the unexpected feature reported above.

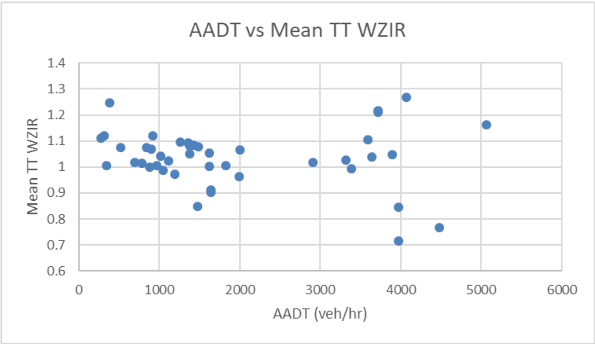


Figure 3. Mean travel time work zone impact ratio (work zone travel time/baseline travel time) versus total traffic volume for all locations combined

Despite the limited nature of the predictive model, this study provides a framework to develop such a model, including work zone selection, data handling, travel time analysis, and regression modeling, as well as future data needs to facilitate an effort to develop a better model. This project identified various limitations spanning from data availability to physical constraints of the work zone and the roadway. Some key limitations are as follows:

- Number of work zones available for the study.
- Consistent availability of various work zone details (such as barrier type, type of work, posted speed limits and distance to upstream advance work zone warning etc.). This information was available for some work zones chosen for the study, but not for all and was thus not used in modeling.
- Availability of reliable incident, special events, and weather data.
- Intersection of reliable work zone, travel time and traffic volume data.
- Knowledge of precise location of bottleneck and propagation of congestion.
- Vicinity to major features such as interchanges and signals may influence the homogeneity and thus the accuracy of travel time and traffic counts available.
- Ability to spatially relate data from multiple sources.

Knowledge of and preparing for the above limitations can be greatly beneficial to future researchers pursuing the study of the impact of work zones on travel time reliability. This knowledge can also be used to guide data collection efforts in the future so that all the limitations are addressed.

INTRODUCTION

State transportation agencies increasingly recognize the importance of travel time reliability to road users, especially those involved in time-sensitive trips for activities such as business meetings, medical appointments, airport departures, and just-in-time freight delivery. Work zones are a major source of travel delay, and the continually varying nature of construction operations can introduce significant travel time fluctuations. With the growing availability of GPS- and Bluetooth-based travel time data, after-the-fact analysis of reliability impacts has become relatively straightforward—but this information is of limited use to work zone designers seeking to estimate and mitigate reliability impacts before construction begins.

Project L08 (Zeeger et al. 2014) of the Second National Strategic Highway Research Program (SHRP2) developed tools for predicting travel time reliability measures and how incidents, adverse weather, and fluctuations in travel demand impact the reliability. The resulting analytical tools, FREEVAL (for freeways) and STREETVAL (for arterials), use analytical inputs like those required by the corresponding methods in the 2010 Highway Capacity Manual (TRB 2010). Outwardly, FREEVAL and STREETVAL look like ordinary Excel spreadsheets, but they incorporate sophisticated macros that compute thousands of combinations of travel conditions and summarize the results as reliability metrics. Due to data limitations, the SHRP2 L08 project did not attempt to directly estimate impact of work zones on reliability. In addition, L08 was based largely on San Diego data, which might not be representative of conditions or work zone practices across the nation.

The National Cooperative Highway Research Program (NCHRP) Project 03-107 (Shoen et al. 2015) studied the impacts of work zones on capacity, free-flow speeds, and the speed-density relationship for both freeway and urban streets. The project identified key aspects of a work zone environment that can affect traffic properties and behavior near the work zone and developed predictive models for estimating the impacts of a work zone. However, the project was restricted in scope to only address impacts on capacity and free-flow speed but did not address average travel time and travel time reliability measures.

Background

Performance of transportation networks is a critical issue in transportation engineering and planning. The efforts in performance evaluation and reliability improvements dramatically affect road users, planning efforts, infrastructure resiliency, and much more. GPS systems can provide real-time spatial measurements at a relatively low data collection cost, especially when considering the high accuracy of the data being collected (Tong et al. 2005). GPS enabled mobile devices such as smart phones have dramatically increased in numbers and can provide accurate location information such as speeds and travel times across key segments (Demers et al. 2006). Since around 2006, probe data from GPS enabled mobile devices and fleet automated vehicle location (AVL) equipment have been providing a new and rich source of traffic data. The coverage, quality, and affordability have been steadily increasing through the years. With new applications emerging at every turn, the adoption and use of probe data in transportation engineering and planning continues apace.

A rapidly advancing application of probe data is mobility performance measures and management. While performance management is not new, both SHRP2 and the Moving Ahead for Progress in the 21st Century Act (MAP-21) have dramatically catalyzed and reinforced their importance. The SHRP2 Reliability Track generated a wealth of information, insights, and guidance on mobility performance measurement, including details on various measures such as travel time indices, the planning time index, buffer time index, semi-standard deviation, failure measure, misery index, and others (Cambridge Systematics 2014). The application of reliability performance measures in the context of work zones has been however rather limited. Edwards and Fontaine (2012) investigated travel time reliability in work zones using private-sector data (data purchased from INRIX, a private-sector data provider).

Project Objective

The primary objective of this project is to develop a framework for predictive analytical modeling of work zone travel time reliability incorporating factors such as hourly volume, work zone configuration, and type of work zone activity. The framework incorporates the processes involving the selection of appropriate work zones to be used for developing the model, identification of the travel time distributions and reliability measures for each work zone, an analysis of the impact of work zone on the travel time reliability measures for each work zone, and developing a predictive model for work zone travel time reliability measures, integrating the data from all chosen work zones.

LITERATURE REVIEW

HCM Methods on Travel Time Reliability (L08)

The L08 project (Zeeger et al. 2014) of the Second National Strategic Highway Research Program (SHRP2) developed methods to study travel time reliability. The methods proposed by the project were incorporated into the sixth edition of the Highway Capacity Manual (HCM) (TRB 2016). L08 considers a two-fold objective to (1) incorporate non-recurring congestion effects into HCM procedures, and (2) expand the analysis horizon from a single study period to an extended time horizon to assess the variability in quality of service provided by a roadway facility.

A key contribution from L08 was a robust definition of travel time reliability measures that have been adopted as standard measures by HCM (TRB 2016). Earlier projects, L02 (List et al. 2014) and L03 (Cambridge Systematics et al. 2013) have looked at metrics for measuring travel time reliability. L03 recommends the use of reliability rating, planning time index, buffer index, 80th percentile travel time index (TTI) and misery index, while L02 uses measures of semi-variance and semi-standard deviation (one-sided measures anchored around free-flow travel time) as travel time reliability measures. Expanding on these, L08 added standard deviation, and failure / on-time measures (percentage of trips with average speed less than a threshold) while also updating the definition of misery index as a complete set of reliability metrics. Figure 4 shows a list of the travel time reliability measures recommended by L08 and shows how some of them are defined through a travel time distribution curve.

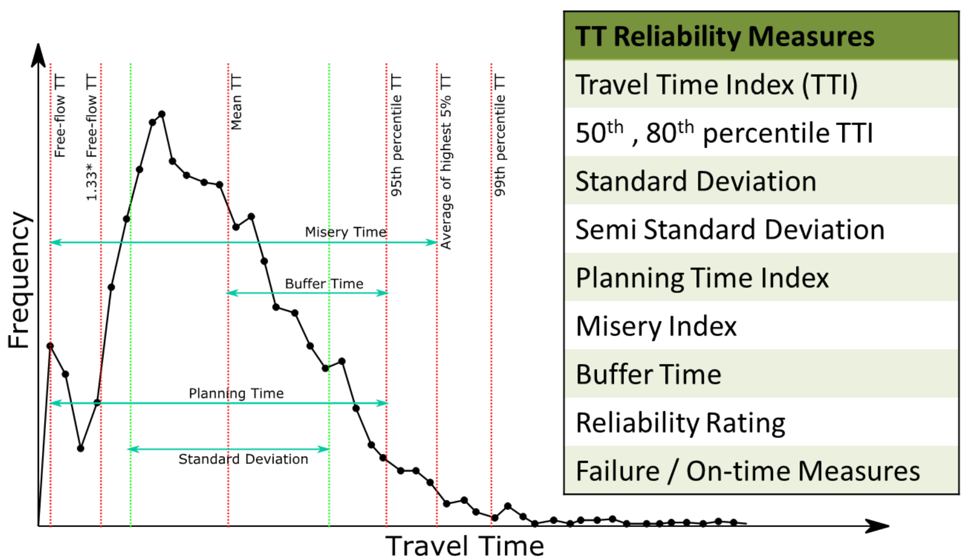


Figure 4. Travel time reliability metrics defined under SHRP2 project L08

L08 further identifies the best indicators of travel time reliability and the metrics to specially focus on, as listed in Table 1 below.

Table 1. L08 recommended best indicators of travel time reliability

Reliability Measure	Definition
Reliability rating	Percentage of trips serviced at or below a threshold travel time index (TTI) (1.33 for freeways).
Planning time index (PTI)	95th percentile TTI (95th percentile travel time divided by free-flow travel time).
80^{th} percentile TTI	80th percentile travel time divided by free-flow travel time.
Semistandard deviation	One sided measure of standard deviation pegged to the free-flow travel time instead of mean travel time.
Failure or on-time measure	Percentage of trips with space mean speed less than 50, 45 and/or 30mph.
Standard deviation	Usual statistical definition.
Misery index	Average of the highest 5% of travel times divided by free-flow travel time.

The L08 project designed separate methodologies to evaluate reliability for freeway facilities and for urban streets. The freeway facilities methodology relies on three main components: a data repository, a scenario generator, and a computational procedure. The scenario generator enumerates a variety of operational conditions expected on the freeway facilities, using the data repository and accounting for various features that introduce variability in performance such as: variability in demand, weather conditions, incidents, work zones and special events. These scenarios are then fed to the computational procedure component. The computational procedure module modifies existing freeway methods available in HCM (TRB, 2010) to compute freeway capacities, speeds, and delays, by adding a mechanism to evaluate the range of scenarios generated, thus producing a set of resulting traffic features. Travel times derived from all scenarios are then assessed for generating travel time reliability metrics.

HCM Methods for Work Zones

The National Cooperative Highway Research Program (NCHRP) project 03-107 (Schoen et al. 2015) updated work zone capacity models in the HCM. While the project focused on developing deterministic models for evaluating traffic operation at both highway and urban streets work zones, the focus in the current study is solely on highway and freeway work zones and thus this study only considers those elements of the project. Towards this objective, the 03-107 project developed methods to model work zone capacity, free-flow speeds, as well as speed-flow relationships for freeway work zones. The derived models were based on review of past literature on the topic, data collected as part of the project, and data obtained from microsimulation efforts as well. In line with the objectives set out, the project contributed predictive models for work zone capacity, free-flow speed, and flow-density relationship estimation.

The project tested a range of independent variables related to work zones that might affect both capacity and free-flow speeds. One of the most critical attributes of a freeway work zone considered was the work zone lane configuration. The project found that using the open-ratio, a ratio of number of open lanes to the total number of lanes at the location, did not reveal the entirety of the relevant information on lane-configuration, since open ratio cannot distinguish between a two to one lane drop and a four- to two-lane drop for example. Instead, a new measure of the lane configuration, the Lane Closure Severity Index (LCSI) was introduced with the following definition:

$$\text{LCSI} = \left((\text{Open ratio}) \times (\text{Number of open lanes})\right)^{-1} \tag{1}$$

In addition to the LCSI, other variables considered by the project were: (1) barrier type, (2) a binary indicator describing where the work zone is in an urban or rural area, (3) lane width – 12 ft, (4) lateral distance from obstacle – 12 ft, (5) a binary indicator of whether it's a left or right lane closure, (6) a two-valued indicator for work intensity, (7) police presence, (8) heavy vehicle percentage, (9) an indicator for day/night, (10) posted work zone speed limit, (11) work zone length, (12) a binary indicator for presence of on-ramps, (13) ratio of non-work zone speed limit to work zone speed limit, and (14) number of ramps within a three mile distance in either direction of the work zone.

Empirically fitted models using the above variables were tested against the available data to derive predictive models for estimating capacity and free-flow speeds. The following are the final models presented.

$$QDR = 2{,}093 - 154 f_{LCSI} - 194 f_{barrier} - 179 f_{area} - 9 f_{lateral\_12} - 59 f_{night} \tag{2}$$

where QDR is the average queue discharge rate (pcphpl), f_{LCSI} is the lane closure severity index, $f_{barrier}$ is 0 for concrete, 1 for cone, drum or barricade barriers, f_{area} is 1 for rural, 0 for urban areas, $f_{lateral\_12}$ is the lateral distance from nearest open lane to work zone minus 12 feet, and f_{day_night} is 0 for day and 1 for night.

$$FFS = 9.95 + 33.49 f_{SLr} + 0.53 f_{wzsl} - 5.60 f_{LCSI} - 3.84 f_{barrier} - 1.71 f_{night} - 1.45 f_{ramp} \tag{3}$$

where FFS is the work zone free flow speed, f_{SLr} is the ratio of non-work zone speed limit to work zone speed limit, f_{wzsl} is the work zone speed limit, f_{ramp} is the number of ramp within three miles in either direction of the work zone and f_{LCSI}, $f_{barrier}$ and f_{night} have same definition as before.

Independent Studies

There have been multiple efforts by independent researchers to study the impact of work zones on roadway performance. Such studies typically concentrate on estimating the impact of work zones on roadway capacity or on expected delays under a variety of control conditions. The HCM lists several studies (Dudek and Richards 1982, Dixon et al. 1996, Sarasua et al. 2004, MnDOT 2004, Notbohm et al. 2007, Elefteriadou et al. 2007, Maze et al. 2000, MassHighway 2006) that derived estimates of work zone capacities on distinct sites for a multitude of work zone lane configurations and arrived at a range of distinct capacity measures. A summary of such studies is provided by Chatterjee et al. (2009). An elaborate, recent review of numerous studies estimating impacts of work zones on freeway capacities and delays (including the ones mentioned in the HCM) is provided by Sun et al. (2018). However, these studies focus solely on measures of performance such as static capacity or average delays, and do not assess the impacts on reliability measures.

Most relevant to this study perhaps, Edwards et al. (2012) used private-sector travel time data (obtained through Virginia Department of Transportation's purchase from a private-sector travel time data provider, INRIX) at work zone locations to see their impact on travel time reliability. The study uses a total of 15 work zones covering freeways as well as arterials in Virginia. The work zone data included information on location of work zone, length of work zone, posted speed limits, lane and shoulder widths, interchange and signals density near work zone, type of area: rural or urban, and ratio of trucks and heavy vehicles in traffic composition. The study however did not have access to hourly traffic counts at any of the locations, and instead used Annual Average Daily Traffic (AADT) volume to represent demand. The authors initially considered four periods corresponding to a.m. peak, p.m. peak, mid-day and off-peak periods to measure three reliability indices, 95th percentile travel time, buffer index and planning time index, at each work zone. Due to lack of availability of detailed hourly volume data, the travel time data was instead aggregated for the entire day for the modeling effort. This results in congested and uncongested traffic conditions getting aggregated together, with potential information loss. Combining data from baseline and work zone periods together due to limited data size, the study found qualitative relationships between reliability measures and AADT per open lane, and between reliability measures in interchange density, while other factors considered such as lane-width, shoulder width, and truck ratios suggested no visible relationships with the reliability measures. The study was unable to find significant quantitative relationships from the studied data.

METHODOLOGY FRAMEWORK

This chapter outlines the methodological framework that was used in the study. The framework was designed based on the initial objectives and was updated throughout the course of the project to adjust for various obstacles and observations. It is anticipated that the analysis framework presented in this report can be used for any future studies on work zone travel time impacts and for identifying additional data needs to facilitate such studies.

Various data requirements for the study are first identified. The details of the source and quality of data collected are covered in the following chapter.

Work zone data: The foremost data requirement is access to high quality work zone data identifying, at least, precise information on the location of the work zone including the upstream and downstream extents, the start and end days for which the work zone was effective, the start and end times for the work zone each day it was active if the work zone is not continuously active, and the lane impact in terms of number of lanes closed due to the work zone. Knowledge of additional details such as the type of work being conducted, type of barrier used, lateral clearance from physical barriers, posted speed limit during the work zone, and location of the bottleneck created due to work zone in case of work zone that extend over a long spatial distance, would also be very relevant.

Travel time data: Another critical data requirement is access to high quality travel time or speed data corresponding to the work zone locations. Travel time collected from probe vehicles over the stretch of roadway is ideal since such data directly reflect travel time distribution for various drivers. A high penetration rate of probe vehicles is desirable, as is a precise control over the stretch of freeway to be studied.

Traffic volume: In addition to the work zone and travel time data, which are critical, traffic volume counts, preferably available at 15-minute or one-hour intervals, are also required. Traffic volumes offer a good estimate of demand (reflecting measure of demand when uncongested, and a demand higher than capacity when congested) and expected congestion levels, and thus have a direct impact on travel times at a location. Knowledge of traffic volume is thus very important to any predictive modeling efforts for travel time under work zone conditions.

Other data: Access to incident, special events, and weather data would be of great benefit as these also directly impact travel time reliability.

Once data sources are identified, the first step would be to identify candidate work zone locations based on data availability. These are filtered to remove work zones that do not allow controlled modeling of travel time reliability with and without the presence of the work zone. Filters used for this purpose are explained in detail in the following chapter.

For each work zone selected after the filtration process, the corresponding travel time and traffic count data are extracted. First a baseline period of time when the work zone is not present is identified in addition to the work zone period to form the total study period. The location is then matched in the travel time and traffic count data sources, and the appropriate information is extracted for the entire study period.

For each candidate site, the average travel time (averaged across all days in the study period) by hour of day was plotted to see the trend of the evolution of travel time over the course of an average day. This is done for both the baseline and the work zone periods and the two trends are compared to each other. Such a time-of-day plot highlights features such as peak periods, level of congestion, and impact of work zone on the travel time for each individual work zone.

Next, the travel time distribution for each work zone for both baseline and work zone periods and the corresponding measures of travel time reliability are derived. The list of travel time reliability measures listed in L08 (see Figure 4) is used for this purpose, with special focus on the mean travel times. In addition, the change in various travel time reliability measures from the baseline to the work zone period is also calculated as an indication of the impact of the work zone.

Finally, data from across all candidate work zone sites are used to develop predictive regression models for work zone impact on travel time reliability. These are designed to predict the percentage change that can be expected to be seen in a travel time reliability measure due to the presence of a proposed work zone. The model uses knowledge of the baseline reliability measure in addition to factors such as traffic volumes, number of lanes, and number of closed lanes due to the work zone.

Summary of methodology:

1. Identify sources for work zone, travel time, and traffic volume data.
2. Identify a list of candidate work zones based on data availability.
3. Identify filters for selecting useable work zones.
4. Extract the appropriate travel time and traffic count data for each finalized work zone.
5. Plot the time-of-day average travel time and traffic count data for each work zone for baseline and work zone periods. Study each work zone independently to note any possible discrepancies or oddities.
6. Plot the travel time distribution for each site corresponding to the baseline and work zone scenarios and calculate the various travel time reliability indices for each case as well as the change between baseline and work zone cases.
7. Develop regression models for impact of work zone on various travel time reliability indices.

DATA COLLECTION

This chapter describes the data collection process used, highlighting how candidate locations were selected, and the sources used for data collection.

In order to ensure a controlled comparison of the impact of work zones on travel time reliability at a location, the following filters were used in selecting candidate locations:

- Work zones should be in regions that experience congested traffic at least once during the day and extend through either the a.m. or the p.m. peak period.
- Work zones should exclusively involve work on the mainline facility with no direct work on ramps.
- Work zones should not involve the winter months of November to February.
- Work zones should not extend across multiple ramps ensuring stable traffic volume and traffic states for the length of the work zone.
- Work zones should exist (continuously) for at least 10 days in duration.
- Work zone should preferably be near an ATR location or have volume information available.

The reasons behind using the above filters are elaborated in the following section.

The data collected for the project is chiefly derived from three sources:

- Work zone data: Information about the work zones are collected from the Wisconsin Lane Closure System (WisLCS) (WisDOT 2014).
- Travel time data: Travel time data corresponding to each work zone is extracted from the National Performance Management Research Data Set (NPMRDS) (FHWA 2013).
- Traffic count data: Wisconsin Automatic Traffic Recorder (ATR) traffic count data are obtained from WisTransPortal.

The following sections further describe each source used for the data collection process in greater detail.

