Setting Work Zone Speed Limits

Final Report
January 2017

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SWZDI
Smart Work Zone Deployment Initiative

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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

Increasing travel demands and an aging highway infrastructure drive the need for extensive construction, maintenance, and utility work zones. The introduction of work zone environments creates risks for both drivers and construction workers due to changes from the normal driving environment. Temporary speed limit reductions are a common countermeasure aimed at improving work zone safety. In theory, reduced speed limits may serve at least three important functions: reduce variability in travel speeds and the potential for work zone crashes, reduce average travel speeds and the severity of crashes when they do occur, and enhance worker safety. Thus, understanding how reducing work zone speed limits impacts travel speeds is an important task.

This project evaluates the impacts of speed limit reductions on drivers' speed selection at both aggregate and disaggregate levels. Data were collected from nine construction work zones in Iowa during 2014 and 2015. The lack of availability of data pertaining to the location, time, and type of activity significantly constrained the level of analysis that could be conducted for this research. Therefore, the crash analysis was not deemed reliable due to the inconsistency among the multiple data sets that were used to determine the location, time, and type of work zone activity. For the speed analysis, a quantile regression model was employed to examine the impacts of speed limit reductions on speed distribution quantiles before and during construction activities. The results show that speeds are consistently reduced when work zone speed limits are in place.

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SETTING WORK ZONE SPEED LIMITS

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

EXECUTIVE SUMMARY

Temporary speed limit reductions are a common countermeasure aimed at improving work zone safety, particularly when the work is occurring on or near the roadway. In theory, reduced speed limits may serve at least three important functions: reduce variability in travel speeds and the potential for work zone crashes, reduce average travel speeds and the severity of crashes when they do occur, and enhance worker safety.

This project involved the investigation of driver speed selection in work zones throughout the state of Iowa. The sites for analysis were chosen based on input provided by the technical advisory committee (TAC). Although the approximate location of each work zone was known, there was no single reliable source to precisely determine the location, time, and type of work zone activity. Four different databases were mined to estimate the specific physical limits of the work zones as well as the time during which each work zone was in place. The four datasets included the following:

- Construction contract documents
- Iowa 511 archive database
- Advanced Traffic Management System (ATMS) database
- Iowa Department of Transportation (DOT) crash database

As noted above, there were significant inconsistencies among these databases in regard to the work zone activities and locations. The work zone daily work reports (DWRs) were not available. In the absence of the DWRs, to obtain reliable work zone activity and location information, the researchers utilized the subset of data for which the available data sources (i.e., contract documents, 511, ATMS, and crash information) were consistent in terms of reporting whether work activity was ongoing at a specific time and location. Data for which one of the data sources indicated that a work zone was present but another source could not corroborate this information were discarded from the subsequent analyses. This significantly reduced the data set available for statistical analysis.

The primary consequence of this data quality issue was that a sufficient amount of data was not available to conduct a reliable crash analysis. Consequently, the research focused on assessing the impact of work zone speed limit reductions on drivers' speed choices. It is presumed these speed changes have a related impact on safety performance, though additional research is warranted to understand the nature of the relationship between speed and safety.

Data were collected from nine construction work zones in Iowa during 2014 and 2015. Similar data were obtained for the preceding years during the same time period when work zones were not in place at these same nine locations. Given the large amount of high-resolution historical data, extensive data reduction procedures were utilized in this big data application.

Quantile regression was employed to examine the impacts of work zone speed limits on speed distribution percentiles before and during construction activities. The results show that speeds

were consistently reduced when work zone speed limits were in place. Overall, work zone speed limit reductions of 10 mph in locations where the normal statutory speed limit was 65 mph showed the largest reduction in all speed percentiles.

It should be noted the present research couldn't include the exact type of work activity due to data inconsistencies. This affects the transferability of results to other sites, and it is highly recommended that work zone activity type should be included in future research to further corroborate the above results.

Some of the innovative aspects of this research are as follows:

- This research reused data being collected with the Iowa DOT's Intelligent Work Zone systems. This ensured that the experimental setup was not influencing the driver behavior. This also ensured that the seasonal variation can be accounted for and drivers were given enough time to adjust to the presence of a work zone.

- Since real-world data was being used, several filters were designed to eliminate any noisy data, which is a commonly occurring phenomenon with permanent sensors.

- High-resolution speed data were collected at multiple sites (constituting more than 7 gigabytes of raw data) and high performance cluster analysis was utilized for data visualization and discovery.

- This study also highlights the inconsistencies that exist in the state of the practice of recording the work activities in real-world work zones (in contrast to pre-designed experimental setups).

CHAPTER 1. INTRODUCTION

It is widely noted that road networks are integral to the social and economic development of a region. With increasing travel demands, the highway infrastructure keeps aging and extensive construction, maintenance, and utility works are needed. According to the Iowa Department of Transportation (DOT), there may be up to 500 road construction work zones in and around Iowa's cities and counties from March through November each year (Iowa DOT 2016). A work zone is defined as an area of a roadway where construction, maintenance, or utility work activities are identified by warning signs that mark beginning and end points. The zone extends from the first warning sign to the last or End Road Work sign (FHWA and others n.d.). Because work zones introduce changes to the normal driving environment, they may alter regular traffic flow conditions. Work zones require extra caution from motorists, as well as from the workers who are exposed and often extremely close to traffic.

The introduction of work zone environments may bring hazards to both drivers and construction workers due to the disruptions to the normal driving environment, including narrower lanes, closed shoulders, lane closures, and lane shifts. One potential hazard to motorists and workers is crash risks. In 2013, 67,523 crashes were estimated to have occurred in work zones nationwide (FHWA Work Zone Management Program 2016). In Iowa, work zone crashes have increased in past 10 years. Figure 1 illustrates the trend of crashes that have occurred in work zones on Iowa's Interstate and state highway systems.

Iowa Work Zone Crashes on Interstates

Iowa Work Zone Crashes on State Highways
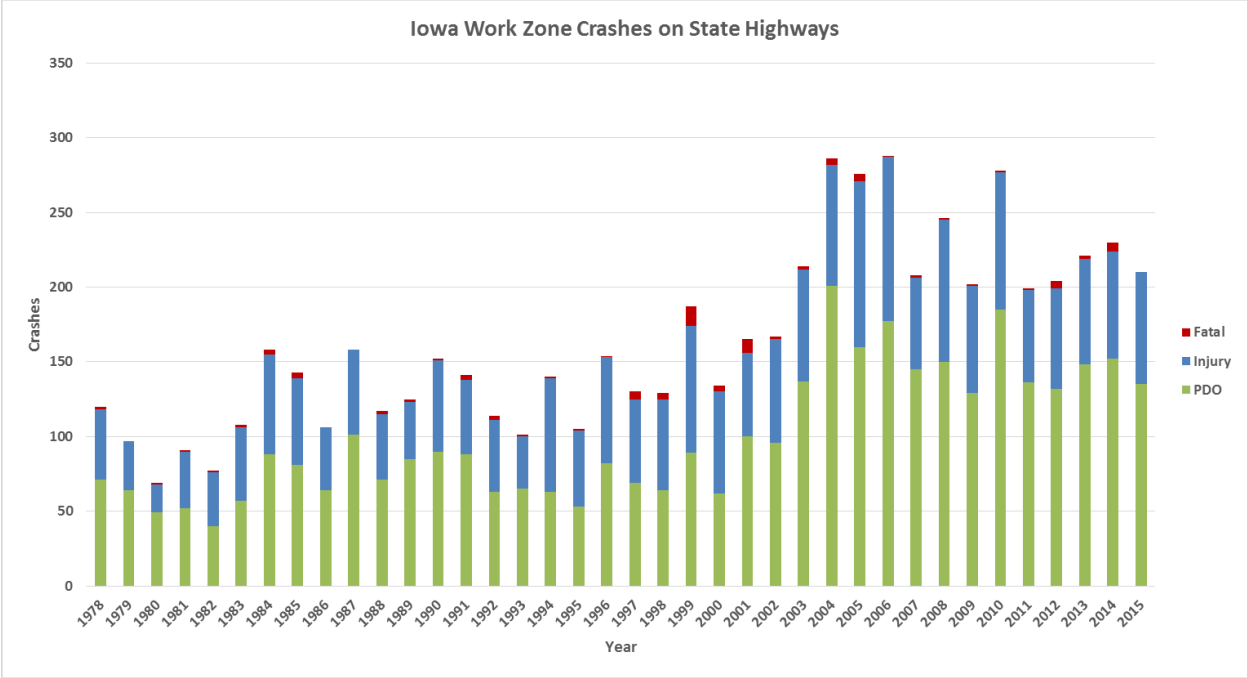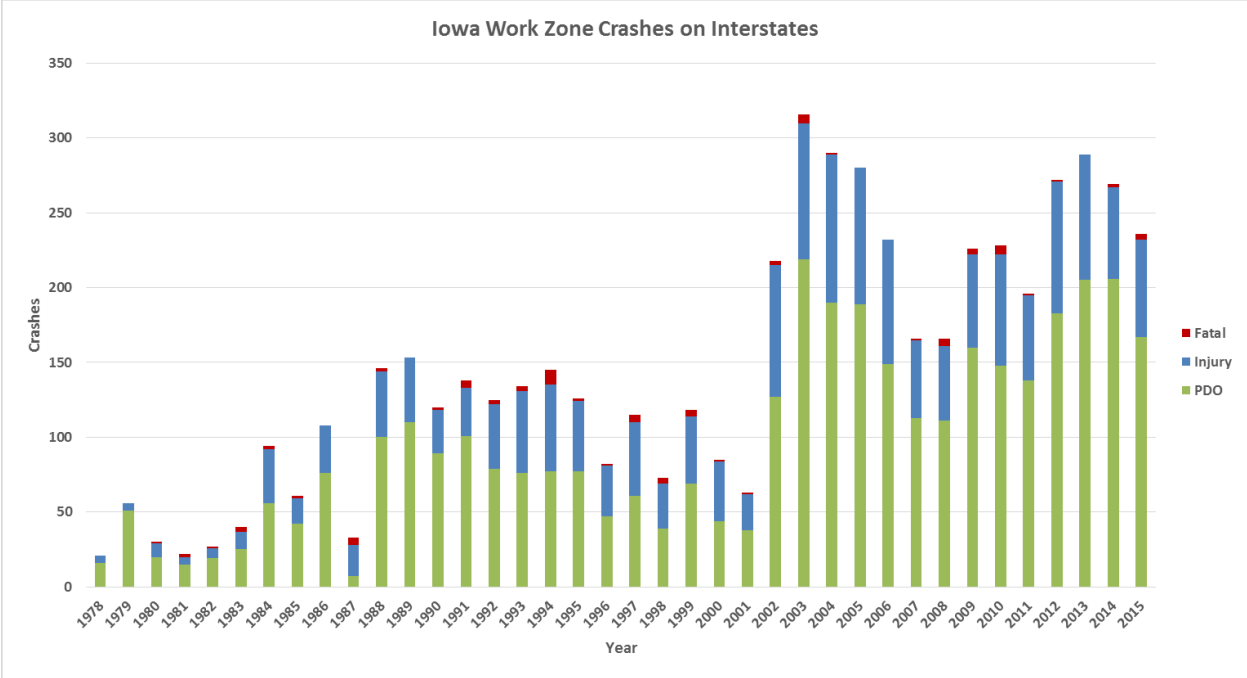
Data source: Iowa Crash Statistics, http://www.iowadot.gov/workzone/wzstats.pdf. Published by Office of Construction and Materials and Office of Traffic and Safety, Highway Division, Iowa DOT, September 28, 2016.