Work Zone Data – WisLCS

The Wisconsin Lane Closure Systems (WisLCS) provided work zone data across Wisconsin for the project. The WisLCS, which is hosted on the WisTransPortal, serves as WisDOT’s central scheduling and reporting system for all highway lane closures and restrictions statewide. Long term flooding, emergency closures, and major events are also included. All work authorized on the freeways and highways is assigned a project ID, and each project is sub-divided into multiple closure IDs corresponding to each lane-closure or restriction (including shoulder closures) work required as part of the project. Each closure is further documented with locational information: (1) the roadway the work was performed on, (2) the start and end locations for the work (either through mileposts, or names of cross-streets), (3) county information; time information: (1) the start and end dates when the work zone was active, (2) the start and end times during the day when work zone was active where applicable; and details on the type of work done.

In order to restrict the candidate work zone locations to those with traffic congestion during the day, the study only investigated freeways and highways in the vicinity of urban regions, thus eliminating some lesser state highways. In the end, a total of 5 interstate freeways, namely I-39, I-41, I-43, I-90 and I-94, and four US highways, namely US 12, US 14, US 18, and US 151 were considered in the study. While WisLCS has information on lane closures dating back to 2008, in order to ensure best intersection of reliable work zone, travel time (2012–present) as well as traffic volume data (varying by location with earliest starting in 2001), only work zones starting from Jan 2012 were considered.

The list of candidate work zones was next trimmed for two criteria: (1) the work being performed should be on the mainline facility and not on a ramp, and preferably be a lane closure, and (2) the work zone should be active through at least one peak period (either a.m. peak or p.m. peak). The former filter was chosen to only study a controlled set of types of work zones where local traffic patterns are likely not to be affected too drastically. The latter filter is used to ensure once again, that the impact of the work zone can be studied during congested peak traffic behavior periods where the presence of the work zone is likely to have the strongest impact on travel times. The data revealed that most work zones in or around urban areas, were set up as night-time-only work areas so that peak period traffic is not affected. The requirement that the work zone be active during at least one peak period during the day, therefore restricted candidates to only “long term” or “continuous” work zones where the lane closures were in place throughout the day on all days the work zone was active. This further eliminated any possible discrepancies in the recorded start and end times of the work zone, and the actual start and end times that the closures were in place on the field.

After removing any work zone that was exclusively active only during the winter months of November to February in order to control for changes to travel time due to severe cold weather and winter storm conditions, the list of candidates was further trimmed to eliminate work zones that were in close vicinity of major freeway interchanges, extended across multiple major ramps, or were excessively long (over 7.5 miles) and including more than five ramps. This was done to ensure that traffic states were consistent through the entire stretch of the analyzed segment with similar demand volumes through the stretch. The motivation for this filter is to avoid locations where the presence of entry and/or exit access points can substantially affect travel times and volumes so that upstream traffic is significantly different from downstream traffic conditions.

A final filter applied was to only consider work zones that were actively in place for a period of at least 10 days ensuring that travel time reliability metrics can be obtained for a statistically significant sample size. Choosing a minimum work zone duration of 10 days further ensures that traffic stabilizes to stable patterns as commuters adjust to the presence of the work zone.

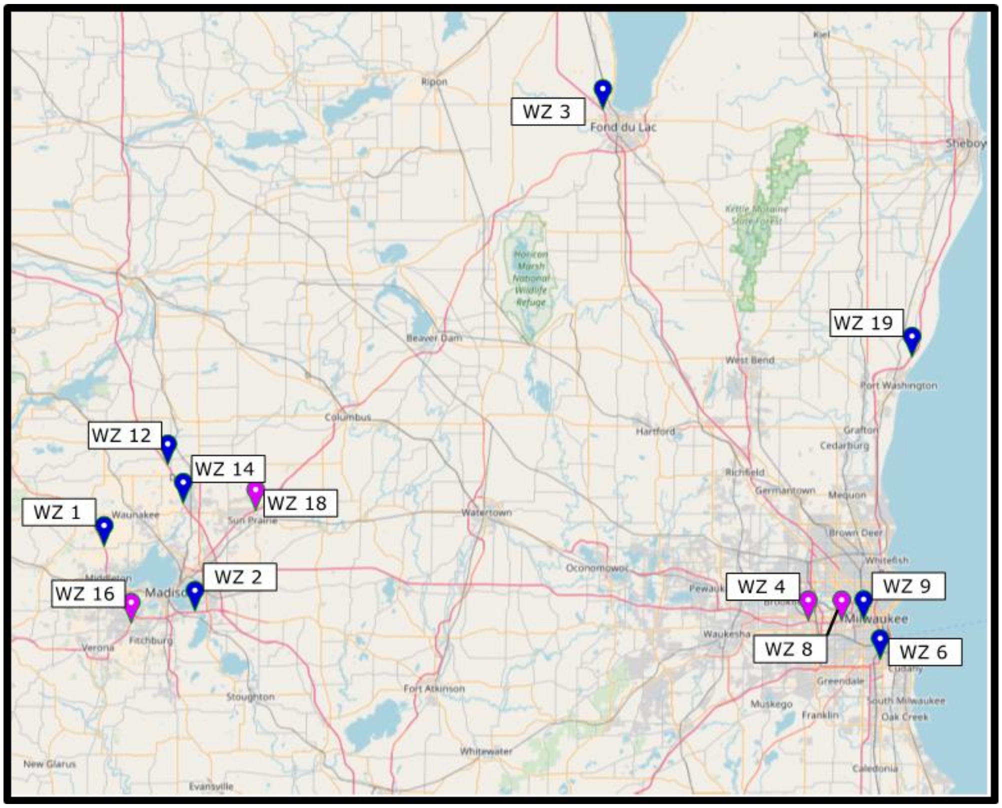
All remaining candidate work zone locations were finally checked for the presence of a nearby ATR (Automatic Traffic Recorder) station where hourly traffic volume data may be available.

The above filters trimmed the scope down from over 30,000 unique closure IDs on the selected freeways and highways, to a total of 19 final candidates. These 19 work zones come from 12 unique projects, with some projects involving a unique work zone on either direction (eastbound as well as westbound, or northbound as well as southbound direction) thus accounting for two work zones. Table 2 shows the final list of candidate work zones selected for the study along with the associated freeway and county, the lane configuration at the location, number of days the work zone was active for, and the length of the studied segment. As seen in the table, most of the selected work zones are either from near Madison (Dane County), or near Milwaukee (Milwaukee County).

Table 2. Final list of work zones selected for the study

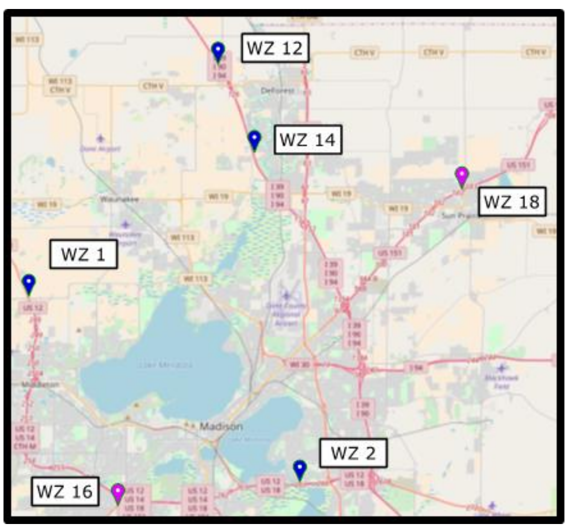
No.	WZ No.	County	Freeway	No. Lanes	No. Dropped Lanes	WZ Duration (days)	Length (mi)
1	1.1	Dane	US 12	2	1	38	2.3
2	1.2	Dane	US 12	2	1	30	2.3
3	2.1	Dane	US 12	3	0	95	1.1
4	2.2	Dane	US 12	3	0	95	1.1
5	3.1	Fond Du Lac	I-41	2	0	14	1.4
6	4	Waukesha	I-94	3	1	255	2.6
7	6	Milwaukee	I-94	5	1	24	0.6
8	8	Milwaukee	I-94	3	1	17	0.3
9	9.1	Milwaukee	I-94	4	2	13	1.4
10	9.2	Milwaukee	I-94	4	1	29	1.4
11	12	Dane	I-39	3	1	80	3.3
12	14.1	Dane	I-39	3	1	67	3.7
13	14.2	Dane	I-39	3	1	24	3.6
14	16.1	Dane	US 151	2	1	58	0.5
15	16.3	Dane	US 151	2	1	64	0.5
16	16.4	Dane	US 151	2	1	58	0.5
17	18	Dane	US 151	2	1	35	5.2
18	19.1	Ozaukee	I-43	2	1	17	6.1
19	19.2	Ozaukee	I-43	2	1	13	6.1

Figure 5 shows the locations for the selected work zones on a map of Wisconsin, with Figure 6 showing the region around Madison and around Milwaukee in better detail.



Blue markers indicate locations with complete traffic count data and purple markers indicate locations with partial traffic count data

Figure 5. Map of Wisconsin showing locations of work zones selected to study



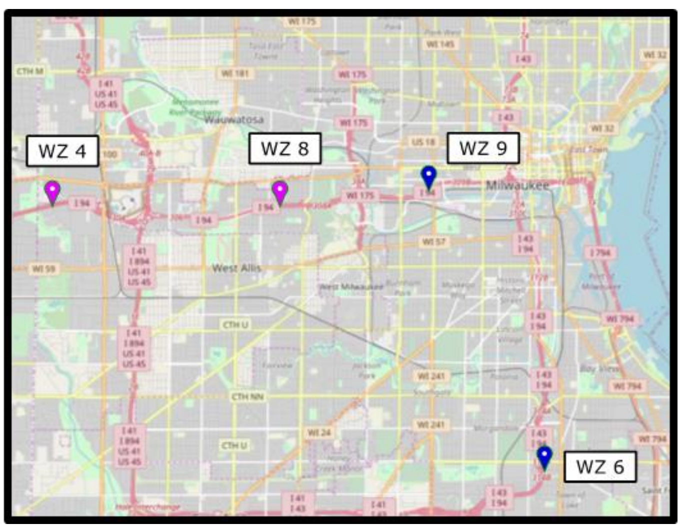


Figure 6. Maps zoomed in to show work zones near Madison (left) and Milwaukee (right)

Travel Time Data – NPMRDS

The National Performance Management Research Data Set (NPMRDS) was used to collect travel time data corresponding to each of the candidate work zones identified earlier. The NPMRDS is a monthly archive of average travel times reported every five minutes (when data are available) on the entire National Highway System. Recorded travel times are based on vehicle probe data from passenger as well as freight vehicles. Travel time data are available from October 2012 for Interstate freeways and July 2013 for the National Highway System, with a substantial improvement in data quality starting March 2014. Figure 7 shows a coverage map for NPMRDS travel time data.

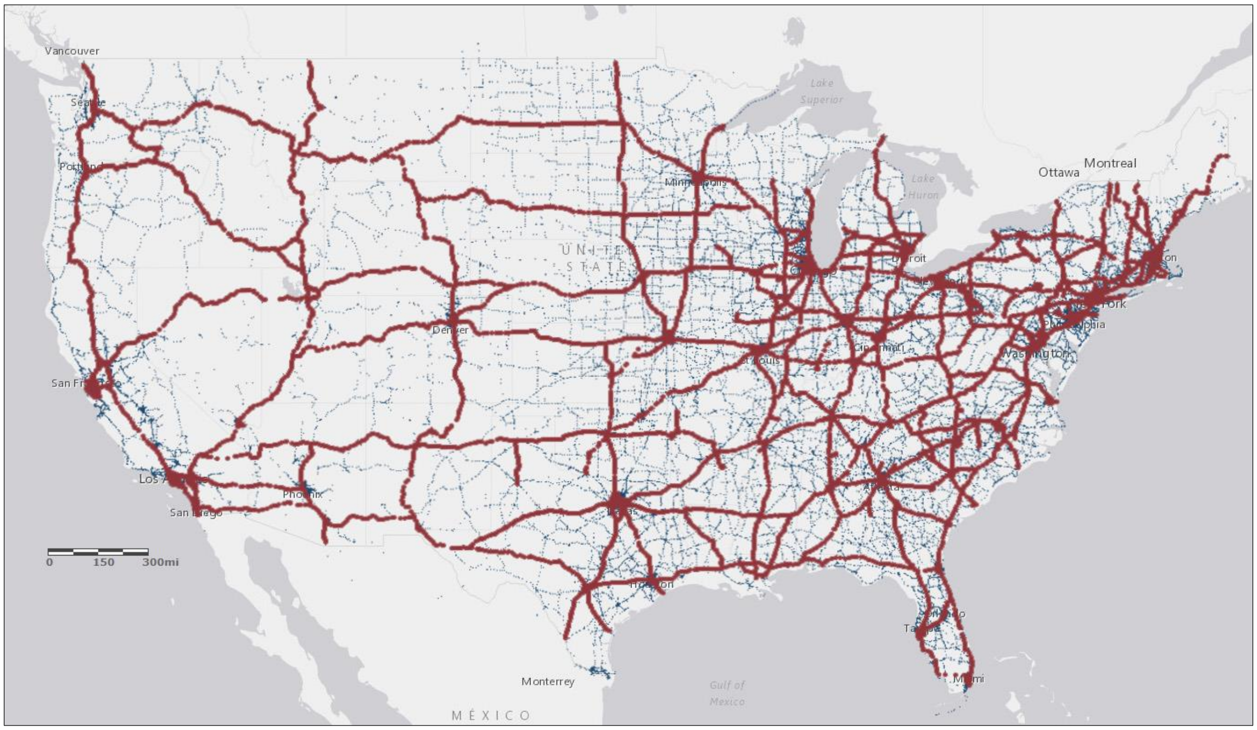


Figure 7. Coverage map for NPMRDS travel time data on the interstate and national highway systems

In addition to the five-minute bins the data are collected at, NPMRDS also allows for travel times to be queried at 10-minute, 15-minute and one-hour bin aggregation periods. Since the traffic volume data are expected to have a one-hour resolution (at best), travel times were also extracted at one-hour intervals to match the fidelity of traffic volume data.

The NPMRDS repository uses Traffic Message Channels (TMCs) to divide the freeways into small sections of roadway where the travel times are measured. TMCs can be of varying lengths and are usually defined based on physical features of the freeway (such as ramps or important milestones) and are usually numbered sequentially along a freeway with specific notations to describe whether they are on the north/east bound direction, or on the south/west bound direction of the freeway.

For each identified work zone, a corresponding list of TMCs defining the work zone stretch was identified. The TMCs chosen in each case construct a continuous roadway segment that completely encompasses the entire stretch of the work zone, extending further upstream to capture formation of queues due to the work zone bottleneck. Travel time for the entire segment during any one-hour period can then be obtained as the sum of the corresponding travel times on the component TMCs. While a length precisely as long as the expected maximum length of queue expected should be used ideally, this is not possible due to both lack of knowledge of the true extent of the queue build up, and variability by time of day and day-to-day in the length of the queue as well as being required to use the TMCs. Selecting a segment that does not capture the entire extent of the queue would underestimate the delays at the location, and thus the impact of the work zone on the travel time, while selecting a segment that is too long runs the risk of averaging out the delays with a larger portion of upstream free flow travel times and possibly the impacts of any secondary bottlenecks formed upstream. This aspect is revisited later in the report under limitations of the study.

Pre-work zone and post-work zone periods of time are decided, extending up to 60 days prior to the start and the end of the work zone respectively forming the baseline period when the work zone was not active to contrast against the active work zone period (duration for which work zone was present). The pre- and post-work zone periods are trimmed on an individual basis to make sure they don't overlap with other closures in the region within the same project, and to exclude any period in the winter months of Nov-Feb (where possible).

The one-hour travel times are extracted for the TMCs identified for the work zone location, for all dates covering the pre-work zone, work zone, and post-work zone days selected. In addition to the hourly travel times extracted for each one-hour period, the aggregate travel times corresponding to (1) a.m. peak, p.m. peak, mid-day (everything between a.m. and p.m. peaks), and night-time (rest of the day) periods, as well as for (2) peak (average over a.m. and p.m. peaks) and off-peak (rest of the day) periods on each day are computed. The a.m. and p.m. peaks in the above cases were identified individually for each work zone location using traffic volume trends, where available during the day (from ATR data), as well as travel time trends during the day. Where neither was possible (hourly traffic counts were not available, and travel time plot did not show a distinct two-peak pattern), fixed default durations corresponding to average trends seen in other locations (a.m. peak as 7 a.m. to 9 a.m., and p.m. peak as 4 p.m. to 6 p.m.) was used. The mid-day and night-time periods were automatically obtained from knowledge of the a.m. and p.m. peak periods in each case.

Traffic Volume Data – ATRs

Wisconsin Department of Transportation (WisDOT 2014) collects traffic volume data at nearly 30,000 sites on streets and highways around the state, including 221 permanent continuous data counting stations primarily located on the highway system. The continuous data stations typically use Automatic Traffic Recorders (ATRs) collecting traffic counts at regular intervals. This ATR data was used, where available, to collect hourly traffic count data corresponding to the work zone locations selected, for the corresponding study periods (including pre-work zone, work zone, and post-work zone periods). Figure 5 showing a map of candidate locations selected for the study, identifies locations with hourly ATR data available for the study period in question. In some cases, a nearby ATR slightly upstream or downstream of the work zone location was used if there was not significant ramp traffic expected to affect the traffic counts between the location of the ATR and the work zone. The obtained traffic counts are separated into days when the work zone was active and when it was not. Further, the hourly volumes are also aggregated, similar to the aggregation of travel times, into peak and non-peak periods of the day, and into a.m. peak, mid-day, p.m. peak and night-time periods of the day.

IMPACT OF WORK ZONE ON TRAVEL TIME RELIABILITY

This chapter describes the framework that was used to study the impacts of work zones on travel time reliability. The study approach was adjusted throughout the research based on the difficulties faced in data collection and data processing, and the final framework presented here represents an explanation of what challenges should be expected, and how to address such challenges, including what additional data should be collected, when doing a similar or related study in the future.

Hour-of-Day Time Series Plots of Travel Time (TT)

Once the appropriate raw data were extracted from the various sources, the first element to address was to observe how average (and median) travel time corresponding to each hour of the day, aggregated over the study period, varied over the course of the day, and how such a time series plot varied between the baseline period when the work zone was not active to when it was active.

As described above, the entire study period was first divided into the baseline and the work zone days. Within each division, the travel times for a given hour of the day (e.g., 4 a.m. to 5 a.m.) were combined across all days in the period to obtain an average (and median) travel time corresponding to that hour of the day. Doing the same for each hour gives 24 values for baseline and 24 values for work zone periods representing the average (and median) travel time for each hour. This was then plotted against time on the horizontal axis.

The general trend of the travel time is expected to reflect typical morning and/or evening hour congestion peaks (corresponding to lower speeds and thus higher travel times), with mid-day values being lower than the peak travel times, and night-time values being somewhat stable and approaching free flow travel time. It is also possible that the travel times indeed do not exhibit any perceivable pattern and remain roughly constant, implying that the location does not get congested during the day.

Further, the average work zone travel time curve was expected to be consistently higher than the baseline travel time curve, suggesting that the presence of the work zone can decrease capacity and/or slow down traffic movement and increase the travel times. This difference in the travel times between the baseline and the work zone cases should be more visible corresponding to the peak periods and might not be significant when baseline travel time is close to free flow travel time. This is justified by the intuitive reasoning that the presence of work zone might not have any noticeable impact on travel times when there is very low demand (and plenty of capacity to spare), while higher demand should suggest the work zone would have greater impact on the travel times. Figure 8 through Figure 10 show the average travel times computed using two separate outlier exclusion rules, as well as median travel times, for work zone 2.1 (work zone with shoulder closures on US 12 near Monona Drive in Dane County).