Figure 1. Number of work zone crashes on Iowa Interstates (top) and state highways (bottom)

The work zone crashes have been divided into fatal, injured, and property damaged only (PDO) categories. Although there are far fewer fatal crashes than other crashes, fatal crashes have the most severe impacts and lead to the greatest societal losses. According to the Iowa DOT's Work Zone Quick Facts website (Iowa DOT 2016), there were 830 work zone motorist fatalities per

year in the US from 2004 to 2013 (10-year average), while in Iowa there were 5 per year on average.

The other adverse effect brought on by work zones is the potential decrease in traffic mobility. Some types of work zone activity, such as lane closures or lane shifts, directly reduce the total capacity. Other construction work might also make the speed-density relationship different from that of the normal traffic flow. Therefore, alleviating the adverse impacts of work zones on safety and mobility has become one of the most critical challenges confronted by traffic engineers and researchers.

Properly managing traffic during construction is essential to maintaining work zone safety and mobility. In the *Manual on Uniform Traffic Control Devices* (MUTCD), a temporary traffic control (TTC) plan is proposed as a measure to be used for facilitating the passage of road users through a work zone. Figure 2 shows a typical TTC work zone layout.
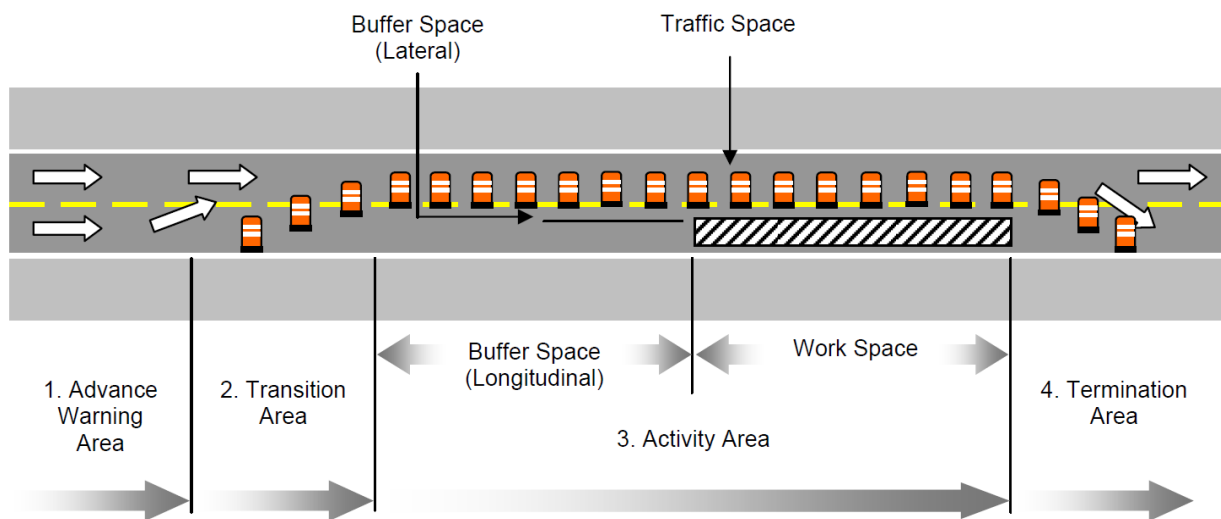
Construction Safety Council (2008)

Figure 2. Components of TTC work zone

Figure 2 illustrates a divided highway with two lanes in one direction and the work space blocking one lane. The main components of a TTC work zone include the advance warning area, the transition area, the activity area, and the termination area. The advance warning area informs drivers about upcoming road conditions. The MUTCD suggests that typical distances for the placement of advance warning signs on freeways and expressways should be as far as 1/2 mile or more (FHWA 2009). The transition area moves drivers from their normal paths if necessary, and the activity area usually has buffer space for protecting workers. The termination area is typically from the end of the work space to the last control device, such as an "End Road Work" sign, and lets drivers move back to their normal paths.

3

There are various kinds of TTC devices used in work zones, such as a single sign or high-intensity rotating, flashing, oscillating, or strobe lights on a vehicle (Construction Safety Council 2008). Figures 3 and 4 show some typical advance warning signs used in Iowa.
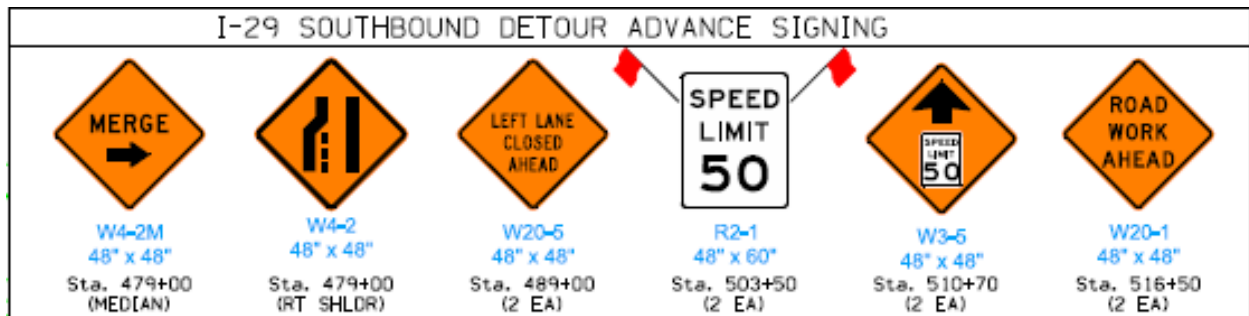
Iowa Traffic Critical Projects 2015, Project 3.2 plans, https://sites.google.com/site/iowatcp2015/tcp-list

Figure 3. Example of advance signing plan on an Iowa road work project

Google Street View. Captured at Sergeant Bluff, IA, 51054 (latitude: 42.377637; longitude: -96.355416), September 2015, © 2015 Google

Figure 4. Example of advance warning sign in an Iowa work zone

In addition to using the typical TTC methods in work zones to manage traffic, various strategies have been implemented by road agencies to mitigate the adverse impacts of work zones on mobility and safety (MnDOT 2002, Bham and Mohammadi 2011, Riffkin et al. 2008, Outcalt 2009). One common countermeasure is reducing the work zone speed limit. Work zone speed

limits are set to provide advanced warning for drivers in areas where the TTC plan may necessitate a speed reduction. Agencies tend to use speed limit reductions to lower speeds in work zones and thus reduce crash risks for both drivers and workers. To identify and arrive at the best work zone speed limit and speed zoning practices, it is imperative that the effects of such policies on highway work zone safety be examined. Answers need to be sought to questions such as what the optimum speed limit reduction may be under any given work zone condition or whether a speed limit reduction is warranted. Thus, evaluating the effectiveness of speed limit reductions provides important guidance for agencies' decisions when developing TTC plans.