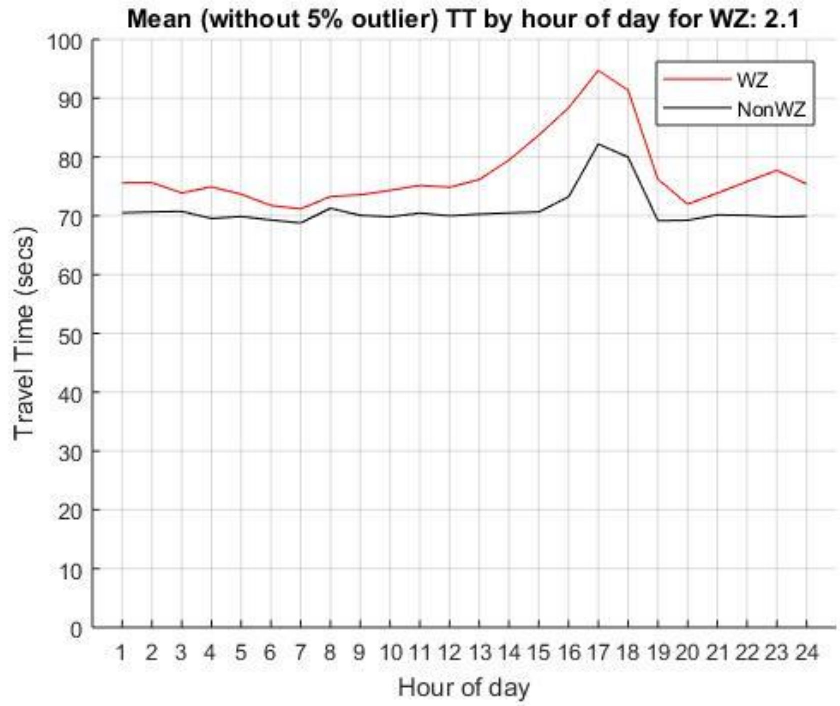


Figure 8. Time-of-day mean travel times (excluding top 5% outlier values) aggregated over all scenerio days for work zone 2.1 (shoulder closure on US 12 in Dane County)

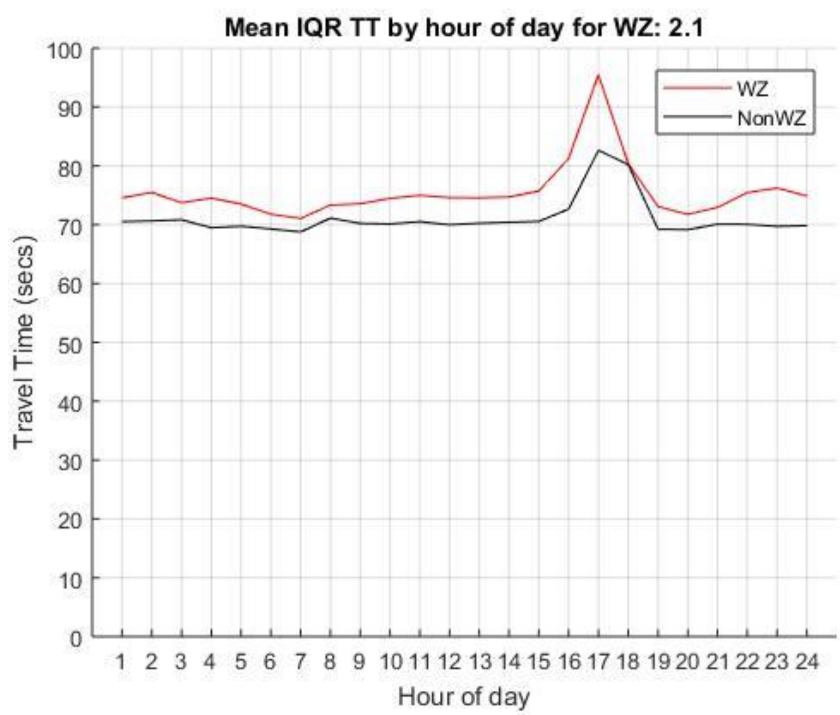


Figure 9. Time-of-day mean travel times (within 1.5*Inter Quartile Range of median) aggregated over all scenario days for work zone 2.1 (shoulder closure on US 12 in Dane County)

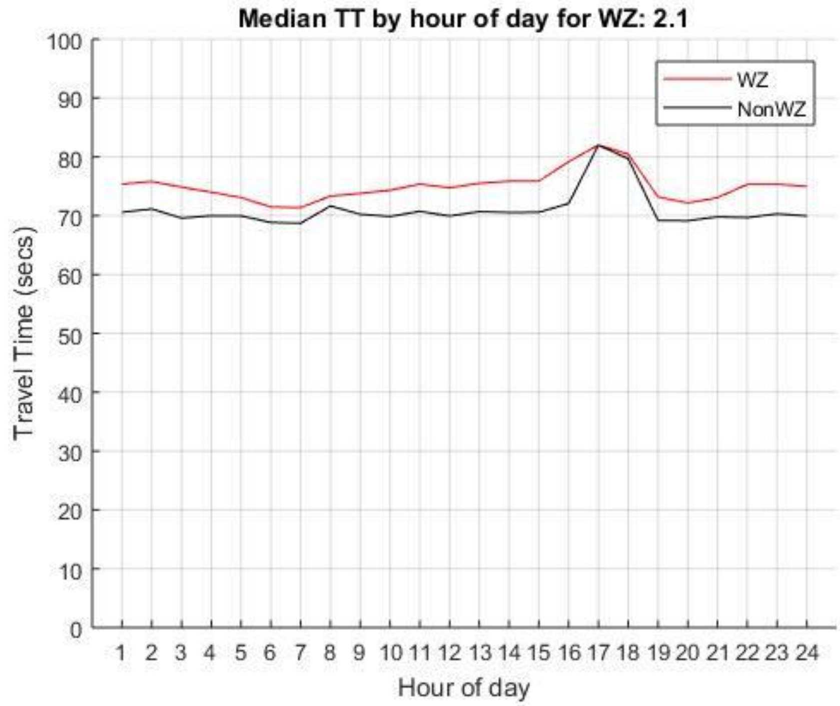


Figure 10. Time-of-day median travel times aggregated over all scenario days for work zone 2.1 (shoulder closure on US 12 in Dane County)

The work zone project also involved lane closures in addition to the shoulder closures, but the lane closures were in play only during night hours and was thus not considered for the study. The graphs all show patterns consistent with the above expectations.

Figure 11, shown at a different location (WZ 4, involving right lane closure on a three-lane section of I-94 from Wisconsin Highway 100 to Sunny Slope Road in Waukesha County), with a more distinctly defined peak period, also conforms to this notion albeit with a stronger impact due to presence of work zone in the peak periods.

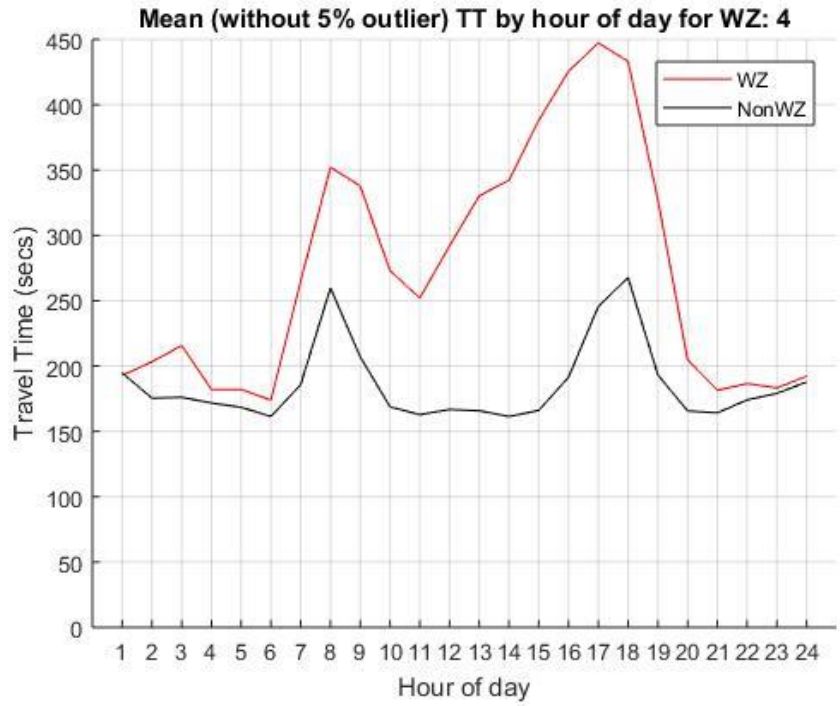


Figure 11. Time-of-day mean travel times (excluding top 5% outlier values) aggregated over all scenario days for work zone 4 (right lane closure on a three-lane portion of I-94 from Sunny Slope Road to off ramp to Wisconsin 100)

Work Zone 2.2 – A Uniquely Interesting Case

While most locations showed travel time patterns that were expected, with travel times increasing during the work zone periods compared to the baseline periods, there were a few exceptions.

Figure 12 shows the travel times for one such location, work zone 2.2 (shoulder closure work zone on three-lane section of US 12 WB between Monona Drive and South Towne Drive in Dane County) (see Table 2).

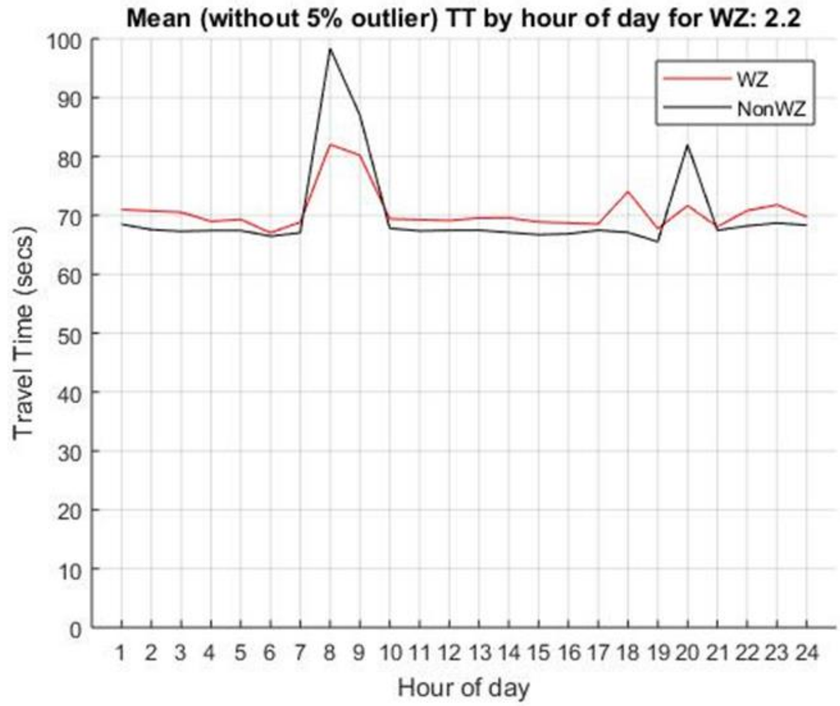


Figure 12. Time-of-day mean travel times (excluding top 5% outlier values) aggregated over all scenario days for work zone 2.2 (shoulder closure on US 12 in Dane County) showing a reduction in work zone travel time during morning peak compared to baseline

While the travel times remain consistently stable through most of the day, increasing slightly when the work zone is active, the location exhibits peculiar behavior during both the morning and the evening peak periods. As seen from the plot, the morning peak travel time in the baseline scenario is roughly 100 secs, roughly 40% increase from free flow travel time. The corresponding morning peak work zone travel time, however, is lower at little over 80 secs reflecting only a 15% increase from free flow travel time and, more surprisingly, a decrease from the baseline travel time at the same hour of the day. The evening peak (lesser congestion than morning peak) also shows the same type of peculiarity with the travel times being lower than the baseline counterparts. Furthermore, the travel times exhibit no distinct peak period during the evening hours when the work zone is active.

The latter can be attributed to the "peak spreading" phenomenon. Such a behavior usually happens when the peak demand is distributed over a longer duration of time. Since the presence of the work zone might convince evening commuters to adjust their evening travel schedule (for those that have the flexibility), it might cause "peak spreading" thus distributing the demand over a longer time period while also improving the "worst" hour travel time in the same process. The former however can only be explained if the presence of the work zone caused a diversion of traffic with a fraction of commuters choosing to take an alternate route to avoid the delays, thus reducing the travel time on the segment during the morning peak when the work zone was active. If this was true, it would be clearly observable in demand with traffic counts seeing a significant drop when the work zone was active compared to the baseline scenario. Figure 13 shows the traffic volumes as obtained from ATR data for the location. The figure shows that the morning peak did not have a significant change between the work zone and baseline scenarios, with the demand increasing when the work zone was active. This does not then support the argument that the travel times decreased due to the presence of the work zone due to diversion of traffic and consequent reduction in traffic demand improving congestion conditions on the segment.

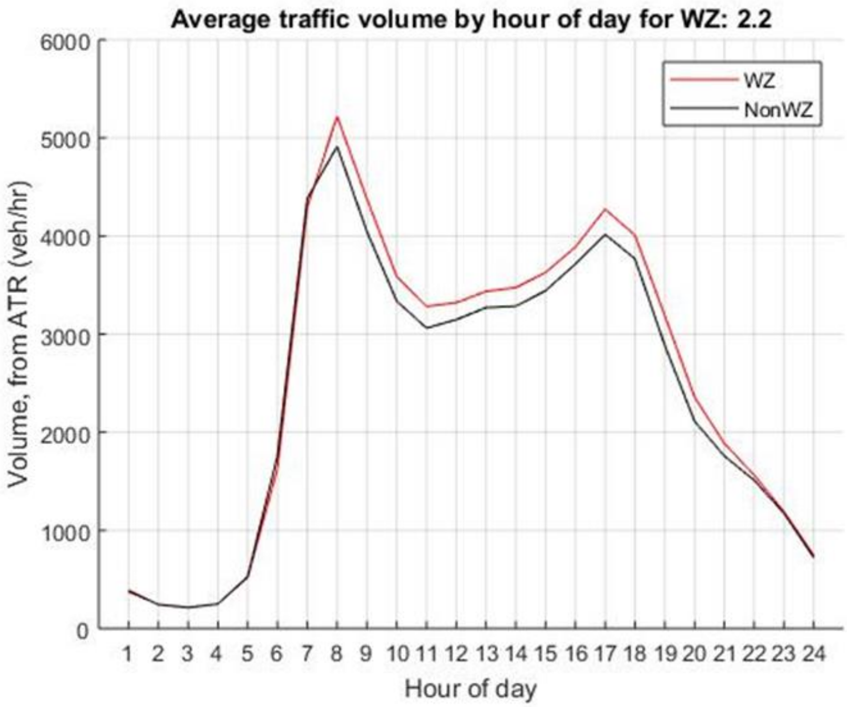


Figure 13. Time-of-day mean traffic counts for work zone 2.2 (shoulder closure on US 12 in Dane County)

The other possible explanation to the decreased work zone travel times could be due to portions of the queue upstream caused due to the work zone not being captured within the segment for which the travel times were extracted. This is further enforced by the fact that the segment considered for this location is indeed short in length. To investigate if this truly was the reason for the peculiarity, travel time around the work zone was extracted for a longer stretch of the roadway, extending further upstream of the work zone location (2.9 miles instead of the 1.1 mile stretch considered originally). The time-of-day average travel times are once again plotted for the new longer stretch of roadway (see Figure 14). However, this does not change the overall trends in travel time seen earlier with the morning peak travel times in the work zone scenario still have lower average travel time than the baseline scenario.

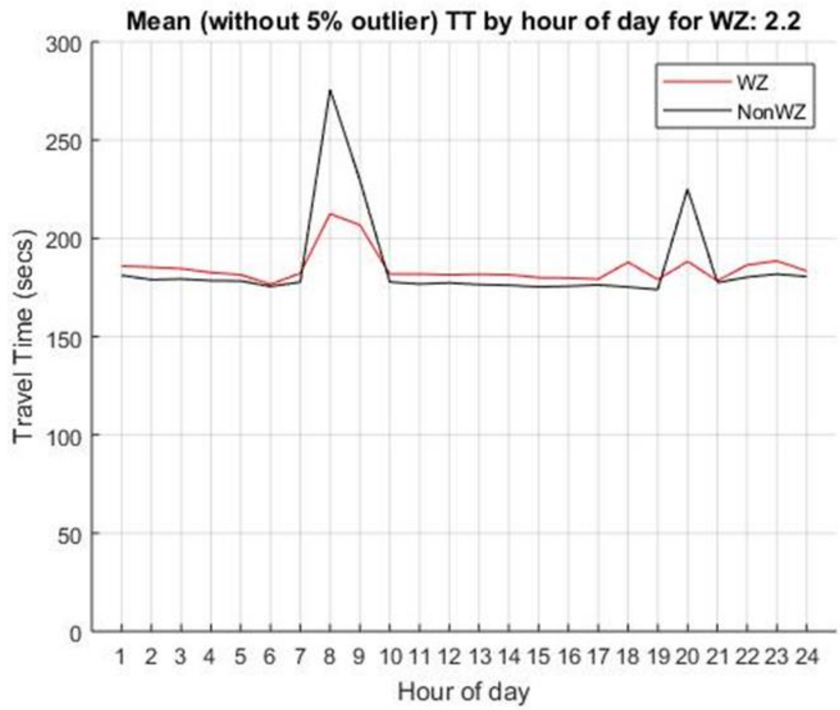


Figure 14. Time-of-day mean travel times (excluding top 5% outlier values) aggregated over all scenario days for work zone 2.2 (shoulder closure on US 12 in Dane County) after length of study zone was extended further upstream

Another possible explanation for the behavior could be the formation of a bottleneck upstream of the work zone either induced due to the work zone itself, or an external unexpected feature near the work zone affecting traffic behavior (such as the presence of a separate work zone project upstream of the location of interest). Due to the nature of the availability of data, this becomes incredibly hard to verify and thus remained outside the scope of this project.

As seen from the above, plotting the average travel time and traffic volumes against time of day for each location individually gives an insight on various traits of the location, how the presence of the work zone affects the travel times, and whether the work zone causes a significant diversion in traffic patterns. It further helps identify special cases which need to be addressed individually in more detail (if data permits). However, as seen from the case of work zone 2.2 here, it is possible that the available data can fail to elaborate why an unexpected behavior is observed.

Travel Time Distributions

Once each work zone location and the corresponding time-of-day plots of travel time and traffic volume have been studied independently, the next step is to study the travel time distribution across all days for each location. The objective here is to move beyond the aggregate measure of travel time (such as the mean and the median travel times) and look at the spread of the travel time distribution and derive various travel time reliability indices as covered under the literature review chapter earlier.

Like before, the hourly travel times are segregated either as belonging to the baseline period or the work zone period. Each group is further subdivided into travel times reflecting only the peak periods (both morning and evening peaks combined) and all off-peak periods (rest of the day) and independently study the travel time distribution for the baseline and work zone cases (1) over the entire day, (2) over the peak periods, and (3) over the off-peak periods. The travel times are converted to travel time index to normalize the data between different work zone locations. The travel time index is calculated as:

$$\text{Travel time index} = (\text{Hourly travel time})/(\text{Free flow travel time for baseline scenario}) \quad \textbf{(4)}$$

Thus, a travel time index value of 1 represents free flow conditions, a value lower than 1 reflects traffic moving at an average speed higher than the free flow speed, and a value higher than 1 reflects traffic moving slower than free flow speed.

Figure 15-Figure 17 show the sample distribution of the travel time indices for each of the ranges of time described above for the baseline and work zone scenarios for one candidate work zone (graphs corresponding to the travel time distribution for other work zones can be found in the appendices). The corresponding values for all travel time reliability measures listed earlier are also computed for each of the cases showing the values for the baseline scenario, the work zone scenario, and the percentage change from the baseline.

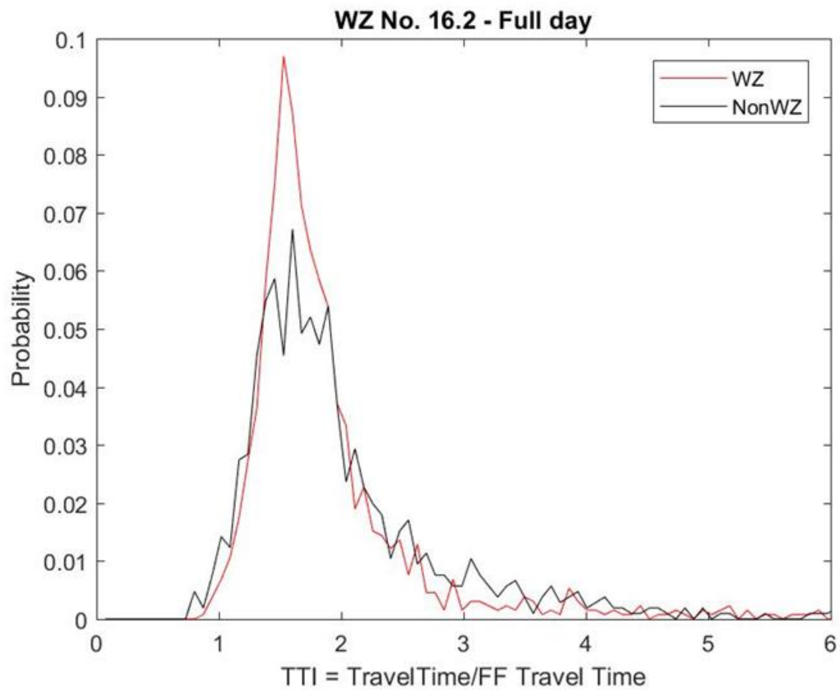


Figure 15. Travel time distribution for work zone 16.2 (left lane closure resulting in a two-lane to one-lane reduction on US 151 SB between merge with US 18 and Raymond Road in Dane County) for the entire day across all days in the study period

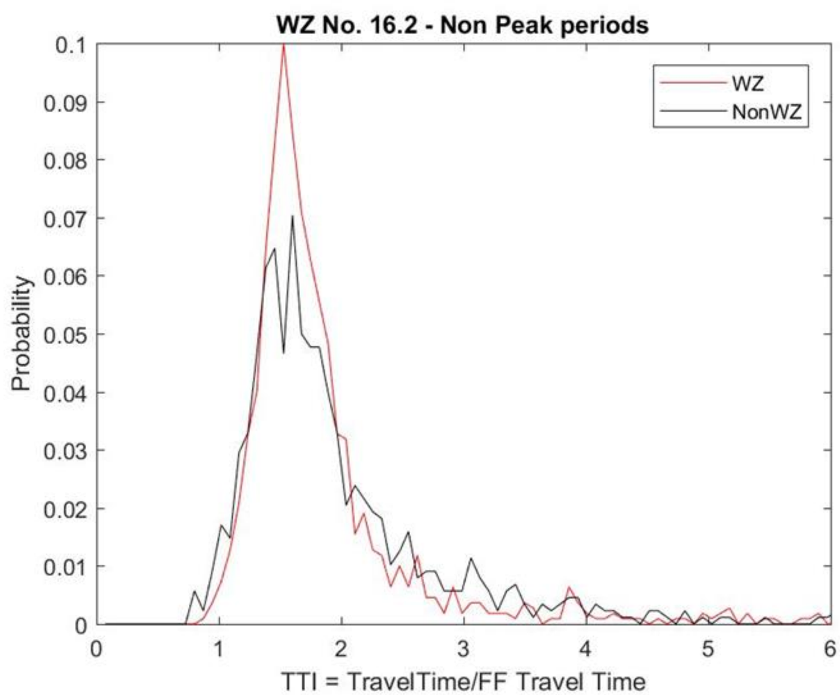


Figure 16. Travel time distribution for work zone 16.2 (left lane closure resulting in a two-lane to one-lane reduction on US 151 SB between merge with US 18 and Raymond Road in Dane County) for non-peak periods across all days in the study period

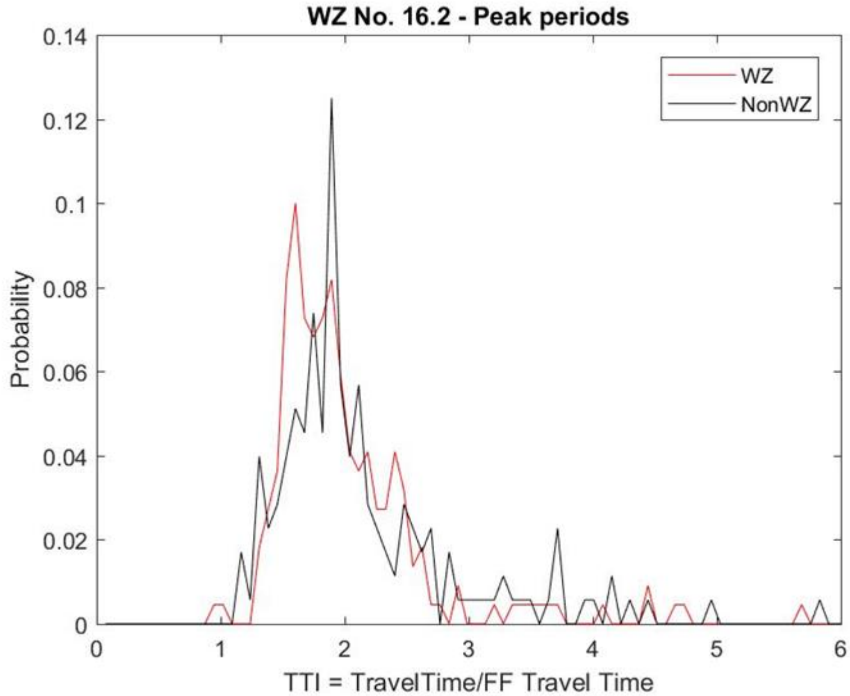


Figure 17. Travel time distribution for work zone 16.2 (left lane closure resulting in a two-lane to one-lane reduction on US 151 SB between merge with US 18 and Raymond Road in Dane County) for peak-periods across all days in the study period

Some common observation from the generated plots is that the most likely travel time indices expected for a location (corresponding to the highest probability within the distribution) are higher when looking at just the peak periods than when looking at the off-peak periods. This is of course expected as the peak periods are likely to involve congestion on the roadway segment. Similarly, for most locations, the distribution for the work zone scenario is somewhat shifted to the right compared to the baseline scenario reflecting a trend for an overall increase in the travel times due to the presence of the work zone. As noted earlier, however, this is not strictly seen for all locations, with some locations having an overall leftward shift for the work zone scenario. A third expected behavior also noticed in most cases, is that the spread of the travel time index distribution is smaller for off-peak periods (where barring an incident, the spread is usually exclusively attributed to heterogeneity in vehicles' desired speeds) than for peak periods (where congestion level might further add to the spread in the distribution).

Impact of Work Zones on Travel Time Reliability (TTR)

While the previous sections describe the process of looking at individual work zones and estimating the travel time distribution, travel time reliability measures and changes to these when the work zone becomes active, these have been exclusively descriptive models where the features are derived using available knowledge of the work zone.

The final component in the study framework is to look at predictive possibilities where the potential impact of a planned work zone on the travel time reliability on the site of interest can be estimated ahead of time. Such a model could be invaluable to the planning process, impact and cost-benefit analysis of work zones, and to educate commuter's decisions and choice of route (diversion) in preparation of the scheduled work zone. The objective of such a model would be to predict various measures of travel time reliability (mean travel times, buffer time, misery index, etc.) when the work zone becomes active, knowing the baseline travel time reliability measure observed, the planned changes to the lane configurations, the type (pavement maintenance, re-striping, expansion of lanes, shoulder or median work, etc.) and/or intensity (high or low impact to traffic behavior) of the work scheduled, the existing traffic volumes at the site, and predicted changes to the traffic volume due to the work zone once it becomes active.

Of the descriptive terms mentioned above, data limitations restricted the ability to use type and intensity of scheduled work as a parameter, since this information was rarely available, and was very loosely defined where it was indeed available. If the work shown here is expanded to a greater scope with a larger number of work zones considered, this could be used as a key attribute on the modeling effort. In addition, numerous other potential features could also be considered depending on the scope of the study and data availability. The following is a list of some such features that may be considered:

- Barrier type used
- Lateral distance to the barrier
- Lane width
- Posted work zone speed limit
- Urban / rural area
- Number of ramps present in or near the work zone

A ratio of the travel time reliability measure when the work zone becomes active to the measure for the baseline scenario, henceforth called the work zone impact ratio (WZIR), is used as a representation of the impact due to the presence of the work zone. A unique work zone impact ratio would be calculated for each travel time reliability measure. A work zone impact ratio with a value equal to 1 represents a scenario where the presence of the work zone has no impact on the travel time reliability measure being observed, a value smaller than 1 represents a decrease in the measure due to the work zone, and a value higher than 1 represents an increase due to the work zone. In addition, a stronger deviation from 1 for the ratio reflects a stronger impact due to the work zone. Intuitively, the presence of the work zone is expected to have an adverse effect on each reliability measure, thus implying that the expected value of the work zone impact ratio is always greater than one.

$$\text{WZ impact ratio: } \mathrm{WZIR}_{\mathrm{TTR\ measure}} = \mathrm{TTRMeasure}_{\mathrm{WZ}}/\mathrm{TTRMeasure}_{\mathrm{baseline}} \quad \textbf{(5)}$$

In order to observe the work zone impact on reliability measures across a range of traffic demand levels, while also not aggregating data between periods with high demand and periods with low demand, each day was divided into four periods: (1) a morning peak period, (2) an evening peak period, (3) a mid-day period ranging from the end of the morning peak to the start of the evening peak, and (4) a night-time period with the rest of the day extending from the end of the evening peak on a day to the start of the morning peak on the subsequent day. Travel time reliability measures were then calculated for each site corresponding to both work zone scenarios and baseline scenarios for the above mentioned four periods of the day, resulting in a total of eight (four by two) data points for each work zone. The corresponding traffic volumes were also averaged for the eight distinct periods (averaged independently for the four periods of the day using only the days when work zone is active, and when the work zone is inactive).

Descriptive Features

In addition to the aggregate traffic volumes across all lanes of the highway during the baseline period, a measure of the change in aggregate traffic volumes during the work zone periods, the average traffic volume per lane (the aggregate baseline volume divided by total number of lanes on the highway), and traffic volume per available lane (aggregate work zone period volume divided by number of available lanes while work zone is active) are also considered.

The lane configuration, including the number of lanes on the roadway, the number of lanes closed due to the work zone, and consequently, also the number of lanes available while the work zone is active, is an integral measure of the severity of a work zone. A work zone involving multiple lane closures is expected to have a more severe impact on traffic than a work zone in the same location with a single lane-closure. Similarly, a two-lane closure on a highway that originally has three lanes is more intense than a similar two-lane closure on a five-lane freeway. The Highway Capacity Manual (HCM) (TRB 2016) methods on work zone analysis suggest using two indices to reflect the lane configuration at a work zone location. The first measure, the open ratio, is simply the ratio of number of lanes available while the work zone is active, to the total number of lanes on the roadway. Thus, the open-ratio is a value between 0 and 1, with a ratio equal to 1 representing no lane-closures and a ratio equal to 0 implying a complete shutdown of the highway.

$$\text{Open Ratio} = (\text{Number of open lanes})/(\text{Total number of lanes}) \qquad \textbf{(6)}$$

HCM (TRB 2016) also recognizes that the open ratio cannot distinguish between multiple setups, such as between a two-lane closure on a four-lane freeway and a single lane closure on a two-lane highway with an open ratio of 0.5 in either case. Field and literature data however has suggested that the capacity of a four- to two-lane drop is significantly larger than the capacity of a two- to one-lane drop. To account for this difference, a new measure, the Lane Closure Severity Index (LCSI), is introduced. The LCSI is calculated as the inverse of the product of the open ratio and the number of open lanes.

$$\text{LCSI} = \big((\text{Open ratio}) \times (\text{Number of open lanes})\big)^{-1} \qquad \textbf{(7a)}$$

$$\text{LCSI} = (total\ number\ of\ lanes)/(number\ of\ open\ lanes)^2 \qquad \textbf{(7b)}$$

Since the LCSI has an inverse relationship with the number of open lanes, a smaller LCSI value represents more favorable conditions where the work zone has milder impact on traffic, with LCSI equal to 1 representing no impact from the work zone with no lane closures, while a higher LCSI value represents higher severity of the work zone.

Dependence on Descriptive Features

First the work zone impact ratio for a travel time reliability measure is plotted against each of the descriptive variables considered independently. This is done to roughly estimate how each variable influences the work zone impact ratio independently. The intent is to see if there are clear linear, polynomial, or exponential trends in the relationships between each feature and the predicted WZIR value.

Figure 18-Figure 21 show the plots obtained for the WZIR corresponding to mean travel time against each feature considered. Figure 18 suggests that most locations have a WZIR for mean travel time within the range of 0.9 to 1.1 with no clear trends for these locations. However, there is a loose trend seen with higher traffic volumes corresponding to higher deviations in the WZIR (albeit, on both directions with respect to the WZIR = 1 axis). An equivalent trend in the plot against traffic volumes per lane is not as easily observed however. Further, the graphs corresponding to the open ratio and the LCSI reveal no trend in data whatsoever.

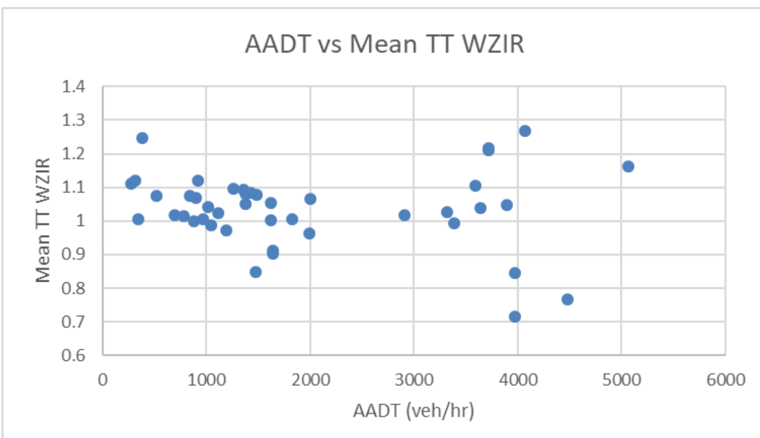


Figure 18. Mean travel time WZIR versus total traffic volume

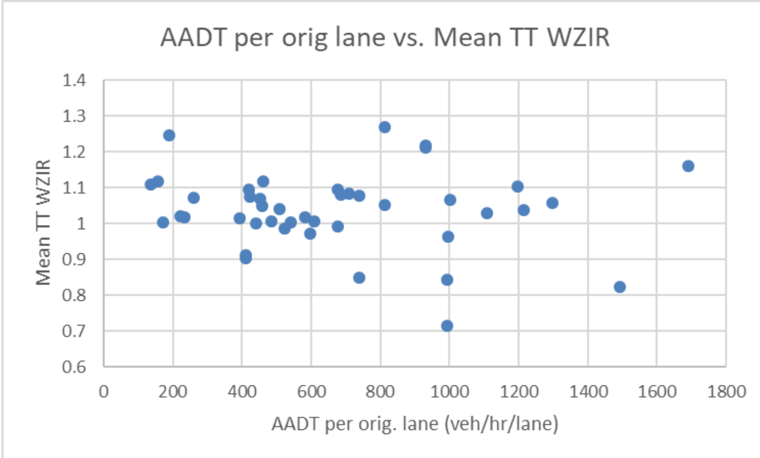


Figure 19. Mean travel time WZIR versus total traffic volume per lane (baseline)

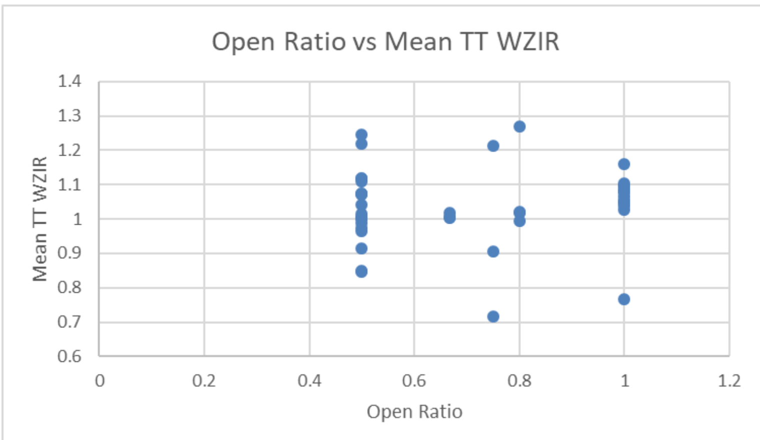


Figure 20. Mean travel time WZIR versus open ratio

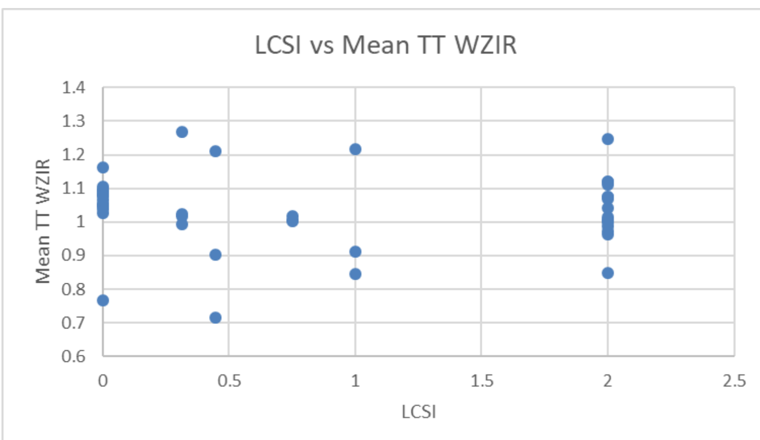


Figure 21. Mean travel time WZIR versus LCSI

To further investigate the loosely seen relationship between traffic volume and WZIR, modeling for the deviation of WZIR from a no-impact value equal to 1 is considered. This is equivalent to measuring the unsigned percentage change in the travel time reliability measure due to the work zone. This value is referred to as the Absolute Work Zone Impact Ratio or the AWZIR, which can be defined as:

$$\mathrm{AWZIR}_{\mathrm{TTR\ measure}} = 1 + \mathrm{Abs}(\mathrm{WZIR}_{\mathrm{TTR\ measure}} - 1) \quad \textbf{(8)}$$

Figure 22 shows a plot for AWZIR versus AADT corresponding to mean travel times for all four periods during a day, and Figure 23 shows the corresponding plot for only the morning and evening peak periods.

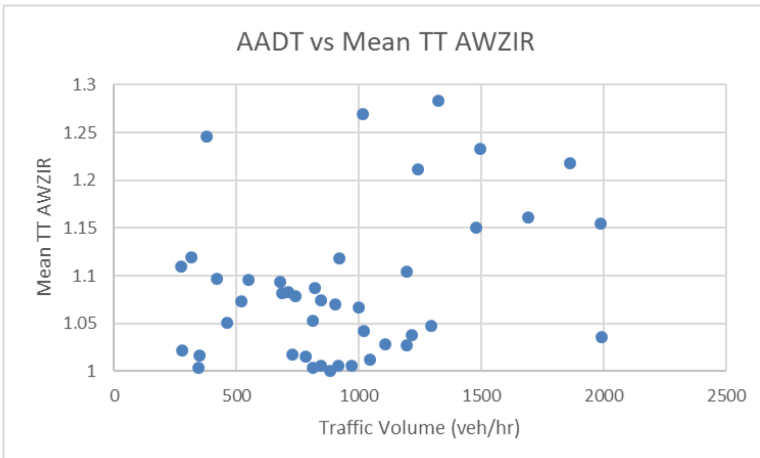


Figure 22. Mean travel time AWZIR versus total traffic volume

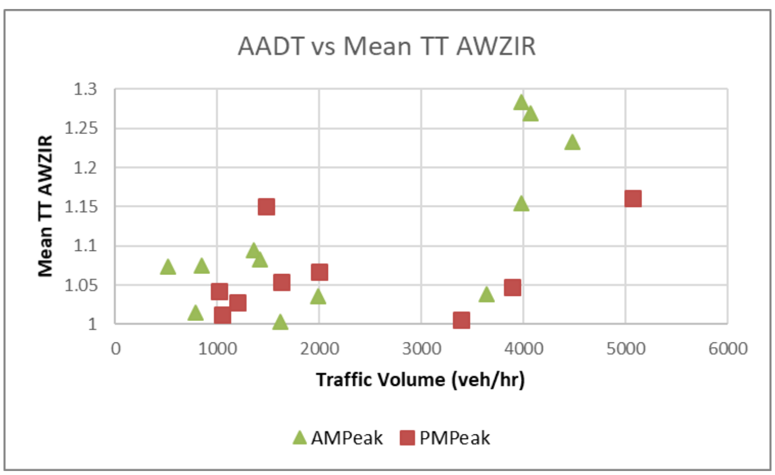


Figure 23. Mean travel time AWZIR versus total traffic volume showing only morning and evening peak hour data

There is a slightly more prevalent relationship observed here with higher AADTs corresponding to higher AWZIR values (more severe impact of work zone on the travel time measure). While the relationship looks roughly linear in nature, there is not enough evidence to support this strongly, and there are large variations seen in the AWZIR values corresponding to higher traffic volumes.

Though the above examples all refer to the mean travel time AWZIR specifically, the same process was also performed for other travel time reliability measures as well.

While there was no strong suggestion of a specific trend of relationship between the WZIR / AWZIR and any of the descriptive features, this does not necessarily mean that the features selected do not carry any information about the WZIR / AWZIR. It is still possible that the combination of all features together allows for a strong empirically derived predictive model to be developed.

Regression Modeling

As the final step, regression models were set up for predicting the work zone impact ratios based on the various parameters considered. A linear regression model was first explored for each of the reliability measure considered independently. The linear regression choice is made based on two aspects: (1) no clear non-linear relationship is evident from studying the influence of each factor independently, and (2) HCM methods used for estimating work zone capacity and free-flow speed both use linear models.

The goodness of fit measures obtained for each of the reliability measure studied showed poor fits (see Table 3). The best fit was observed for the AWZIR measure of mean travel time (R squared = 0.303), median travel time (0.267) and buffer time index (0.247) in one of the models, and the fits for misery index and standard deviation of travel time being exceptionally poor. Models using polynomial forms of the various factors, as well as some models with combination factors (product of two factors) were further considered but failed to achieve a good fit.