In cooperation with the Iowa DOT, this project aimed to assess the effectiveness of speed limit reductions in work zones and investigate the impacts of different speed limit reduction schemes on capacity.

This research examined 12 projects completed in 2014, 6 projects completed in 2015, and 3 additional ongoing projects in 2016 across Iowa, with projects varying from urban high-density areas to rural high-speed areas. The final analysis included 9 of the 12 work zones based on data availability.

The emphasis of the study was on evaluating the impacts of work zone speed limit reductions on vehicle speed characteristics, including median speed, speed variation, and speed distribution, in uncongested conditions. A large amount of traffic flow data from 2012 to 2016 was utilized to conduct the study. A quantile regression model was estimated to examine changes in the overall speed distribution at sites between the periods before and during work zone activities.

Report Content

The remainder of this report is structured as follows. Chapter 2 reviews the current research on several related topics. Chapter 3 describes and addresses the issues encountered during data collection, validation, and reduction. Chapter 4 includes a preliminary exploration of the speed data for different work zone speed limit reduction strategies. Chapter 5 details the impacts of speed limit reductions on drivers' speed choices as revealed by statistical assessments. Chapter 6 summarizes the main conclusions of this project and identifies limitations and avenues for future research.

CHAPTER 2. LITERATURE REVIEW

Working in close proximity to moving traffic is a potentially hazardous but necessary situation when conducting roadwork. Previous research has examined the relationship between crash risk and speeds in work zones. To alleviate potential risk, work zone speed limits are typically reduced with an intent to safely accommodate construction workers as well as motorists. Some researchers have studied several different types of speed control, especially speed limit reductions, and the extent to which drivers comply with work zone speed limits. Moreover, researchers have also examined other factors, such as road segment characteristics, to evaluate the impacts of work zones on traffic speeds.

Speed and Crash Risk

Speed has been cited as one of the major factors in crashes. Research has shown that crash frequency and severity are both influenced by various speed characteristics (Aarts and Van Schagen 2006, Garber and Ehrhart 2000, Renski et al. 1999).

Aarts and Van Schagen (2006) reviewed several studies focusing on the relationship between crash rates and speed characteristics (i.e., average speed and speed dispersion). The evidence in those studies showed that crash rates increased more quickly on minor roads than on major roads as speed increased. At a more detailed level, lane width, junction density, and traffic flow were found to interact with the speed–crash rate relationship. In addition to the average speed, speed variation was also an important factor in determining crash rates; larger differences in speeds between vehicles were related to higher crash rates.

In a study conducted by Garber and Ehrhart (2000), the factors affecting crash frequency were examined, including the speed characteristics, i.e., the mean speed and standard deviation of speeds, as well as flow and geometric characteristics. A case study of two-lane highways in Virginia indicated that, of all of the independent variables considered, the standard deviation of speeds seemed to have the greatest impact on the crash rates.

In addition to crash frequency, Renski et al. (1999) analyzed the relationship between crash severity and speed limit increases by using a case study of North Carolina Interstate highways. The authors found that increasing speed limits from 55 to 60 mph and from 55 to 65 mph increased the probability of crashes that resulted in minor injuries, but increasing speed limits from 65 to 70 mph did not have a significant effect on crash severity.

It is noteworthy that these previous studies may not reflect the current on-road situation, especially drivers' increasing use of cell phones in recent years. Such behavior may lead to distracted driving and the occurrence of crashes.

Speed Control Strategy

Past research has examined the efficacy of several speed control strategies in reducing work zone speeds. One common approach is to post a reduced regulatory speed limit sign in work zone areas. Porter et al. (2007) investigated the relationships between 85th percentile speeds and the standard deviation of speeds with different work zone speed limit reductions on four-lane freeways. The authors employed a seemingly unrelated regression model and concluded that the 85th percentile speed and the standard deviation of speeds were both significantly impacted by speed limit reductions. The 85th percentile speeds in work zones with reduced speed limits were lower than in work zones with no reduction, and the amount of the decrease in speeds was positively correlated with the amount by which the speed limit was reduced. The standard deviation of speeds was also lower in work zones with a posted speed limit reduction of 10 or 15 mph than in work zones with no posted speed limit reduction.

A study conducted by Finley et al. (2014) in an Ohio work zone evaluated the process of establishing speed zones. The research team observed drivers' speed choices upstream of and adjacent to several work zones with reduced speed limits. The authors made a chart of speed limit recommendations based on various scenarios combining different speed limit reductions and different work activities.

In addition to static posted regulatory speed limit signs, another measure usually used to reduce speed in work zones is the variable speed limit (VSL) sign. VSL signs use sensors to detect current traffic or weather conditions and then dynamically change the posted speed limit accordingly. Kang et al. (2004) and Lin et al. (2004) utilized dynamic linear functions to estimate nonlinear traffic flow relationships and applied the functions to data from the detector guiding the VSL display. The simulation results showed that the speed variance of vehicles in work zones was lower when there was VSL control, which is beneficial to safety. To better assess the effectiveness of VSL signs, the Virginia DOT conducted a project focusing on work zone VSL system design (Fudala and Fontaine 2010). VSL systems were installed in high-volume urban work zones, and a before-and-after evaluation of the system was conducted. The researchers also simulated different sites to measure the impacts in various scenarios. They concluded that VSL signs could improve the traffic operations in terms of safety and congestion when the demand is below capacity and recommended a cost-benefit analysis before long-term deployments.

Other speed control strategies have also been studied. Jeihani et al. (2012) investigated the impacts of dynamic speed display signs (DSDS) on drivers' speed choices through a survey and a field study. The authors found that DSDS could reduce speeds but the effects declined with time. Another countermeasure to control work zone speeds is setting rumble strips to alert motorists about changes in the roadway environment. In one study sponsored by the Strategic Highway Research Program (SHRP), portable rumble strips (PRS) were tested for their effectiveness (Stout et al. 1993). The results showed that PRS could provide a measurable reduction in average speed and speed variation and increase drivers' recognition of work zone signs.

Driver Compliance and Reaction

Compliance with posted work zone speed limits has been found to be a common issue, and several studies have been conducted to examine drivers' compliance with posted speed limits (Haglund and Aberg 2000, Mannering 2007) and drivers' reactions to reduced speed limits (Finley 2011).

In a study of four work zones in Missouri, Bham and Mohammadi (2011) determined that the construction activity in these work zones significantly decreased the average speeds of passenger cars and trucks, by 3.5 and 2.2 mph, respectively, compared to times of inactivity. Speeds remained above the posted speed limits regardless of whether activity was ongoing. Reduced lane widths were revealed to be the most effective factors in reducing average speeds (Bham and Mohammadi 2011).

Brewer et al. (2006) examined the level of driver compliance to three devices: speed display trailers, changeable message signs, and orange-bordered speed limit signs. The results indicated that speed display trailers, which detect and display a vehicle's speed, were more effective in improving compliance than static speed limit signs (Brewer et al. 2006). McMurtry et al. (2009) also reviewed the effectiveness of different signage. The results showed at a 95% confidence level that average speeds did not decrease significantly when using static speed limit signs compared to variable speed limit signs, but speed variation in general decreased (McMurtry et al. 2009).

A study was conducted on three short-term work zones on Interstate 70 in rural Missouri to determine the effects of three speed limit signage scenarios: no posted speed limit reduction, a 10 mph posted speed limit reduction, and a 20 mph speed limit reduction. The 85th percentile speeds were found to be 81, 62, and 48 mph, respectively. These differences were statistically significant, indicating that the reduction in the posted speed limit was effective in lowering speeds in the context of short-term work zones (Hou et al. 2013).

It was also discovered that compliance decreased as the difference between the usual speed limit and the posted work zone speed limit increased. In Missouri, a work zone speed limit of 50 mph saw even less compliance than a work zone speed limit of 60 mph (Bham and Mohammadi 2011), and a study conducted in Australia yielded similar findings (Blake 1992). Overall, several studies have concluded that although certain measures can be taken to try and slightly reduce speeds, motorists regulate their speeds as they feel necessary (Finley 2011, Brewer et al. 2006).

In terms of police enforcement, Benekohal et al. (1992) evaluated the effects of police car presence on vehicle speeds at rural Interstate work zones in Illinois. The authors concluded that motorists traveled about 4.3 to 4.4 mph slower when there were police patrols. However, motorists became 2.4 to 3.0 mph faster after police left.