Table 3. R squared measures for linear models fitted over all data points

		Reliability metric						
Work zone	**Linear Model Parameters**	**Mean TT**	**Median TT**	**Std. Dev. TT**	**95th %ile TT**	**Misery Index**	**Buffer Time Index**	**Planning Time Index**
WZIR	V, OR, L, P	0.177	0.215	0.013	0.188	0.024	0.111	0.114
WZIR	V, L	0.024	0.005	0.011	0.055	0.017	0.02	0.077
WZIR	VL, #TL, L	0.024	0.012	0.034	0.129	0.039	0.167	0.169
AWZIR	V, OR, L, P	0.243	0.218	0.012	0.225	0.016	0.169	0.136
AWZIR	V, L	0.231	0.175	0.008	0.184	0.015	0.096	0.095
AWZIR	VL, #TL, L	0.303	0.267	0.044	0.119	0.049	0.247	0.196

*Parameter key: V: total traffic volume, VL: traffic volume per open lane, OR: open ration, L: LCSI, #TL: total number of lanes, P: peak (1) or non-peak (0) period

To verify if the regression modeling can be improved by filtering certain outlier cases out, data points that represented either work zone with only shoulder work (and hence open ratio = 1), or where accurate hourly traffic counts were not available for both work zone and baseline scenarios were discarded. Regression models were once again fit to this tighter selection of 29 data points. Table 4 shows goodness of fit for three models used for predicting AWZIR for various travel time reliability measures. As can be seen, the regression models predicting mean and median travel times see a substantial improvement, with an R squared value of 0.496 for mean travel time AWZIR and 0.469 for median travel time AWZIR for the best fit model. Table 5 shows the regression analysis results for the best fit model, a linear model for mean travel time AWZIR using traffic volume per open lane, total number of lanes at the location, and open ratio as the descriptive parameters. Equation 9 shows the corresponding regression equation obtained.

Table 4. R squared measures for linear models fitted over smaller selection of data points

		Reliability metric						
Work zone	**Linear Model Parameters**	**Mean TT**	**Median TT**	**Std. Dev. TT**	**95th %ile TT**	**Misery Index**	**Buffer Time Index**	**Planning Time Index**
AWZIR	VL, #TL	0.377	0.402	0.035	0.075	0.03	0.005	0.012
AWZIR	VL, OR	0.492	0.428	0.029	0.082	0.029	0.077	0.053
AWZIR	VL, #TL, OR	0.496	0.469	0.056	0.083	0.051	0.082	0.057

*Parameter key: V: total traffic volume, VL: traffic volume per open lane, OR: open ratio, L: LCSI, #TL: total number of lanes, P: peak (1) or non-peak (0) period

Table 5. Model fitting results for best fit model

Parameter	Coefficient	Std. Error	t Stat	P-value
Intercept	1.182	0.084	14.023	2.38E-13
Volume per open lane	7.37E-5	1.52E-5	4.8459	5.55E-5
No. of total lanes	0.0066	0.0145	0.4536	0.65402
Open Ratio	-0.31998	0.1315	-2.4332	0.02246

$$\mathrm{AWZIR}_{\mathrm{mean\ TT}} = 1.182 + 7.37 \times 10^{-5} \times VL + 0.00657 \times TL - 0.31998 \times OR \qquad \textbf{(9)}$$

where *VL* is the traffic volume per open lane at the work zone, *TL* is the total number of lanes at the location and *OR* is the open ratio.

While the tighter selection of data points improves the goodness of fit for modeling mean travel times, the R squared values are still low, and the model still performs poorly on other reliability metrics. The overall poor goodness of fit suggests strongly that work zone impacts on travel time reliability might be distinctly unique to work zones and depend on a multitude of peculiar factors that are not easily measurable. However, it is also entirely possible that a study with a larger scope would be able to find more definition in the data resulting in better fits.

Limitations

Through the course of the project, various limitations were identified that a researcher needs to look out for or can hinder development of a good predictive model if not addressed. Data availability, both in terms of quality and quantity of data available, is by far the biggest challenge. The following is a summary of limitations faced in the study:

- Intersection of reliable work zone, travel time and traffic volume data at locations of interest.
- Access to a larger and more diverse work zone data set with supporting traffic count data.
- Availability of consistent, detailed work zone characteristics such as type of work and barrier type for all work zones.
- Detailed knowledge of traffic conditions near work zone such as queue lengths.
- Spatial data density for NPMRDS data.
- Ability to spatially relate data acquired from multiple sources.
- Accurate weather, incident and specials events data.
- Proximity of work zone to significant features such as large interchanges that result in complex traffic dynamics and are hard to model.

Data Requirements

One objective for this project was to identify what type, quality, and quantity of data is required to successfully study work zones and model their impact on travel time reliability. This section tries to detail the data requirements for such a project, including some that were available for the study and some were partially or not available at all. These requirements are highlighted below as these can be quintessential knowledge to any future projects that explore similar objectives.

- A large work zone dataset that offers a diversity of unique work zones to be studied.

  Access to a large work zone dataset, preferably with a coverage of a diversity of work zones is important. The final selection of work zones that offer high quality data that can be used for modeling travel time reliability might involve filtering the work zone dataset available, making it important to start with a large set. Having diversity is similarly important to have significant representation of a variety of work zone features, such as a mix of single lane and large multilane highways, and single lane and multi-lane closures.

- Detailed knowledge of work zone properties.

  This study shows that using only the lane-configuration and traffic demand is not enough to model work zone travel time reliability. Access to detailed work zone properties information such as type of work being performed, type of barriers used, lateral distance from barrier, posted work zone speed limit and distance to upstream advance work zone warning would be vital to a good modeling effort. For Wisconsin, this data was available in part through the Wisconsin Transportation Management Plans (WisTMP) system, but was not available for all work zones considered. HCM work zone capacity and free-flow speed models also use the above parameters further strengthening the need to have access to these.

In addition, roadway geometry detail for the location of the work zone should also be acquired, including lane-widths, ramp and intersection densities three miles upstream and downstream of the work zone, type of terrain and whether the work zone is in an urban or rural area. Knowledge of precise location of the bottleneck within the work zone, and how this might change over the lifespan of the work zone can be useful for long work zones. This is discussed again towards the end of the current section.

- Supporting hourly traffic count data with dense coverage to allow a large intersect with work zone locations.

  Travel times at a location change drastically during the day from off-peak to peak periods as congestion builds and dissipates. Studying travel time distributions and travel time reliability metrics, thus, is most relevant when not aggregated across entire days. Travel time reliability should then, be studied for shorter periods, such as for a.m. peak, p.m. peak, mid-day, and night-time periods independently. Predictive modeling for reliability thus in turn can't rely on aggregate AADT volumes and require access to hourly traffic counts instead.

  During the study, access to locations with hourly traffic counts was perhaps the most limiting restriction in the choice of work zones modeled. Denser coverage of hourly counts would be greatly beneficial to work zone reliability studies.

  Access to traffic counts on nearby ramps and interchanges is also highly desirable as this can expand on the work zone selection process allowing for more complex geometrical layouts with presence of multiple on and off-ramps to be selected. When ramp counts are available, mainline work zone demand can be better estimated and verified.

- Dense travel time data.

  Access to dense travel time data is similarly important. NPMRDS dataset has a very good coverage of highways across the country. Travel times are not available at all locations for all years though, so it is wise to check for availability of data for the time-period being studied. Further, a high temporal density, or a larger representative coverage of probe vehicle data (so that there are multiple recorded travel times even when traffic counts are low) would greatly benefit the accuracy and thus the usability of travel time data.

- Accurate weather conditions, incident, and special events data.

  Access to accurate weather conditions, incident and special event data can be greatly useful to filter non-recurring conditions within the work zone study period and can improve the accuracy of any predictive model developed. Such data are not always available at high accuracy and the researchers should be aware of the limitations in the data available to them.

- GIS integration for reliable and scalable spatial correlation between all data sources.

Since various sources need to be tapped to collect the multitude of data available for the study, good GIS integration of the datasets could greatly benefit in finding correlations. This becomes especially beneficial when the scale of the project is increased to cover a large set of work zones.

- Traffic behavior data near the work zone.

  Access to traffic behavior data near the work zone is greatly desired for the study even if not initially obvious. Availability of loop-detector data recording speeds and densities at regular distances through the stretch of roadway studied offers multiple potential benefits including an ability to verify traffic count data, adjust for ramp volumes, and accurately estimate the extent of congestion propagation. Knowledge of the length of congested traffic created is important in choosing the section size for the study of travel times. This aspect is further detailed below.

Bottleneck Location and Extend of Queue

As mentioned earlier, the precise location of the bottleneck within a work zone as well as the length of queue created due to the bottleneck are both of relevance to studying impact of work zone on travel time accurately. Figure 24 illustrates scenarios where the bottleneck location varies within work zone, and where the queue created is either contained within, or spills beyond the upstream end of the section analyzed for travel time. A bottleneck created closer to the downstream end (schematic on the left in figure) of the analyzed segment would have a stronger influence on the segment travel time with the congestion potentially impacting the entire study section, while a bottleneck closer to the upstream end (middle schematic in figure) might lead to measurement being dominated by the large fraction of unimpacted free-flow travel times. Similarly, in situations where the study section does not stretch far enough upstream to capture the entire queue created (left two schematics) would underestimate the impact of the work zone on travel times compared to a situation where the entire queue created is contained within the study segment (schematic on the right).

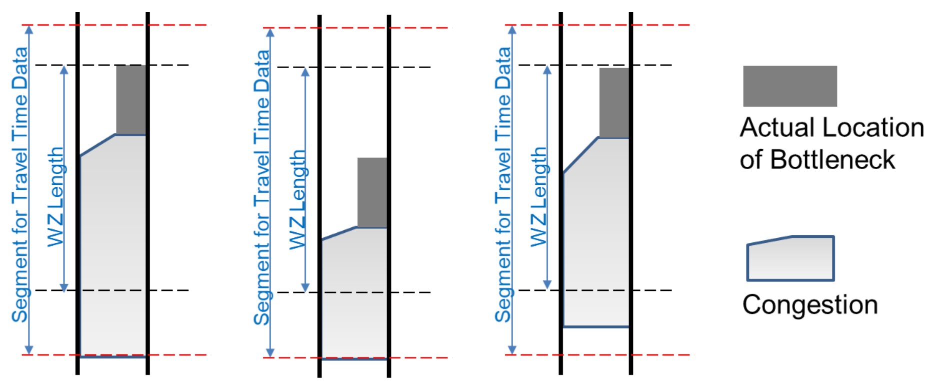


Figure 24. Schematic showing impact of precise location of bottleneck and extent of queues created on delay captured

CONCLUSIONS

This research attempted to establish a framework for predicting the impact of work zones on travel time reliability. In this study, travel time data from work zones across the state of Wisconsin, where the team had access to archival work zone and hourly traffic count data in addition to travel time data, was analyzed.

Through the project, 19 work zone sites in the state of Wisconsin were explored. Each site was studied individually first, before aggregating data across locations to try to derive an empirical model for predicting travel time reliability for work zones.

A key observation of interest was that the impact of the work zone on the travel time reliability measures stayed within a 10% range compared to the baseline scenario where the work zone is not active in a majority of the locations explored, with higher variations typically seen on roadways with higher traffic volumes. This suggests that work zones do not significantly impact the travel time reliability on smaller highways that see lighter overall congestion patterns.

Another finding of interest was that the travel times at multiple locations were seen to in fact improve while the work zone was active when compared to the baseline scenario. In other words, the presence of the work zone had a beneficial impact on the travel times (reducing them) at the location instead of having a detrimental effect (increasing them). Some possible explanations include variations in demand, using a short segment that does not extend enough to cover the entire queue buildup and thus the entirety of delays induced, or activation of nearby upstream or downstream bottlenecks influencing traffic behavior. Investigating traffic counts revealed that demand did not change in one such location explored and extending the travel time study section further upstream also did not change the observed behavior. The true cause could not be isolated and identified in the study due to lack of supporting information on traffic behavior at the location and is left for future studies to investigate.

Further, the study found a loose dependence between traffic volume and the impact of work zone on travel time, with higher traffic volumes usually corresponding to stronger impact of the work zone. This is most visibly noticed with respect to the mean travel time where larger deviations from the baseline mean travel time correspond to larger traffic volume on the site. However, the deviation in travel time is observed to be in either direction, an increase as well as a decrease compared to the baseline scenario. An alternate interpretation of this would be that the range of spread of work zone TT impact ratios observed, increase with traffic volumes so that locations with low volumes have a tighter range of possible deviation from baseline scenario.

Perhaps most importantly, after trying multiple regression modeling structures, and investigating the relationship between multiple candidate factors and the impact of work zones on travel time reliability, there was no clear predictive model that performed well and offered a strong goodness of fit. This strongly suggests a notion that traffic volumes and lane configurations offer only a partial understanding of the impacts of the work zone on travel times. A good predictive modeling effort would require detailed data on an exhaustive list of work zone features to model a larger number of explanatory variables such as barrier type, nature of work, etc. This would in turn require access to a larger sample of work zone data.

The study was further able to identify various limitations that should be addressed to develop a good predictive model for impact of work zones on travel time reliability. Data availability, both in terms of quality and quantity of data available is the biggest hurdle. The findings from this work indicate that a larger set of work zones are needed to be able to derive statistically significant models. Further, knowledge of various work zone details such as barrier types, exact nature of work, posted speed limits, lateral distance to the obstacle, etc. is very important, as is detailed knowledge of the location of the bottleneck and how it potentially moves over the course of the work zone for longer work zones. As is expected, better availability of hourly traffic counts with larger and denser spatial coverage would be helpful in expanding the number of work zones that can be studied. Availability of traffic data, such as through static loop detectors at regular frequencies along and upstream of the work zone can be vital in estimating how far queues propagate and thus, inform the selection of length of section to be studied. Accurate weather, incident, and special event data can also be critical and identifying non-recurring behavior that can be filtered out.

Knowledge of and preparing for the above limitations can be greatly beneficial to a researcher pursuing the study of the impact of work zones on travel time. This knowledge can also be used to guide data collection efforts in the future so that all the limitations are addressed.

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APPENDIX A: ALL TRAVEL TIME DISTRIBUTION PLOTS

<table>
<tr><td></td><td>Work zone 1.1
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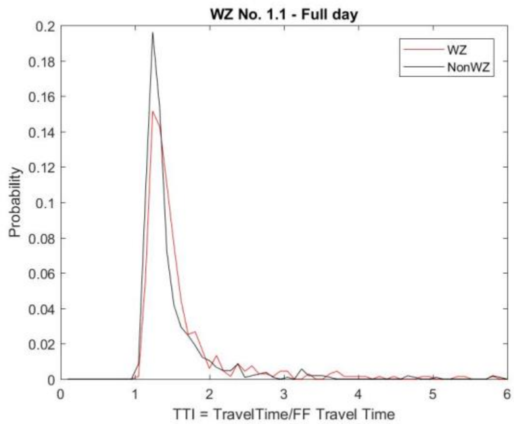
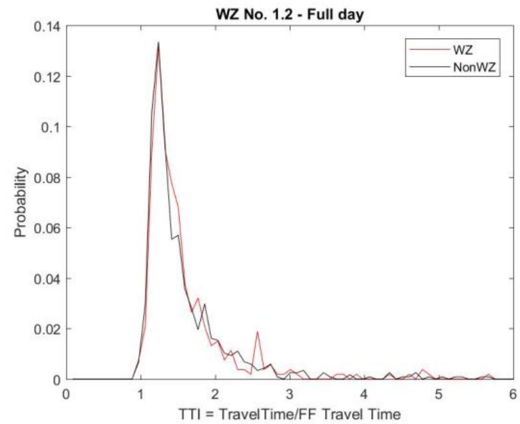
Two- to one-lane reduction, US 12 SB, Dane County</td></tr>
<tr><td>Full Day</td><td>
</td><td>
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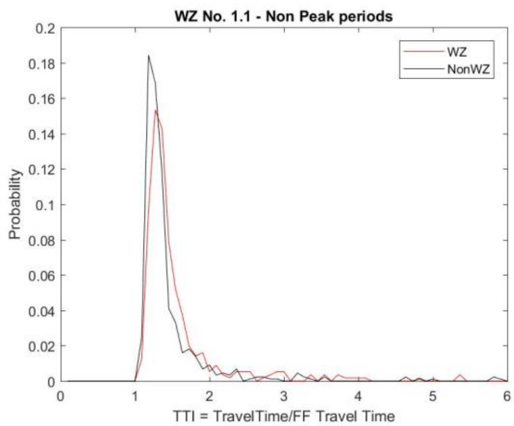
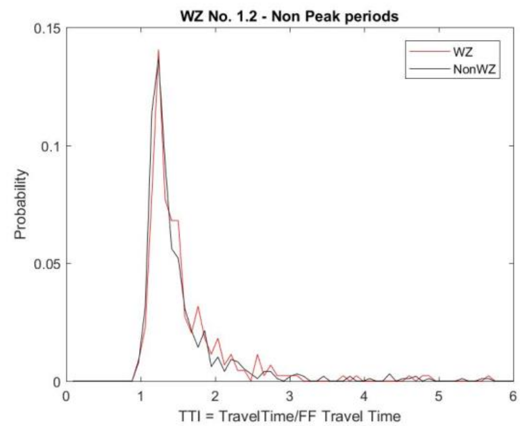
<tr><td>Off-peak Periods</td><td>
</td><td>
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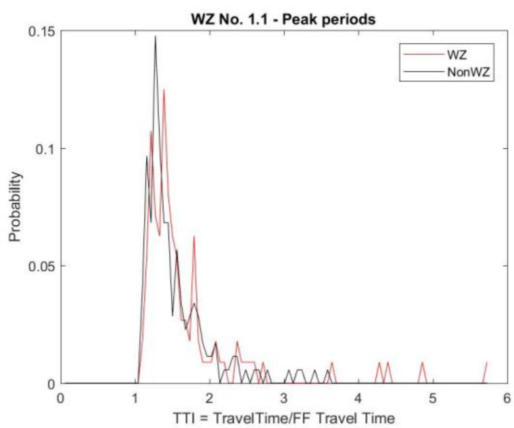
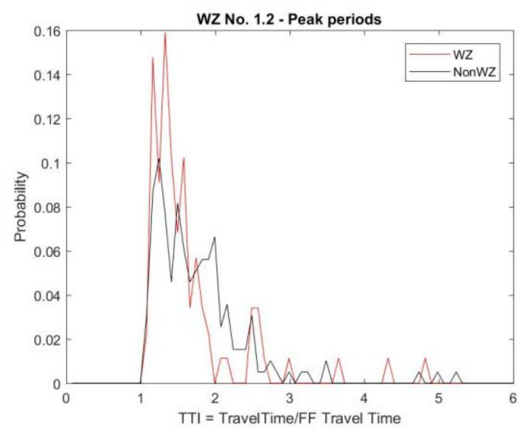
<tr><td>Peak Periods</td><td>
</td><td>
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Figure A.1. Travel time data for work zones 1.1 and 1.2

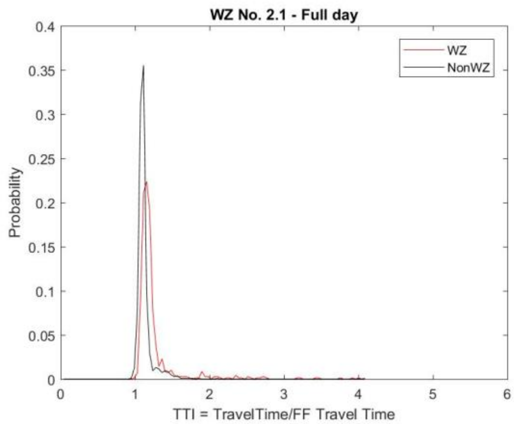
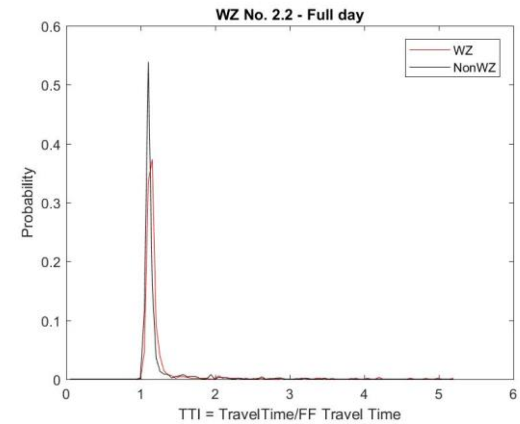
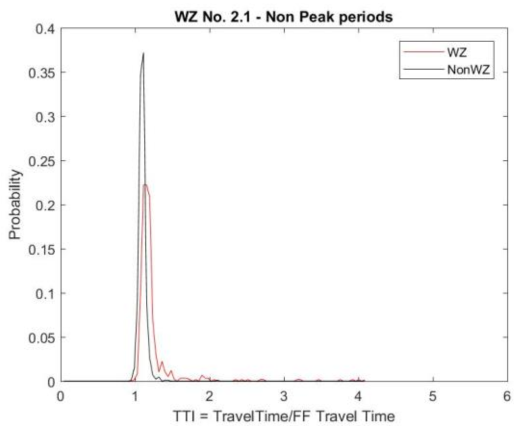
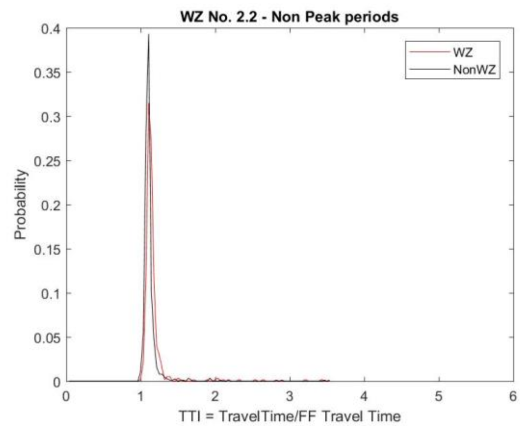
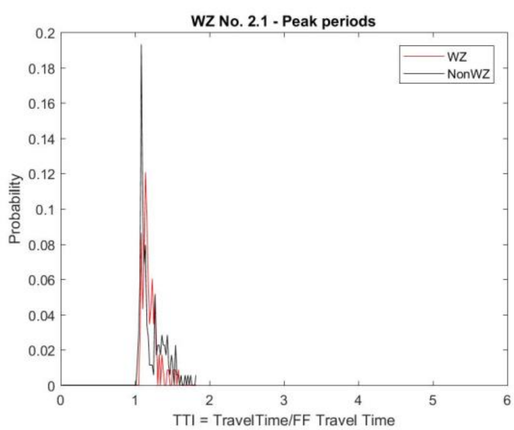
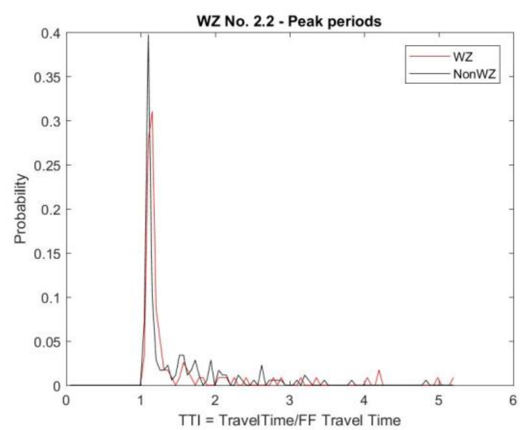
	Work zone 2.1 Shoulder closure, three lane US 12 NB, Dane County	Work zone 2.2 Shoulder closure, three lane US 12 SB, Dane County
Full Day		
Off-peak Periods		
Peak Periods		

Figure A.2. Travel time data for work zones 2.1 and 2.2

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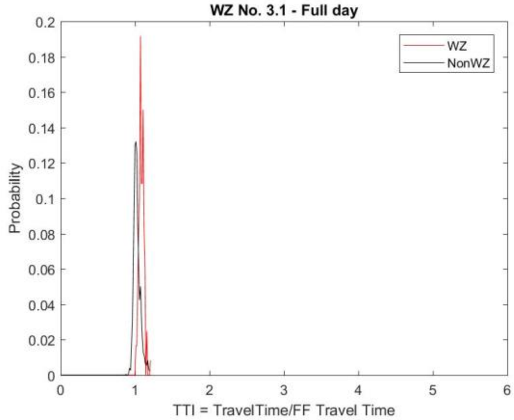
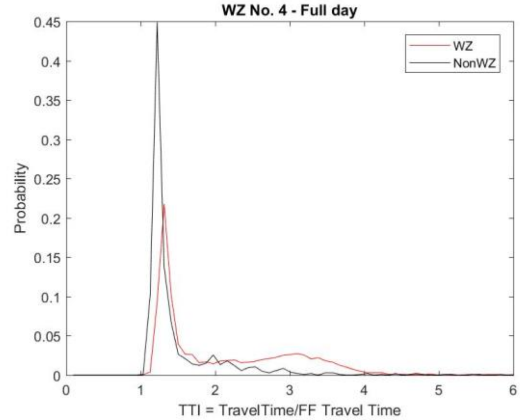
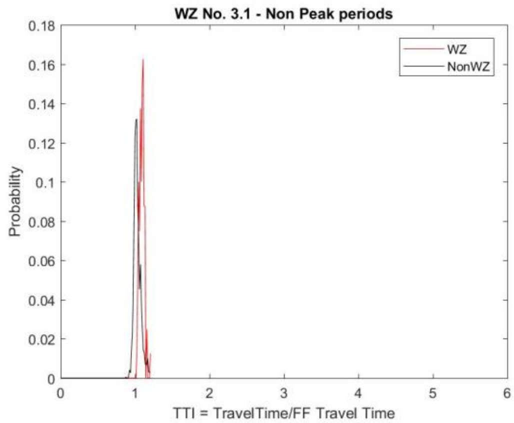
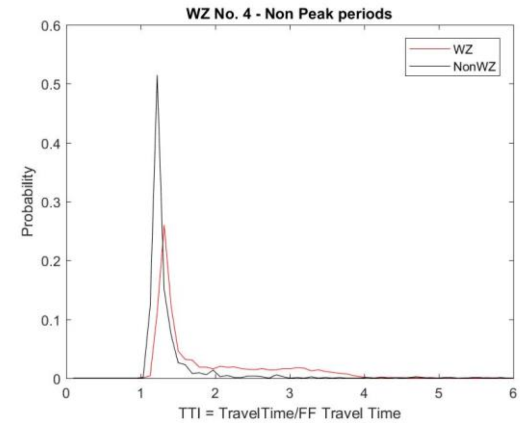
<tr><th></th><th>Work zone 3.1
Shoulder closure, two lane I 41 NB,
Fond Du Lac County</th><th>Work zone 4
Three- to two-lane reduction, I-94 EB,
Waukesha County</th></tr>
<tr><td>Full Day</td><td>
</td><td>
</td></tr>
<tr><td>Off-peak Periods</td><td>
</td><td>
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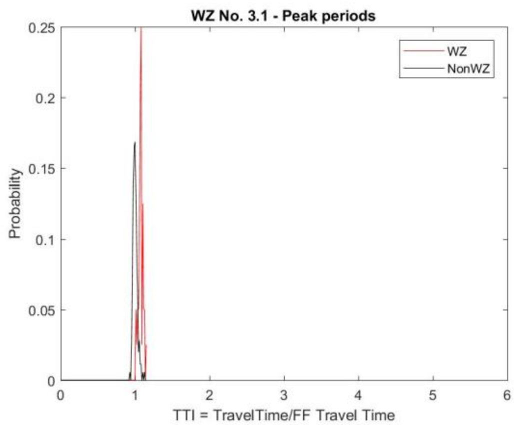
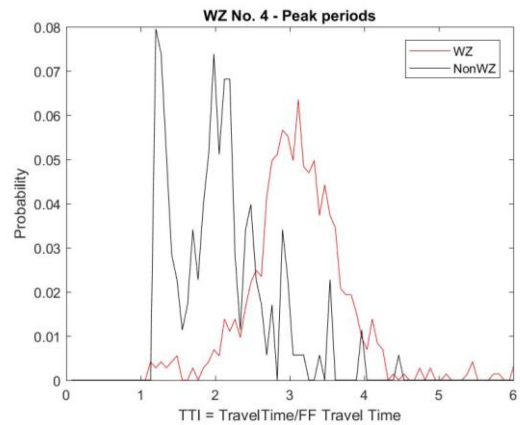
<tr><td>Peak Periods</td><td>
</td><td>
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Figure A.3. Travel time data for work zones 3.1 and 4

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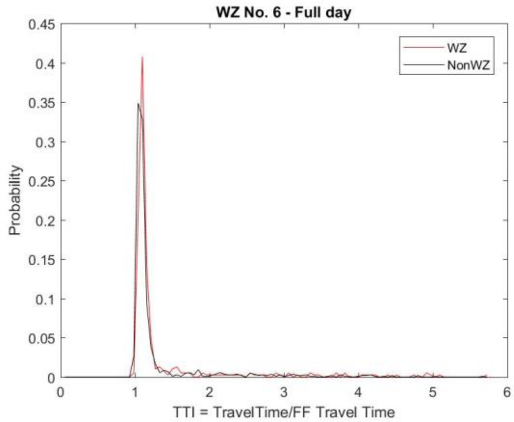
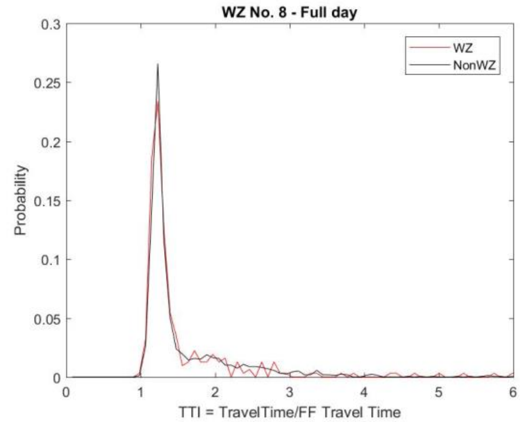
Three- to two-lane reduction, I-94 WB, Milwaukee County</th></tr>
<tr><td>Full Day</td><td>
</td><td>
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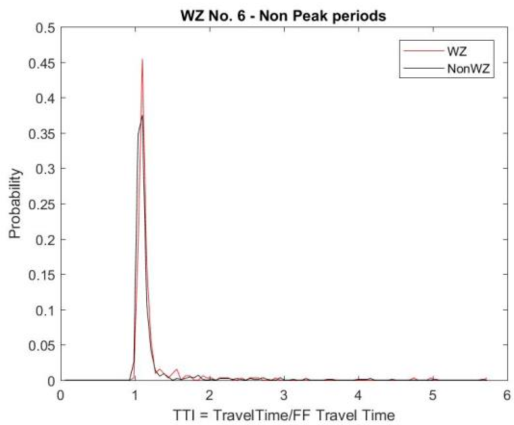
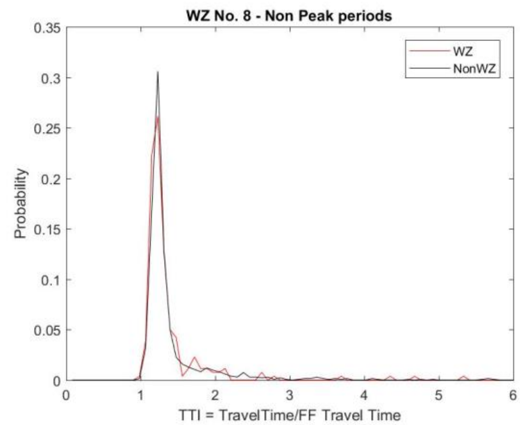
<tr><td>Off-peak Periods</td><td>
</td><td>
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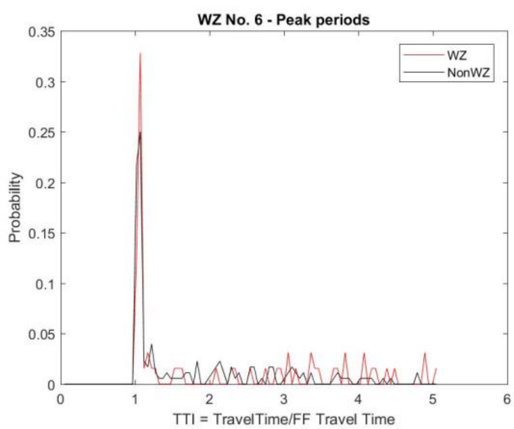
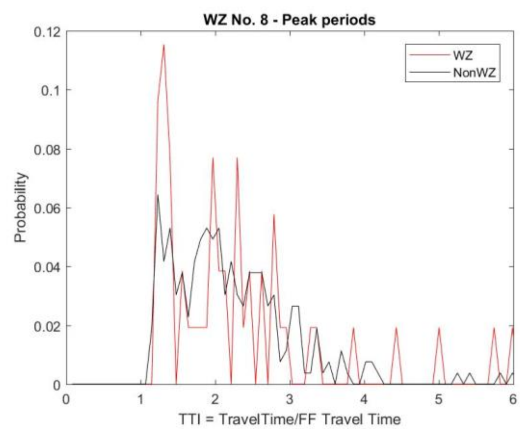
<tr><td>Peak Periods</td><td>
</td><td>
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Figure A.4. Travel time data for work zones 6 and 8

<table>
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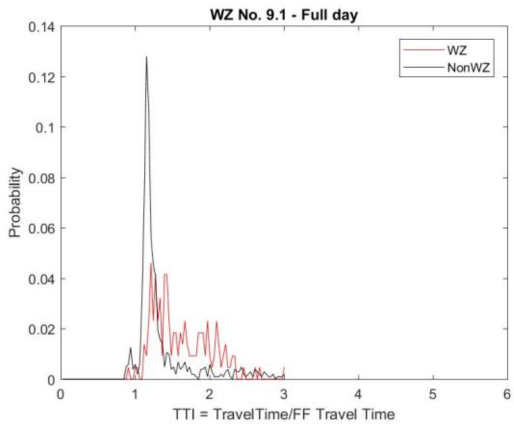
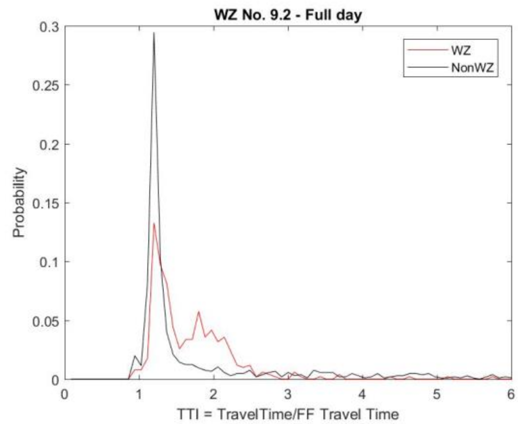
Four- to two-lane reduction, I-94 WB,
Milwaukee County</td><td>Work zone 9.2
Four- to three-lane reduction, I-94 WB,
Milwaukee County</td></tr>
<tr><td>Full Day</td><td>
</td><td>
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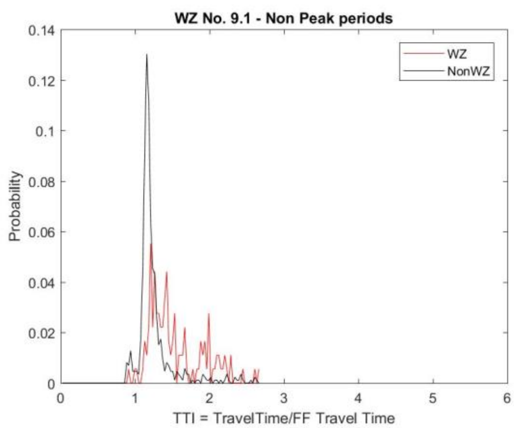
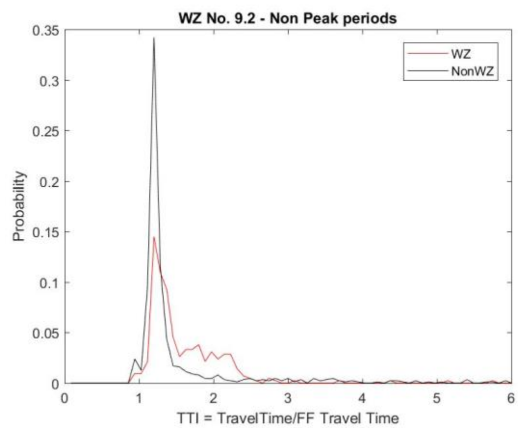
<tr><td>Off-peak Periods</td><td>
</td><td>
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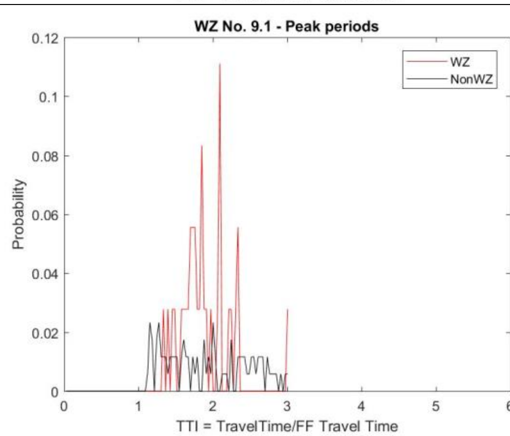
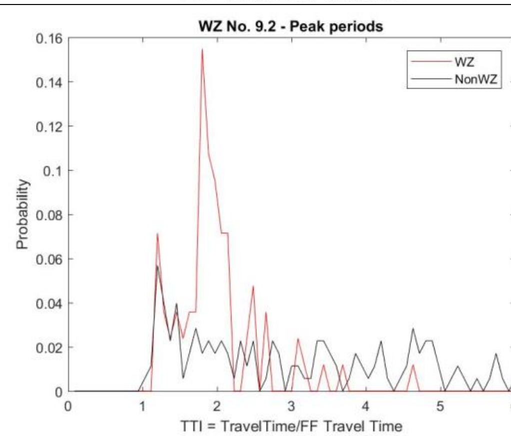
<tr><td>Peak Periods</td><td>
</td><td>
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Figure A.5. Travel time data for work zones 9.1 and 9.2

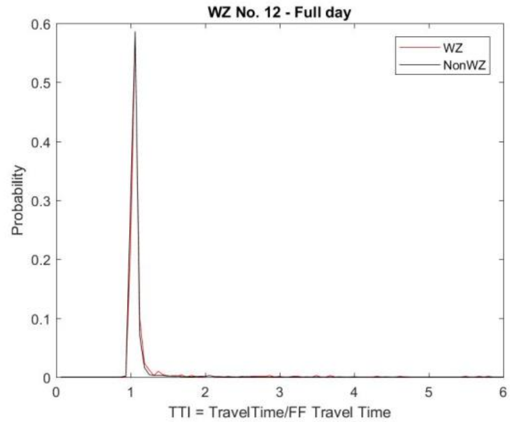
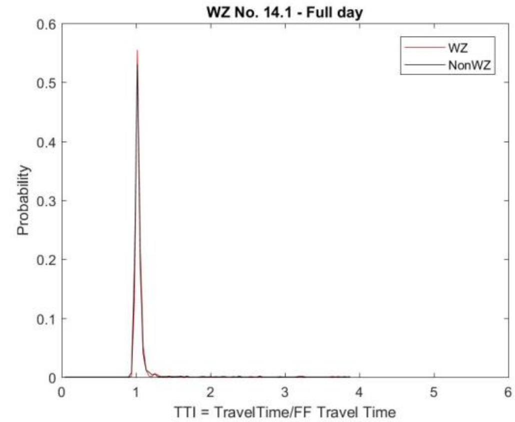
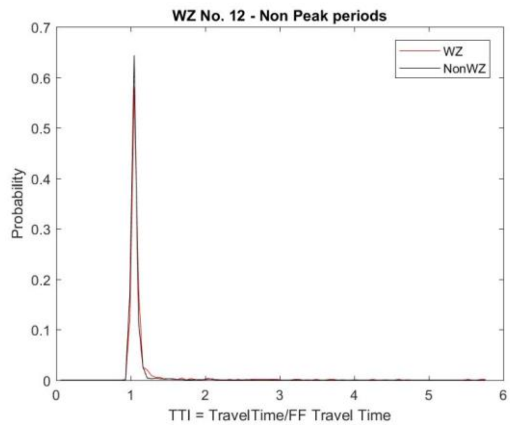
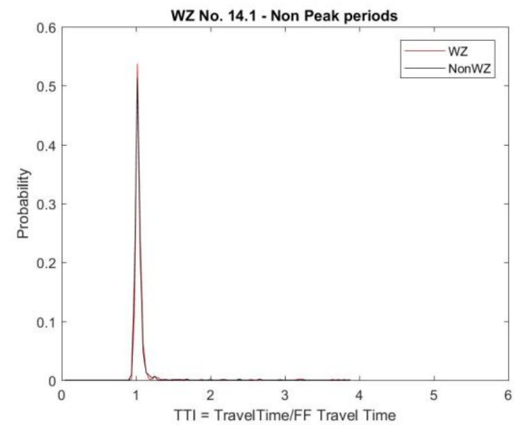
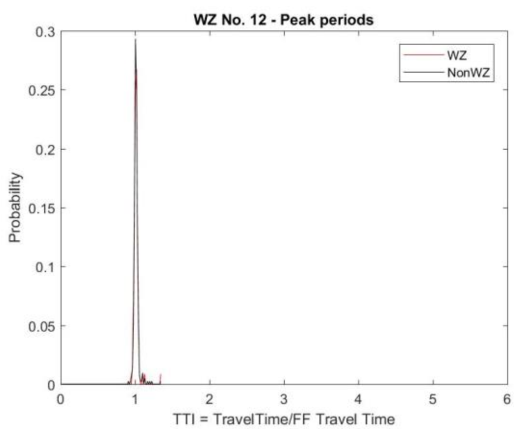
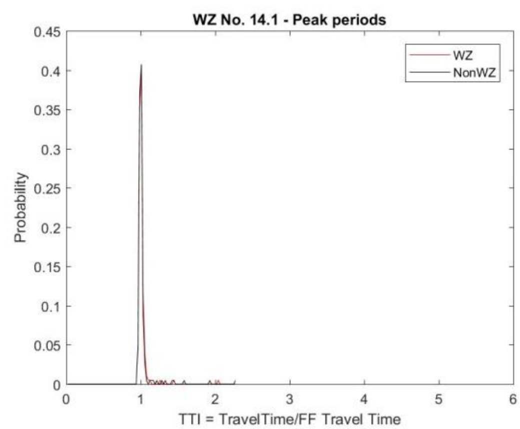
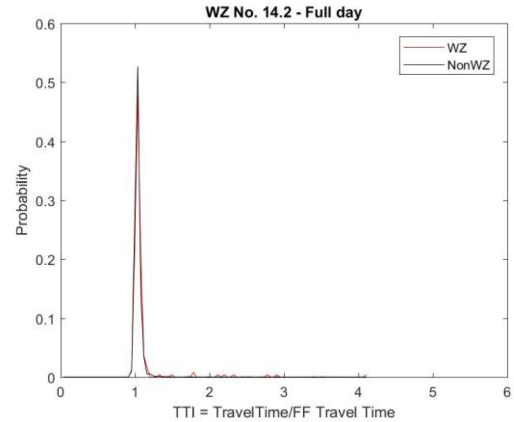
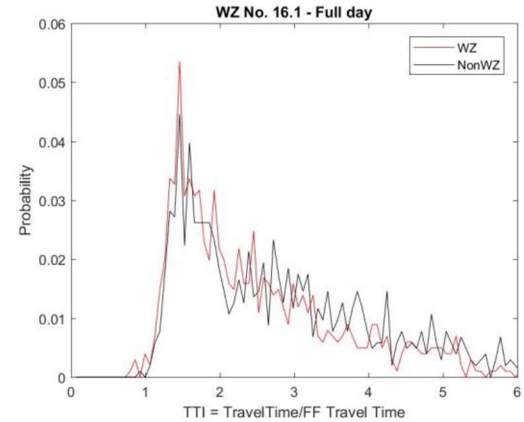
	Work zone 12 Three- to two-lane reduction, I-39 NB, Dane County	Work zone 14.1 Three- to two-lane reduction, I-39 NB, Dane County
Full Day		
Off-peak Periods		
Peak Periods		