Research conducted by Wasson et al. (2011) also found the presence of police enforcement to be an effective means of speed reduction. The results showed that the mean speed decreased by

8

approximately 5 mph during periods of exceptionally high enforcement compared to periods of no enforcement. Despite this reduction, 75% of passing vehicles were observed to be exceeding the speed limit, even on patrolled segments, and of those vehicles in violation, 25% were exceeding the speed limit by more than 5 mph (Wasson et al. 2011).

Additional work by Finley (2011) indicated that the presence of police enforcement, in conjunction with the normal operating speeds of the roadway and the current situation of the construction zone, dictates the size of the speed reduction (Finley 2011). A comparison of 85th percentile speeds upstream and downstream from work zones in different conditions showed that motorists decreased their speeds in work zones when they perceived a need to do so.

Debnath et al. (2012) reviewed four types of work zone speed control measures to determine the effect each had on speed limit compliance. Enforcement measures, such as speed cameras or police presence, were found to be the most effective methods of controlling work zone speeds. Informational measures, including static and variable message signage, were determined to yield small to moderate effects. Several major causes of noncompliance with work zone speed limits included drivers' failure to notice signs and the public's inadequate understanding of roadwork risks and hazards (Debnath et al. 2012).

Another study conducted by Medina et al. (2009) focused on the spatial effects of speed reduction treatments on vehicular speeds. In order to determine optimal treatment location, the researchers collected field data 1.5 miles downstream of the actual treatment to see how drivers would react after passing the treatment. They found that using speed photo radar enforcement reduced the downstream speed of cars by 2 to 3.8 mph and of trucks by 0.8 to 5.3 mph on average.

Other Factors

Drivers' speed choices may not only be affected by speed limit signs or other speed control methods; drivers also tend to respond to the driving environment, including road characteristics, weather conditions, etc., especially in work zones. Porter et al. (2007) studied the impacts of road geometry on speed distribution and found that when the lane width was less than 15 ft, the 85th percentile speed tended to be 6% slower than normal. In general, narrower lanes leave less lateral distance between vehicles in adjacent lanes or between vehicles and shoulder obstructions, requiring more of motorists' attention and influencing motorists to reduce speeds (Maze et al. 2000). Other factors found to be significant in the study by Porter et al. (2007) include vertical road alignment and construction type.

It should be noted that the road, weather, and traffic conditions of work zones also play an important role in speed reduction. Speed is not determined by any isolated factor but rather by a comprehensive process. Although limited by the data available from work zones, this project attempted to identify the effects of speed limit reductions on speed changes in work zones.

CHAPTER 3. DATA MINING

For this project, work zones at several key construction projects across Iowa were studied. Projects were chosen from the Iowa DOT's Traffic Critical Projects (TCP) program. The Iowa DOT had initiated the TCP program and deployed Intelligent Work Zone (IWZ) systems (Iowa DOT n.d.) to improve safety and mobility on Iowa's highest demand roadways. For this study, we initially chose 21 IWZs from the list of TCPs from 2014 to 2016. Figure 5 shows the locations of those IWZs.
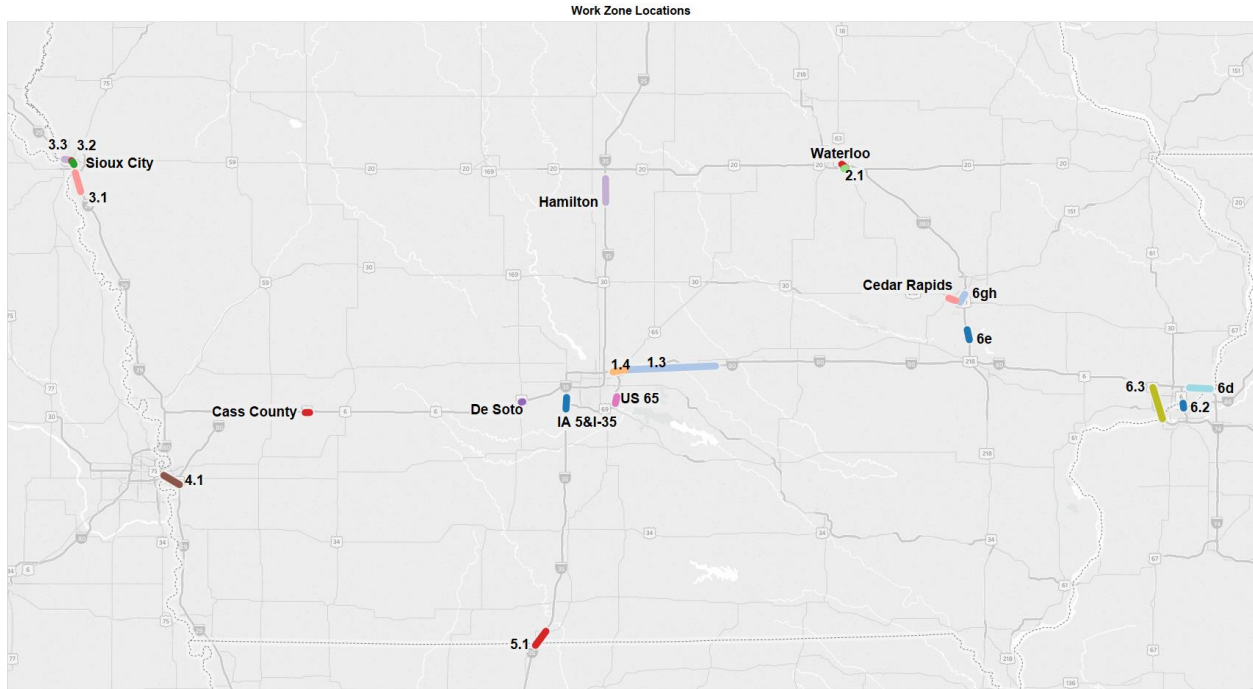
Figure 5. Locations of all work zones in study scope

Twelve IWZs were completed in 2014, six were completed in 2015, and three were ongoing in 2016. No sites with speed limit reductions from 70 to 65 or 60 mph were included in the study because none of the IWZ sites met that criteria.

A total 115,158 observations were analyzed as a part of this study. Efforts were made to ensure that each of the segments analyzed had more than 400 observations. This was to ensure statistical significance. The work zones were chosen based on the availability of base condition data. This required that a permanent sensor was present at the site before the work zone was deployed and during the deployment of the work zone. This criterion was satisfied by a limited number of work zones in Iowa.

The basic information for these 21 work zones is shown in Table 1.

Table 1. Initial work zone information

Work Zone ID	Length (mi)	Year	Traffic Configuration	Road Work Comments
1.3	24.7	2014	Lanes shifted to the median, lane closures at night only	New paved shoulder construction
1.4	3.53	2014	Project specific traffic control	Interstate reconstruction in urban area; high traffic volume with congested work areas
2.1	0.67	2014	Single lane closures with temporary barrier rail and glare screen	Bridge deck overlay
4.1	5.7	2014	Project specific traffic control	Interstate reconstruction in urban area; high traffic volume with congested work areas
Cass County	1.23	2014	Lane closures, except for August, allowed	Ditch repair outside traveled way of Interstate
Cedar Rapids	1.95	2014	Two-lane, two-way operation	Multilane highway reconstruction on opposite side of median
De Soto	0.45	2014	Nighttime lane closures only	Revetment on river bank below Interstate
Hamilton	6.44	2014	Two-lane, two-way operation	Interstate reconstruction on opposite side of median
IA 5 & I-35	3.16	2014	Traffic separated from each other and work area by temporary barrier rail and glare screen	Six-lane pavement reconstruction
Sioux City	0.87	2014	Project-specific traffic control	Interstate reconstruction in urban area; high traffic volume with congested work areas
US 65	1.87	2014	Two-lane, two-way operation	Overflow bridge construction
Waterloo	1.53	2014	Night work lane closures only	HMA resurfacing and patching
3.1	5.4	2015	Project-specific traffic control	Interstate reconstruction in urban area; high traffic volume with congested work areas
3.2	1.06	2015	Project-specific traffic control	Interstate reconstruction in urban area; high traffic volume with congested work areas
3.3	1.78	2015	Project-specific traffic control	Interstate reconstruction in urban area; high traffic volume with congested work areas
5.1	7	2015	Two-lane, two-way operation	Interstate reconstruction on opposite side of median
6.2	2	2015	Single lane closures with temporary barrier rail and glare screen	Bridge deck overlay
6.3	9.61	2015	Two-lane, two-way operation	Interstate reconstruction on opposite side of median
6e	2.8	2016	-	-
6d	5.8	2016	-	-
6gh	4.3	2016	-	-

In addition to the work zone data, other elements were collected to assess the impacts of speed limit reduction on driver speed selection: vehicle speed data and work zone spatial-temporal settings. The processes of data collection, validation, and fusion are described below.