Figure A.6. Travel time data for work zones 12 and 14.1

<table>
<tr><td></td><td>Work zone 14.2
Three- to two-lane reduction, I-39 NB,
Dane County</td><td>Work zone 16.1
Two- to one-lane reduction, US 151 NB,
Dane County</td></tr>
<tr><td>Full Day</td><td>
</td><td>
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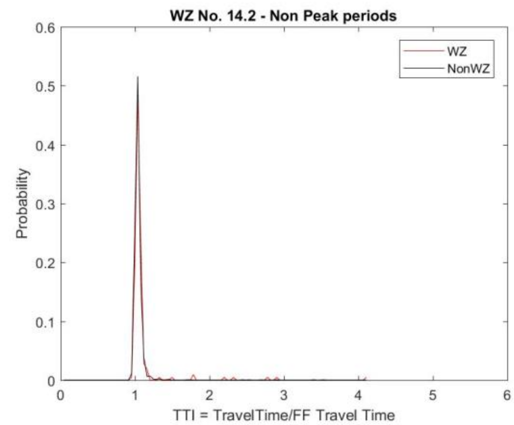
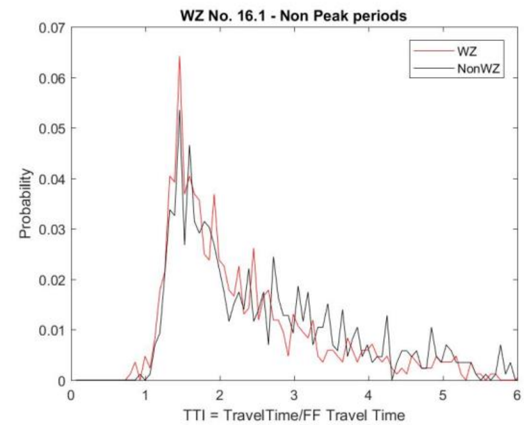
<tr><td>Off-peak Periods</td><td>
</td><td>
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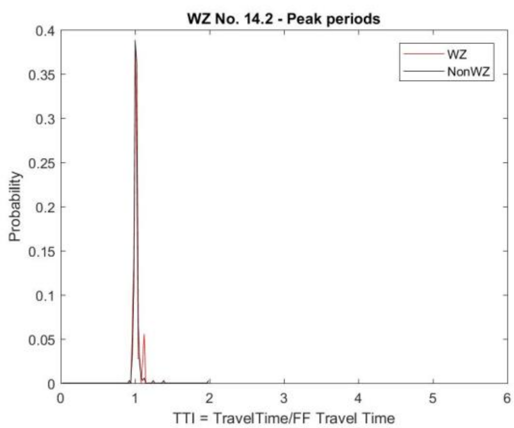
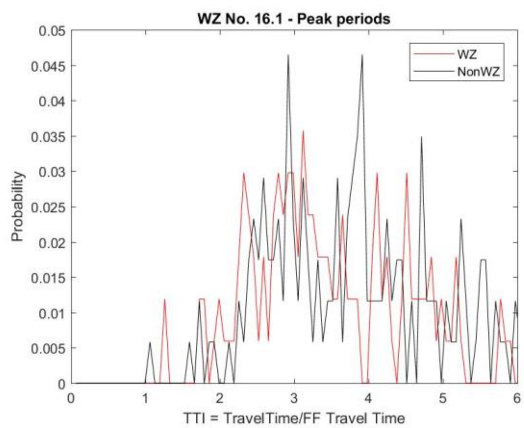
<tr><td>Peak Periods</td><td>
</td><td>
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Figure A.7. Travel time data for work zones 14.2 and 16.1

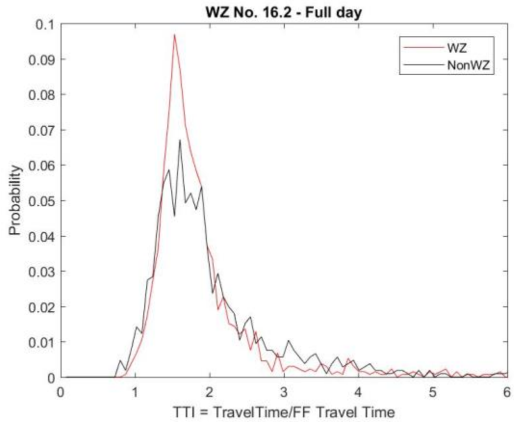
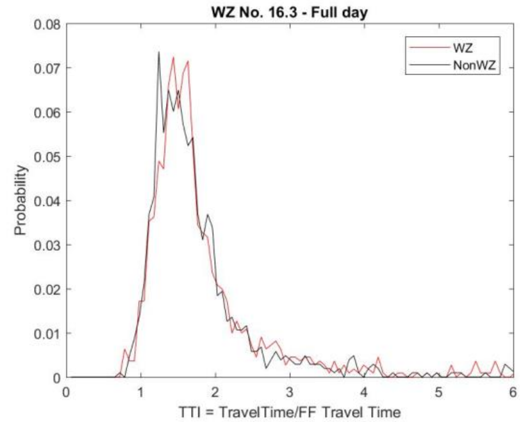
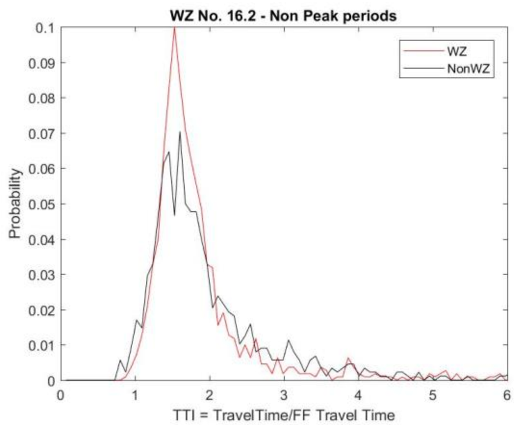
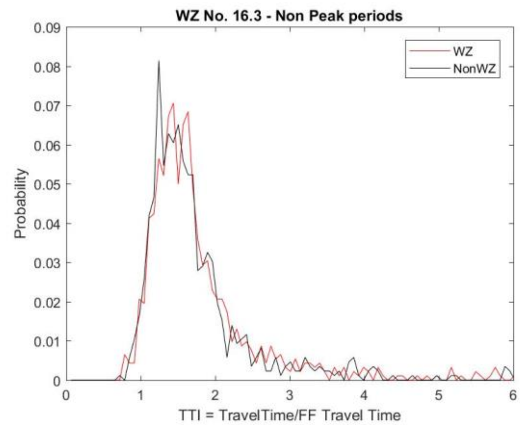
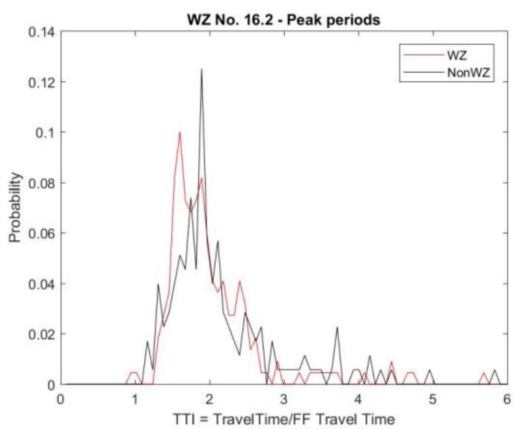
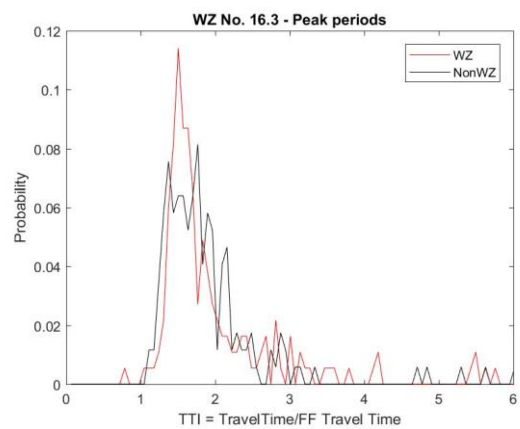
	Work zone 16.2 Two- to one-lane reduction, US 151 SB, Dane County	Work zone 16.3 Two- to one-lane reduction, US 151 NB, Dane County
Full Day		
Off-peak Periods		
Peak Periods		

Figure A.8. Travel time data for work zones 16.2 and 16.3

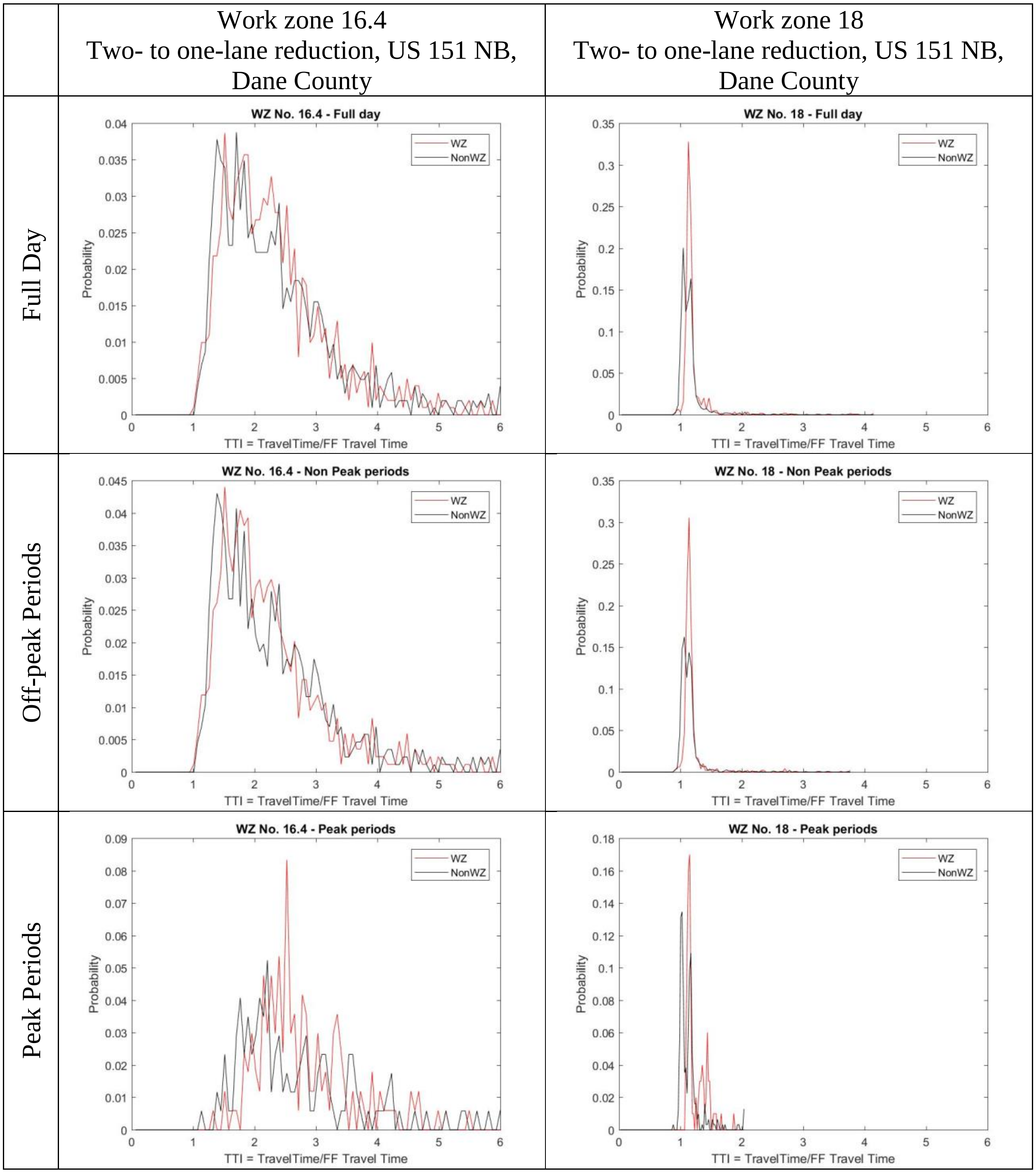


Figure A.9. Travel time data for work zones 16.4 and 18

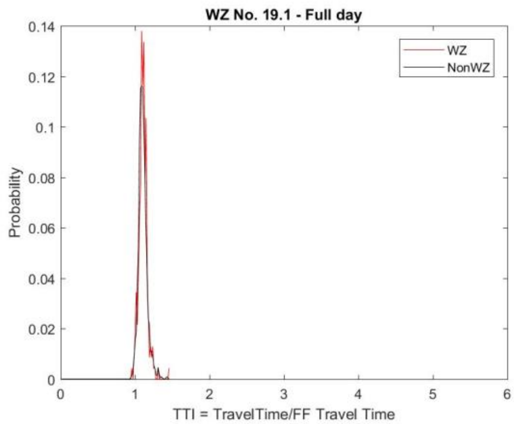
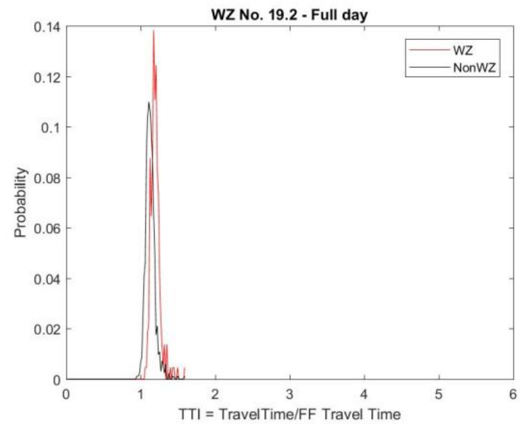
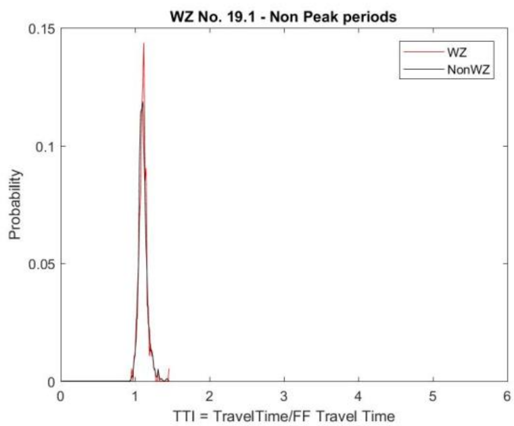
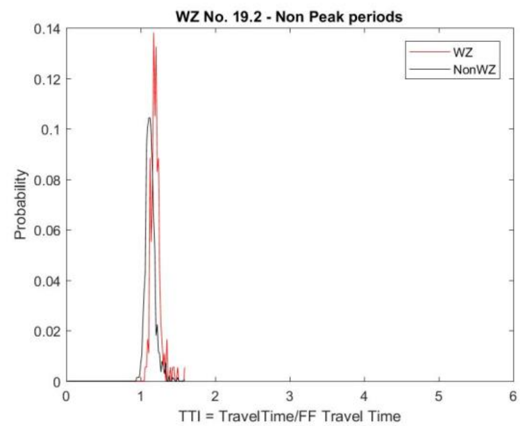
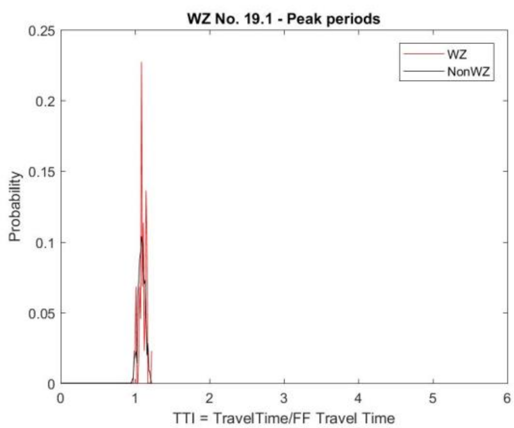
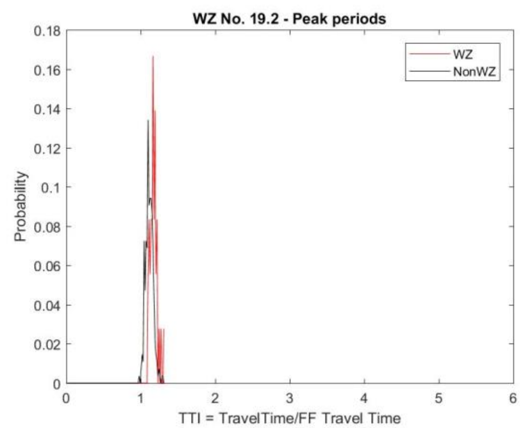
	Work zone 19.1 Two- to one-lane reduction, I-43 NB, Ozaukee County	Work zone 19.2 Two- to one-lane reduction, I-43 NB, Ozaukee County
Full Day		
Off-peak Periods		
Peak Periods		