Data Sources

Vehicle Speeds With/Without Work Zones

Vehicle speeds were collected by Wavetronix radar sensors and stored in a TransSuite Data Portal maintained by the Iowa DOT. For each of the traffic-critical work zones monitored during the 2014 and 2015 construction seasons across the state, a massive amount of field data was obtained over the time period from 2012 to 2015. These data allowed for an assessment of speeds during the construction period as well as during the same time period from the preceding calendar year. This process resulted in a total database file size of more than 7 gigabytes. The data elements obtained included vehicle counts, average speeds, and sensor time occupancy in five-minute intervals for each traffic lane.

Spatial-Temporal Settings of Work Zones

Additionally, spatial-temporal information detailing each work zone's layout and activities was needed for this study. The spatial and temporal boundaries of the work zones provide information as to when and where each work zone was in place, which is crucial for conducting a before-and-after study to ascertain operational and safety impacts. The type of work zone activity is also important because it might impact both drivers' speed choices and crash risks differently across work zones. However, the daily work reports (DWRs) were not available as per the Iowa DOT's privacy policies. Therefore, the precise work zone spatial-temporal settings and activities could not be obtained directly to the level of precision necessary. Consequently, to allow for a sufficiently robust analysis that identifies the impacts of speed limit reductions, additional data sources were used to deduce the periods of work zone presence and the periods of normal (i.e., non–work zone) driving conditions.

Construction Contract Documents

Construction contract documents, available from the Iowa DOT, contain the planned start and end dates of each work zone project. However, it is important to note that these documents provide only implicit guidance because the actual in-field construction may vary significantly from the project plans and letting information.

Iowa 511 Archive Database

The Iowa 511 archive database records the start and end times of any events involving road closures on specific roadways that have been reported through the Iowa 511 system. These events include right/left lane closures, lane reductions to one or two travel lanes, shoulder closures, ramp closures, and other construction events. The periods of those closure events are

only recorded by date in this database and range from one to three days to several months. The database is updated whenever information is provided by field crews. There is no field check or enforcement policies to ensure that the field crews report the openings and closings in a timely fashion.

Advanced Traffic Management System (ATMS) Database

Advanced Traffic Management System (ATMS) message archives provide a roster of information at one-minute intervals regarding traffic control plans throughout the state. This database consists of information regarding the starting date and time of various traffic control plans corresponding to a number of highway operational characteristics. In addition, it also records the type of traffic control in place within each lane that has undergone lane closure or blockage during pertinent events, such as road construction, utility work, or crash occurrences.

Data Issues

Sensor Issues

The sensors used to collect data for the speed analysis were Wavetronix SmartSensor HD devices with dual radar measures. Data collected from the sensors could potentially be affected by adverse weather, lane change movements, or system communication errors. Generally, noisy sensor data is the first issue faced in any field data analysis, with sensor errors including extreme vehicle count or speed values, missing vehicle count or speed data in a record, and violations of the expected average vehicle length estimates. In this study, we examined 169 sensors located in work zones and filtered the data to remove such anomalies.

In addition to noisy sensors, sensor coverage is also an issue in speed analysis. There were a total of 40 directional work zones in our study, while there were only 169 directional sensors installed in those work zones. On average, less than 5 sensors were available in each work zone. Thus, data from those sensors could only represent the point speeds at a few specific points in each work zone. Ideally, speed data would be collected continuously over the physical bounds of the work zone. Nonetheless, these point speeds provided a general representation of changes in driver behavior over the course of the work zone.

Work Zone Period Identification

As described above, the exact spatial-temporal characteristics of the work zones were difficult to determine. Although multiple data sources were utilized, data inconsistencies were found across the databases, and, in the absence of any ground truth data, it was not possible to verify whether the inconsistencies resulted from missing or incorrect data. This issue was vital to this project because any incorrect deduction of work zone presence would lead to inconsistent conclusions. Consequently, this project used a conservative approach and hence only those time periods for which all the data sources consistently marked the presence or absence of a work zone were used

for analysis. This resulted in a significant reduction in the data available for analysis and made crash analysis infeasible.

Data Validation and Reduction

Given the size of the traffic database and the variety of quality assurance/quality control issues, an extensive data reduction procedure was conducted, as illustrated in Figure 6.
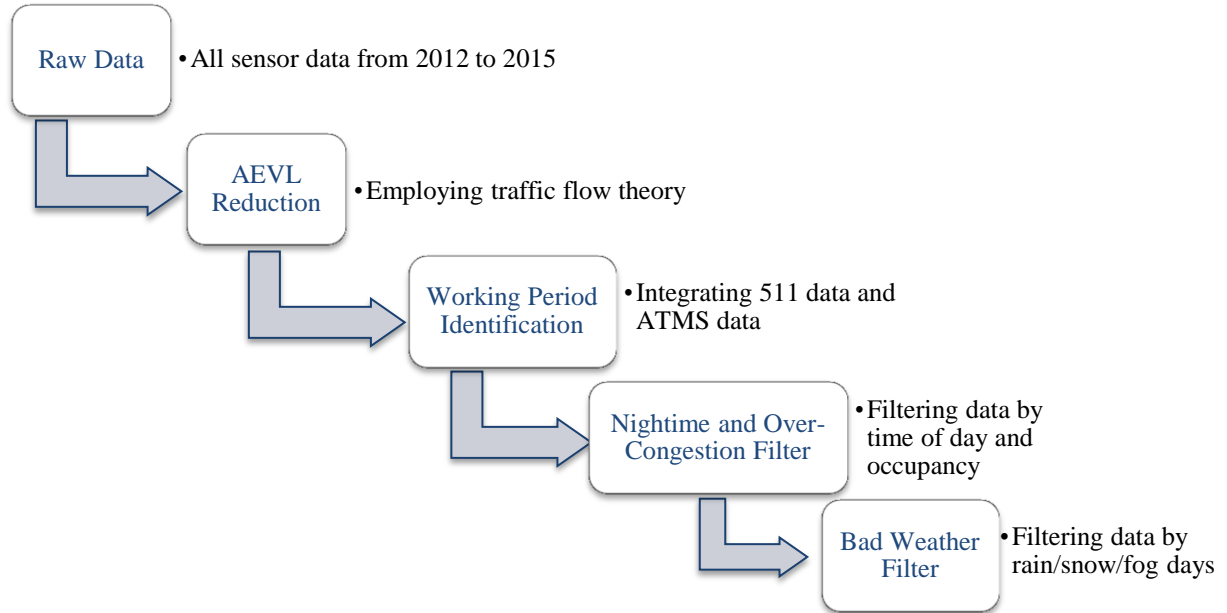
Figure 6. Data reduction procedure

This procedure comprised three primary steps, each of which is explained in further detail below.

Step 1: Reduce Sensor Data

Traffic flow theory was used to identify faulty sensors and other data quality issues. A method proposed by Wells et al. (2008) was employed that examines the relationships between speed, volume, and occupancy to identify loop sensor errors. The method obtains the average effective vehicle length (AEVL), which can be estimated by the following equation:

$$AEVL = (5280 \times Speed \times Occupancy) \div Volume \tag{1}$$

where AEVL is in feet, speed is in miles per hour, occupancy is a fractional number between 0 and 1, and volume is in vehicles per hour. According to reports from the Federal Highway Administration (FHWA) (2004) and Minnesota Department of Transportation (MnDOT) (Minge et al. 2012), the possible vehicle lengths should fall within the range of 10 to 75 ft.

Consequently, data were excluded from the analysis if the calculated AEVL fell outside of the range of 10 to 75 ft.