Figure A.10. Travel time data for work zones 19.1 and 19.2

APPENDIX B: TRAVEL TIME RELIABILITY METRIC WZIR AND WORK ZONE FEATURES

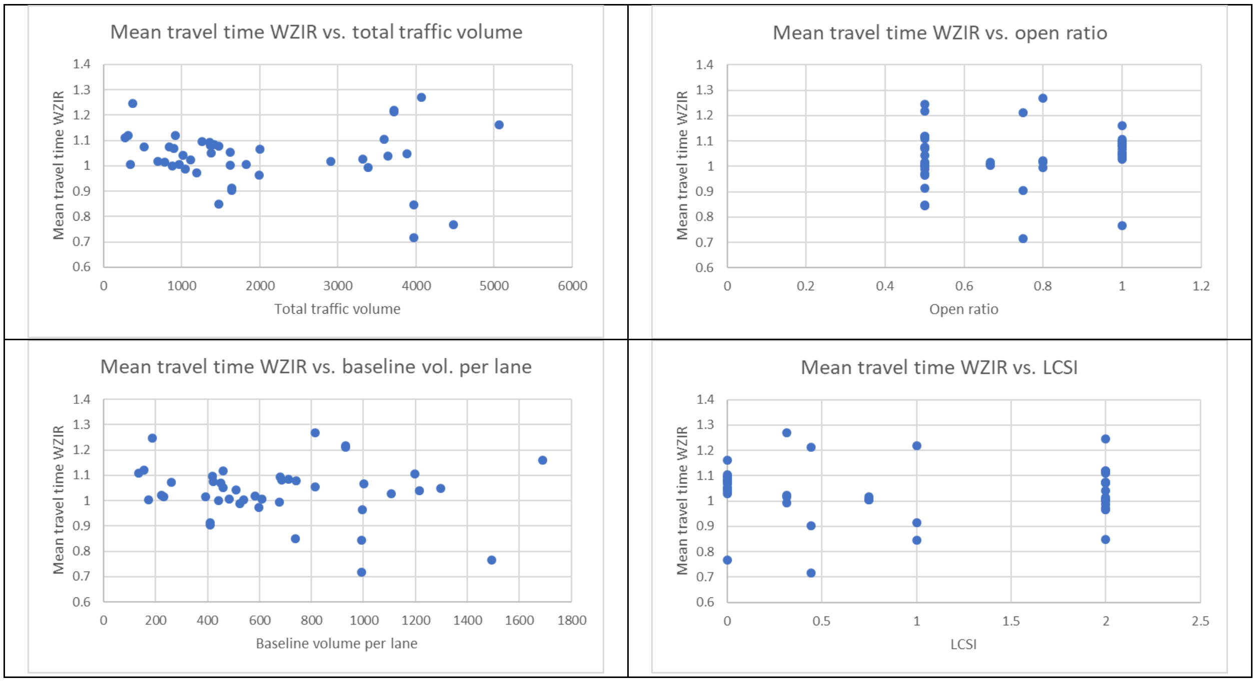


Figure B.1. Mean travel time WZIR

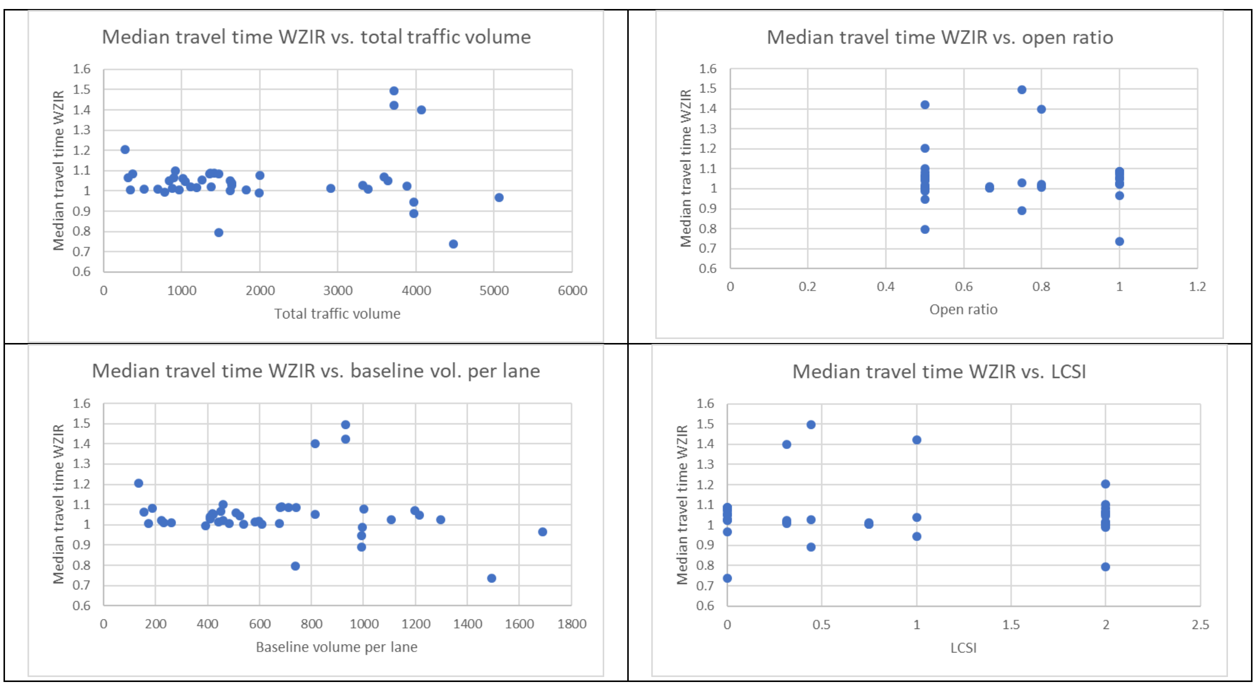


Figure B.2. Median travel time WZIR

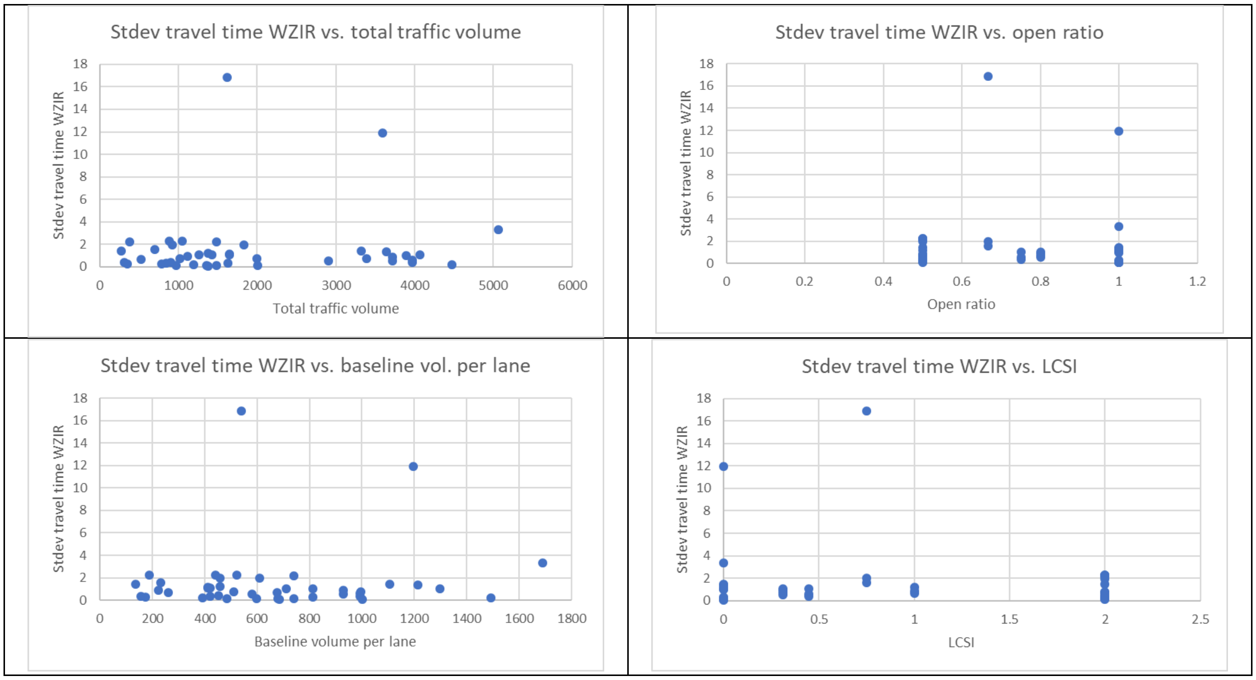


Figure B.3. Standard deviation of travel time WZIR

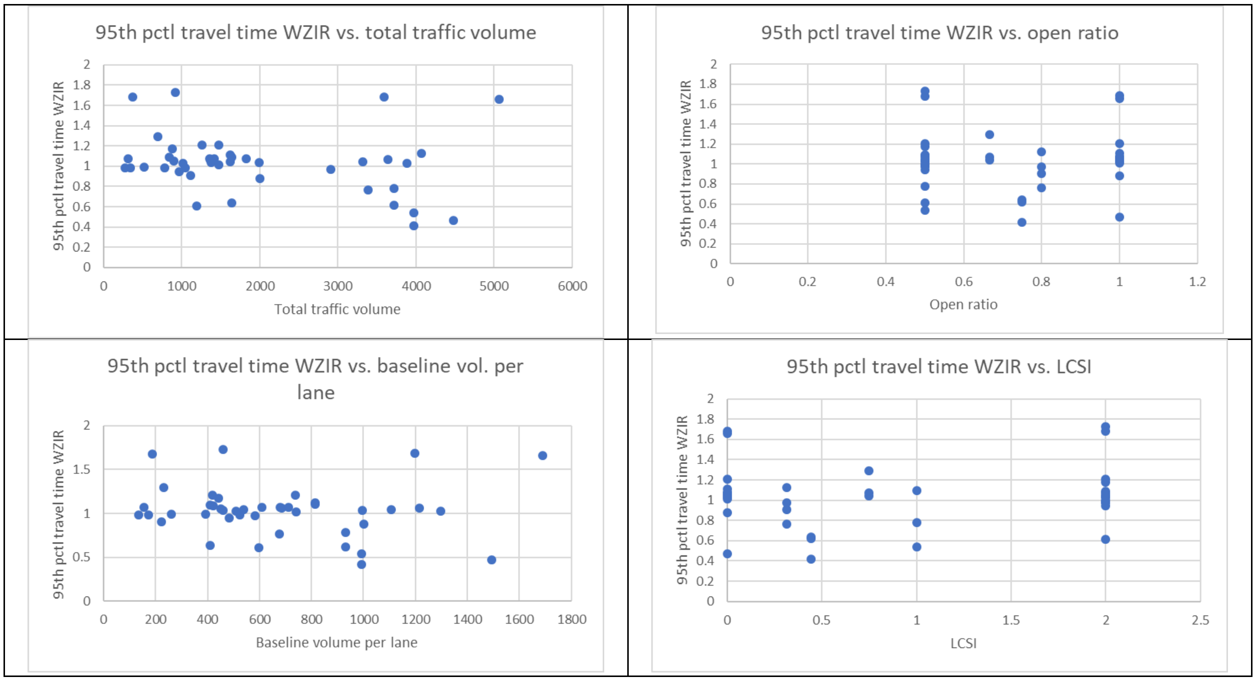


Figure B.4. 95th percentile travel time WZIR

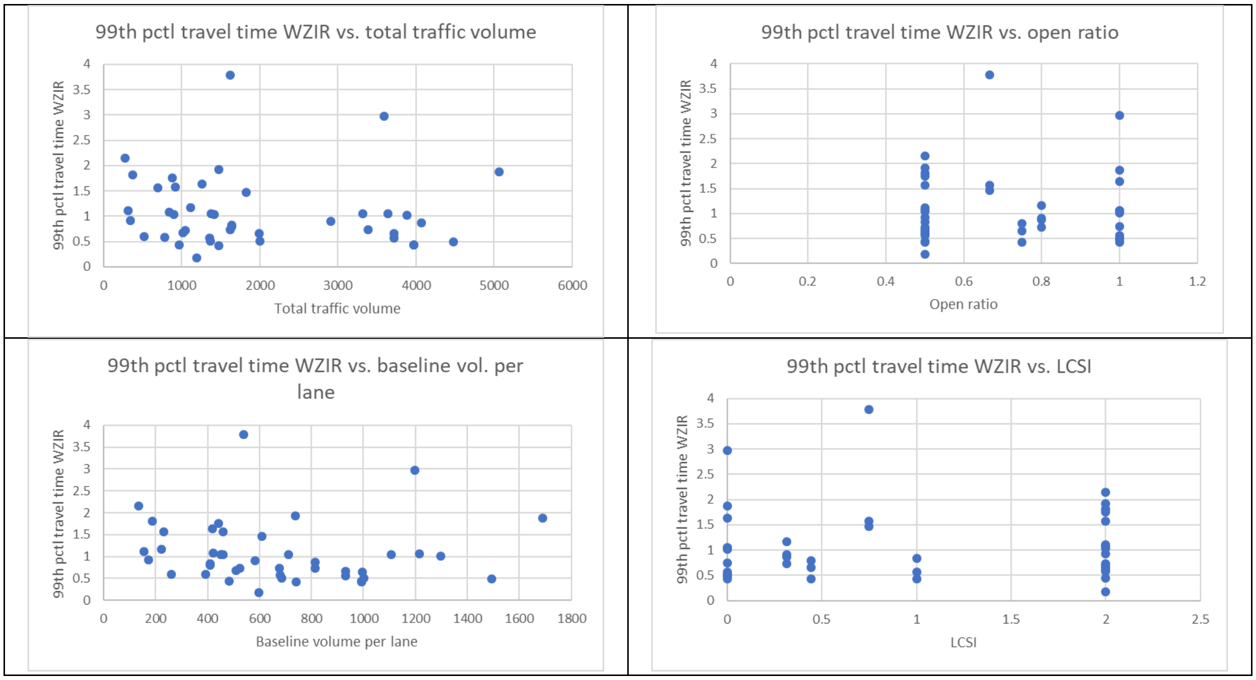


Figure B.5. 99th percentile travel time WZIR

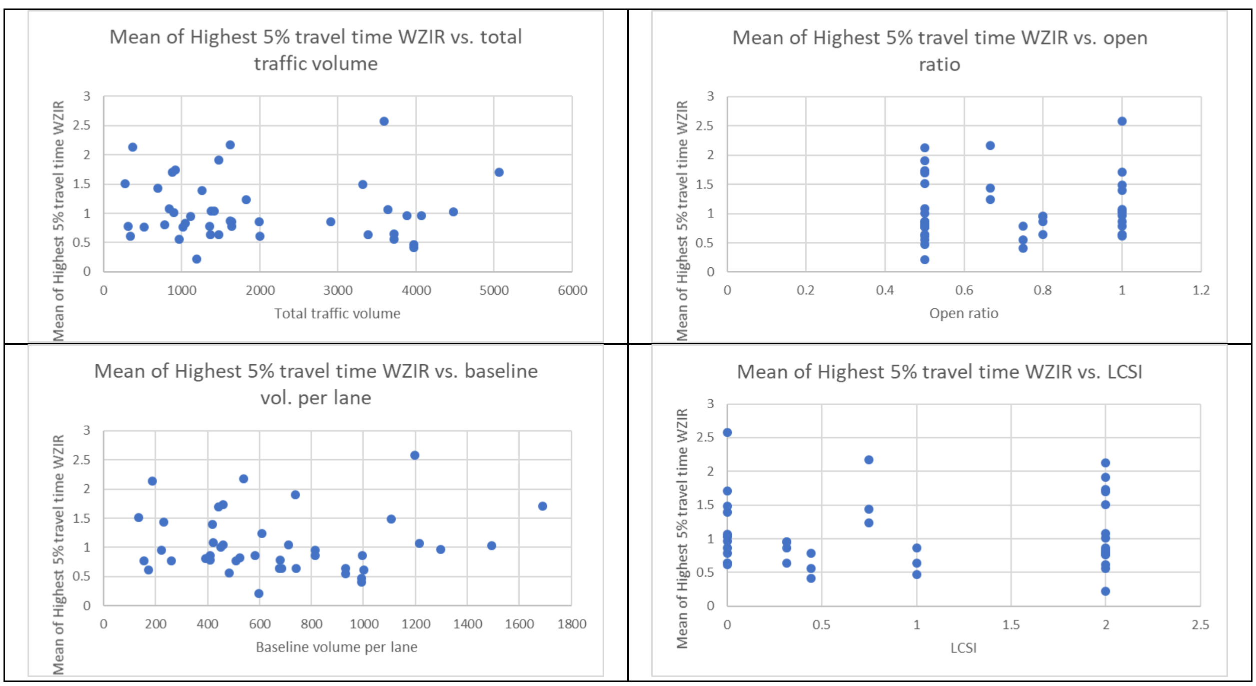


Figure B.6. Mean of highest 5% travel times WZIR

Figure B.7. Misery index WZIR

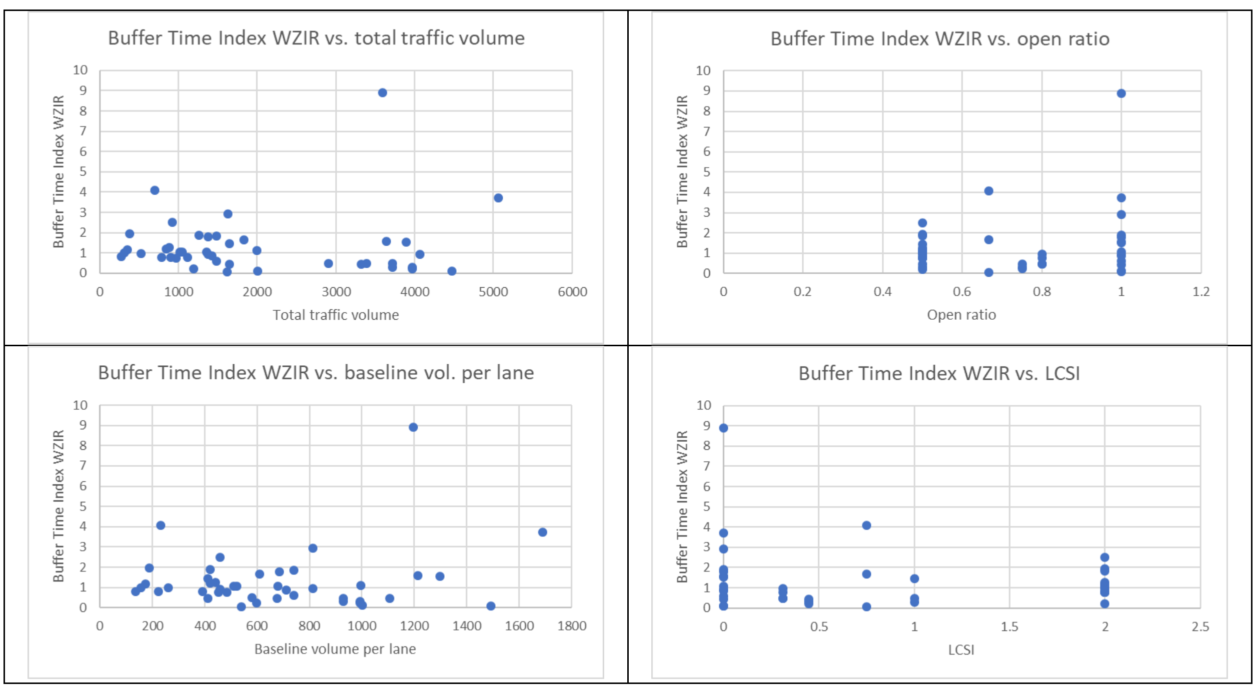


Figure B.8. Buffer time index WZIR

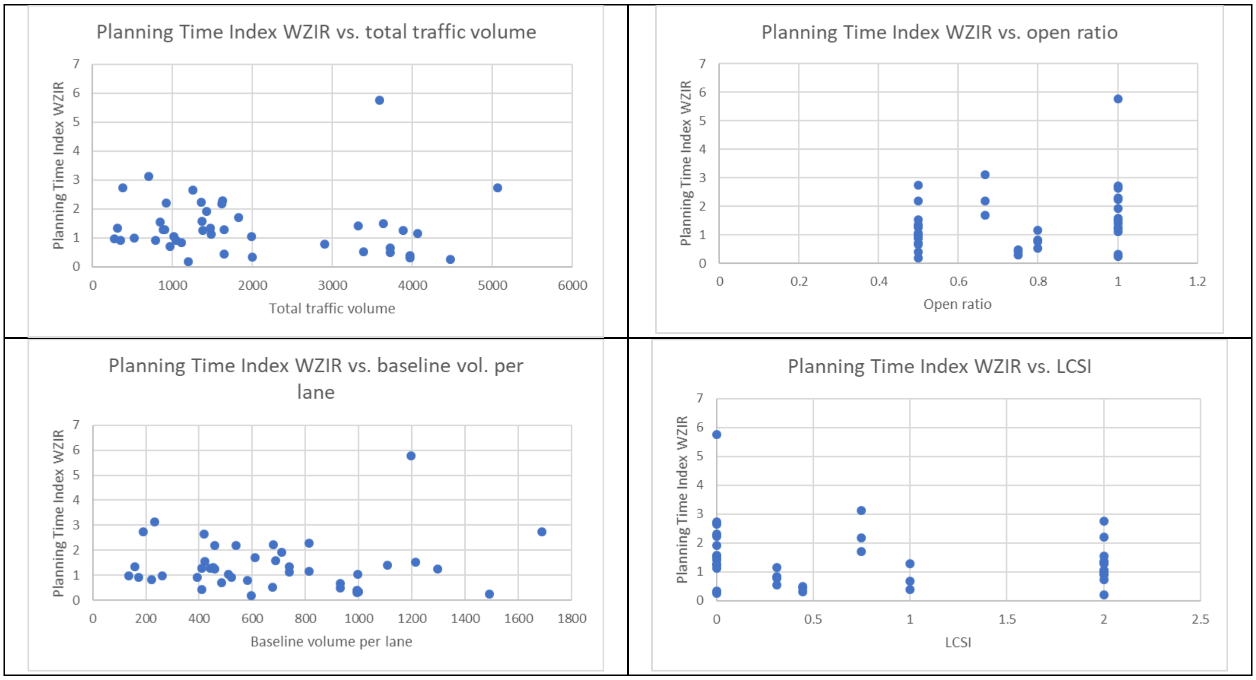


Figure B.9. Planning time index WZIR