Figure 7 shows occupancy versus speed curves for different vehicle volumes.
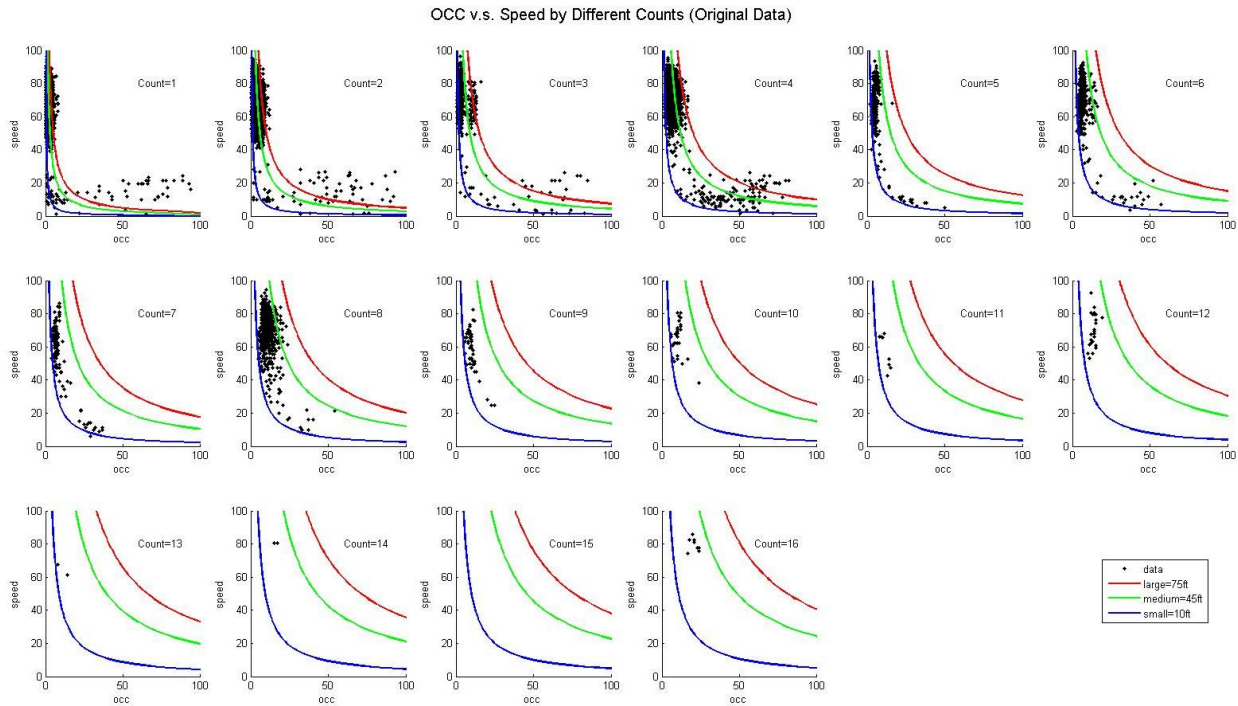
Figure 7. Example of data reduction by using traffic flow theory

In this figure, the red line (75 ft) and blue line (10 ft) in each chart define the boundaries of all single vehicle sizes passing through the sensor. The green line represents medium-sized vehicles with lengths of 45 ft. The black dots represent vehicle-level speed and occupancy data. Note that, at low volumes, some data points exceeded the boundaries of regular vehicle length. These data were treated as faulty and were eliminated from the dataset. This step resulted in 24.45% of the data being filtered out.

Step 2: Identify Dates of Work Zone Presence and Normal Condition

One practical challenge in extracting the traffic data was determining those periods when a work zone was in place. In order to effectively compare between the sensor data obtained in normal conditions and those when a work zone was in place, data were compared across several sources: (1) police-reported crash database, (2) 511 information database, (3) Iowa DOT ATMS database, and (4) construction project letting information. Figures 8 and 9 illustrate how to use that information to determine the experimental (i.e., work zone) and control (i.e., normal, before the start of the work zone period and without traffic control devices or lane closures) groups for the purposes of the before-and-after analysis.
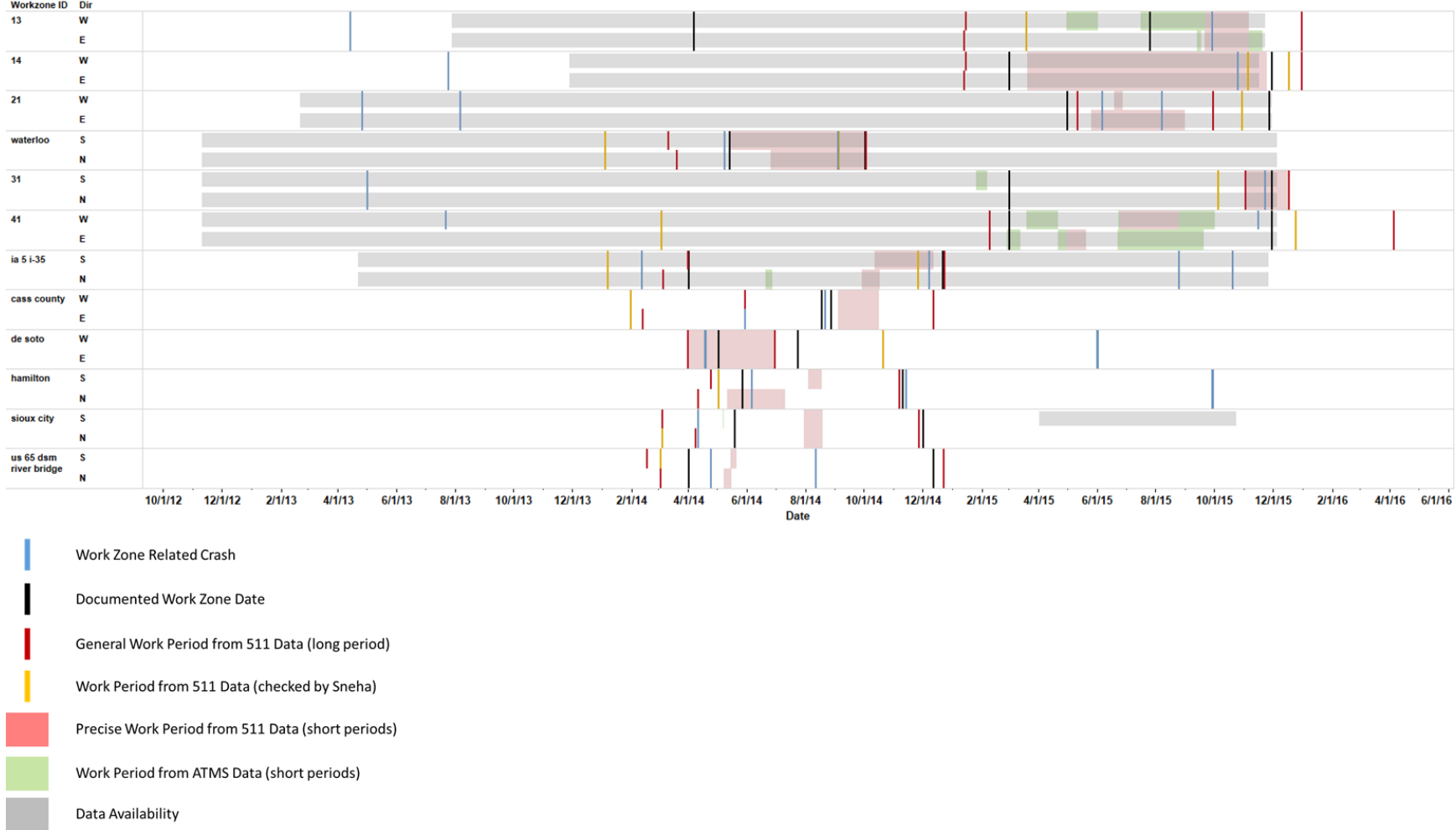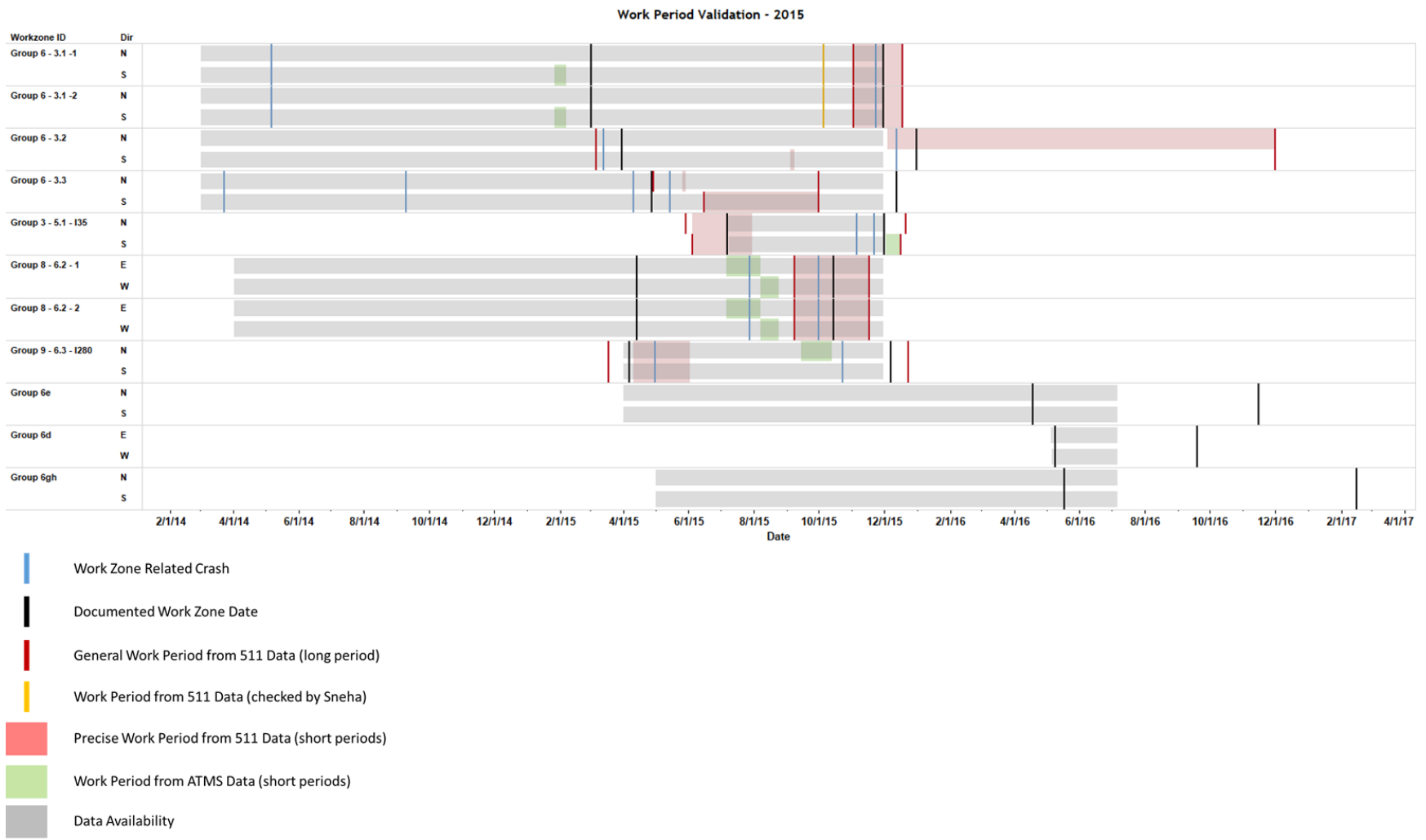
Figure 8. Work zone presence validation (2014)

Figure 9. Work zone presence validation (2015)

In Figures 8 and 9, the x-axis represents continuous time and the y-axis represents the presence of discrete work zones. The grey shaded areas represent the time periods during which the data sources indicated that a work zone was present in each direction. All validation results were applied only when there were data available.

To build an experimental group consisting of all areas with a work zone, first all the available project letting information was reviewed for each work zone area. The start and end dates corresponding to the letting information are marked as black bars in the figures. Second, we extracted all the pertinent events, such as road construction and roadwork, from the 511 and ATMS databases. By examining those event types, two subsets of event periods were extracted and used to determine the time periods during which work zones were in place according to each resource. The precise 511 work zone dates (short time periods containing 511-indicated lane closure events) are indicated by red shading in Figures 8 and 9, and the precise ATMS work zone dates (short periods containing ATMS-indicated lane block events) are indicated by green shading in the figures. By considering cases where there was overlapping information regarding work zones in both the 511 and ATMS data, the most conservative date range was selected for each work zone.

To build a baseline group consisting of all normal, non-work-zone areas, similar data were extracted from the preceding calendar year. Then, all the dates where a work zone–related crash was reported were filtered out of the database. The crash dates are represented by blue bars in Figure 8. Second, the general 511 lane closure periods (red bars and orange bars) from the preceding year were also avoided. Thus, by combining available data from the same data sources used to build the experimental group, the normal traffic periods could also be deduced.

To further balance the size of the experimental and control groups, the items in the control (normal, non-work zone) group were selected for the same months as those in the experimental group, but in the earliest prior year for which data were available. By doing this, potential latency effects were minimized, as were seasonal impacts on traffic flow or driver behavior.

Step 3: Extract Data from Daytime, Free-Flow Periods

For the purposes of this study, data were obtained only for daytime traffic. Daytime conditions tend to be more representative of normal traffic than nighttime conditions, and the sensor data are also generally less reliable at night. It was found that during the nighttime there were reductions in speeds due to data aggregation issues related to the fact that speeds of 0 mph were measured in periods when no vehicles were observed. Consequently, only the time period from 7 a.m. to 9 p.m. was used for this analysis.

In order to avoid data for which reductions in speed occurred due to congestion, the data were reduced by filtering out any time periods that reported a sensor occupancy of greater than 20%. This threshold is representative of overcongested conditions because it is a likely breakpoint of the catastrophe model in traffic flow theory (Hall 1987). This breakpoint is illustrated in Figure 10, where the top chart shows a speed and occupancy curve with the full range of occupancy values and the bottom chart shows a curve with only low occupancy values ($< 20\%$).
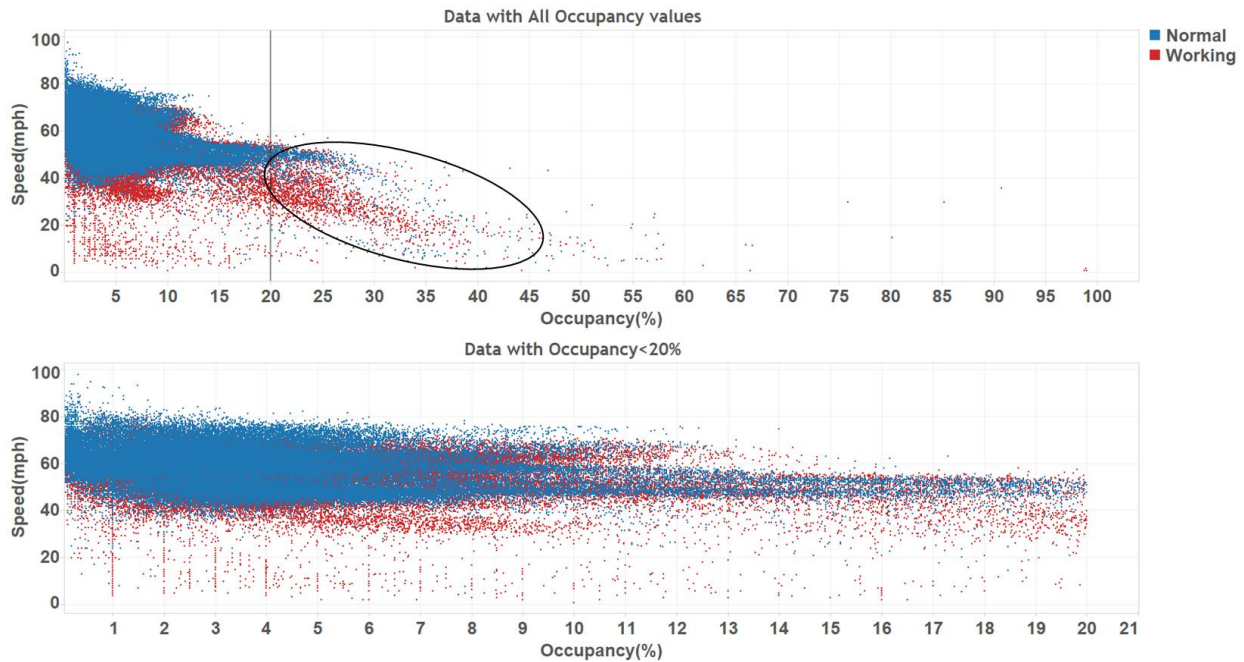
Figure 10. Congestion conditions indicated in speed and occupancy curves

It can be observed that speeds tend to be steady when occupancy is less than 20% and start decreasing linearly when occupancy rises above 20% until it reaches 100%. After this step of data reduction, 37.12% of the remaining data were filtered out.

Step 4: Extract Data from Good Weather Days

Generally, weather has been considered to be an important factor in drivers' speed selection. To ensure that any observed speed reduction was caused by the work zone speed limit reduction, the researchers attempted to minimize the speed limit reduction impacts from bad weather impacts. Because obtaining accurate temporal-spatial weather data for the several previous years was not feasible, historical weather records from the Weather Underground website were used to identify bad weather days (i.e., those days having "rain," "snow," or "fog" in the Event column). Table 2 lists the nearest weather station for each work zone. After this step of data reduction, 41.15% of the remaining data were filtered out.

Table 2. Weather station near each work zone

Work Zone ID	Direction	Weather Station Code	Latitude	Longitude
3.1	N	Sioux Gateway (KSUX)	42.40002	-96.3861
3.1	S	Sioux Gateway (KSUX)	42.40002	-96.3861
IA 5 & I-35	N	Des Moines International (KDSM)	41.53256	-93.666
IA 5 & I-35	S	Des Moines International (KDSM)	41.53256	-93.666
2.1	E	Waterloo Municipal (KALO)	42.55247	-92.3988
3.2	N	Sioux Gateway (KSUX)	42.40002	-96.3861
3.2	S	Sioux Gateway (KSUX)	42.40002	-96.3861
4.1	E	Omaha (KOMA)	41.31248	-95.8962
3.3	N	Sioux Gateway (KSUX)	42.40002	-96.3861
3.3	S	Sioux Gateway (KSUX)	42.40002	-96.3861
6.2 (2)	W	Quad-City International (KMLI)	41.44971	-90.5025
Waterloo	N	Waterloo Municipal (KALO)	42.55247	-92.3988
Waterloo	S	Waterloo Municipal (KALO)	42.55247	-92.3988
6.2 (1)	E	Quad-City International (KMLI)	41.44971	-90.5025
6.2 (1)	W	Quad-City International (KMLI)	41.44971	-90.5025

Additional Step: Verify Speed Limit for Each Work Zone

In this analysis, it was important to know the speed limits during the working and normal periods. In addition to using the project information, we also verified all the work zones' normal speed limits by checking the corresponding Google Street View images. To do this, we searched around each work zone's starting point in each direction and captured the nearest sign to obtain the speed limit for that work zone. An example Google Street View image is shown in Figure 11.

Google Street View. Captured at Van Meter, IA, 50261 (latitude: 41.541599; longitude: -93.999228), in August 2015. © 2015 Google

Figure 11. Speed limit verification

Some work zones may have varying normal speed limits that change somewhere along the length of the work zone segment. Such work zones were broken into two parts with different normal speed limits and were classified as two work zones. For example, the speed limit of project 6.2 near Davenport, Iowa, and Moline, Illinois, changed from 55 mph to 50 mph in the northbound direction across the state line in the non–work zone portion and changed back to 55 mph after the work zone area. This work zone was separated into two parts, as illustrated in Figure 12. Thus, the first part of the work zone (the green dashed line in the figure) has 55 mph as the normal speed limit while the second part of the work zone (the blue dashed line in the figure) has 50 mph as the normal speed limit.
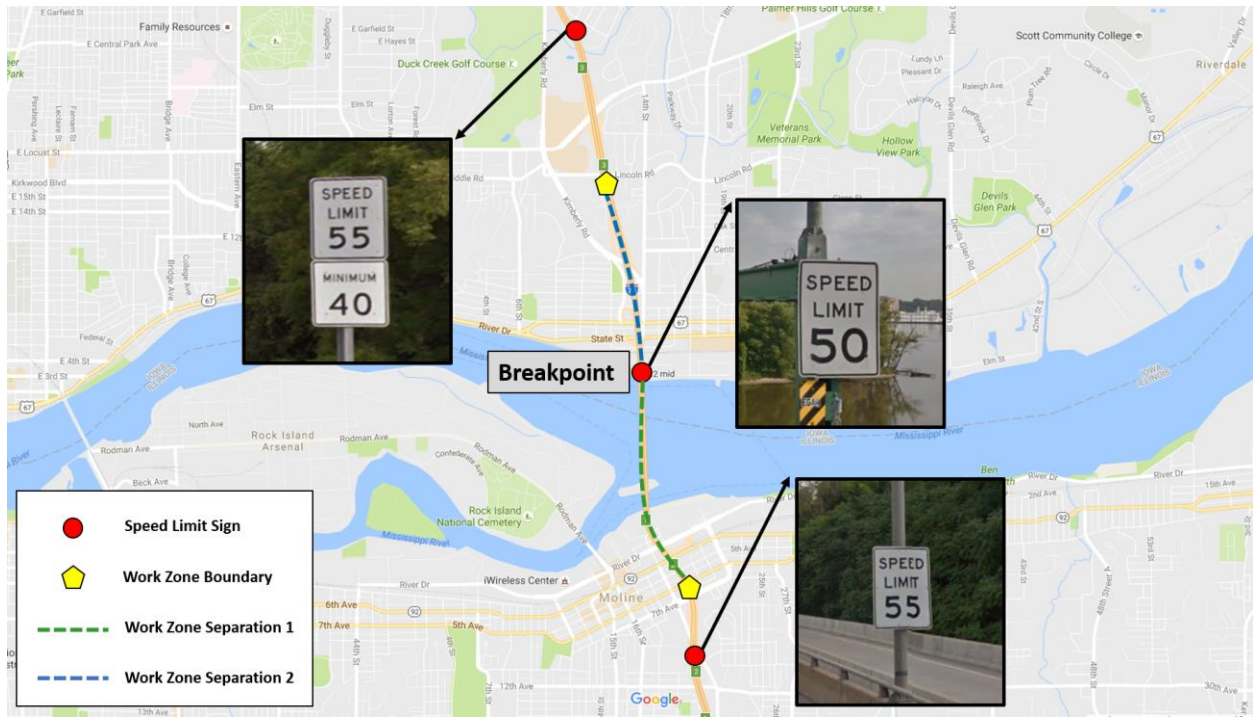
Travel direction: Northbound; Speed limit signs captured in September 2015 using Google Street View. © 2015 Google

Figure 12. Dividing a work zone according to changes in its normal speed limit

After the entire data reduction procedure, the amount of data had decreased significantly. From 7 gigabytes of raw data, 14.9 megabytes of data remained for modeling, as shown in Figure 13. The following chapter details the statistical analysis of the data to assess the impact of speed limit reductions on drivers' speed choices.
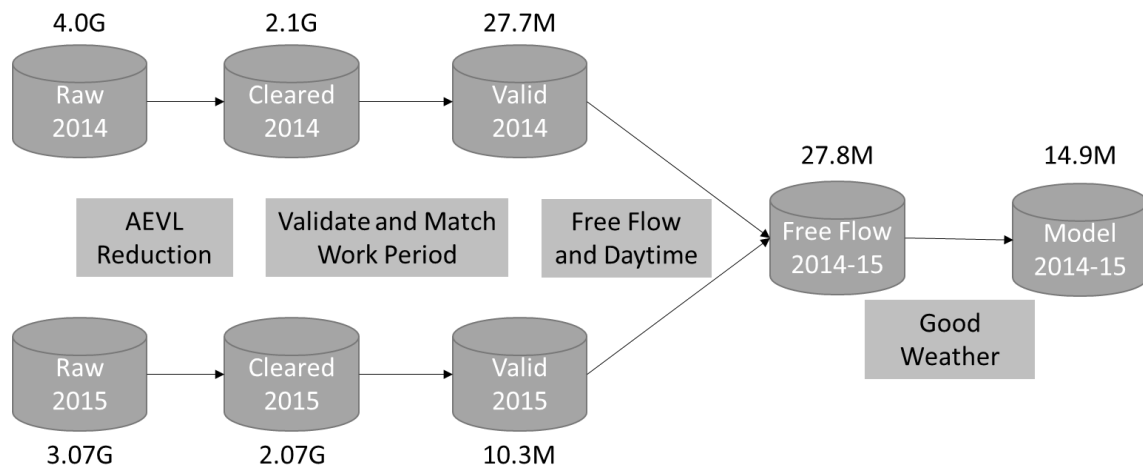
Figure 13. Data size changes during reduction

CHAPTER 4. EXPLORATORY ANALYSIS

Basic Information

After the data reduction, speed data from nine highway segments across the state were left as study subjects. These segments were identified as locations where high-priority work zones were in place during the 2014 and 2015 construction seasons. Table 3 provides a summary of the work zones, including the length of the work zone, the statutory speed limit, and the speed limit reduction (if applicable).

Table 3. Information on the studied work zones

Work Zone ID	Direction	Length (mi)	Statutory Speed Limit (mph)	Speed Limit Reduction (mph)
3.1	N	5.33	70	15
3.1	S	5.33	70	15
IA 5 & I-35	N	3.16	70	15
IA 5 & I-35	S	3.16	65	10
2.1	E	0.67	65	10
3.2	N	1.06	55	5
3.2	S	1.06	55	5
4.1	E	5.7	55	0
3.3	N	1.78	55	0
3.3	S	1.78	55	0
6.2 (2)	W	0.9	55	0
Waterloo	N	1.52	55	0
Waterloo	S	1.52	55	0
6.2 (1)	E	1.1	50	0
6.2 (1)	W	1.1	50	0

For the normal (i.e., non–work zone) period, data from the same month and day as the work zone period data were chosen in one of the preceding years (2012, 2013, or 2014) for comparison purposes. Data were not included if one of the three data sources noted above indicated that a work zone was in place during that time period. In such instances, data from similar time periods were identified using a similar screening procedure. Table 4 integrates all available information on the normal and work zone periods for each road location.

Table 4. Work zone and non–work zone periods of studied work zones

Work Zone ID	Direction	Normal Analysis Period			Work Zone Analysis Period		
		Start Date	End Date	Good Weather Days	Start Date	End Date	Good Weather Days
3.1	N	1/2/13	1/30/13	15	11/2/15	11/30/15	16
3.1	S	1/2/13	1/30/13	15	11/2/15	11/30/15	16
IA 5 & I-35	N	7/29/15	8/17/15	12	9/29/14	10/17/14	10
IA 5 & I-35	S	7/29/15	8/17/15	12	9/29/14	10/17/14	10
2.1	E	8/15/13	9/7/13	17	7/15/15	8/7/15	18
3.2	N	9/4/14	9/8/14	2	9/4/15	9/8/15	1
3.2	S	9/4/14	9/8/14	2	9/4/15	9/8/15	1
4.1	E	4/30/13	5/13/13	6	4/30/15	5/13/15	6
3.3	N	9/26/14	9/29/14	4	5/26/15	5/29/15	1
3.3	S	9/9/14	9/30/14	11	9/9/15	9/30/15	9
6.2 (2)	W	9/20/14	9/25/14	5	9/20/15	9/25/15	6
Waterloo	N	1/26/15	5/3/15	59	6/26/14	10/3/14	54
Waterloo	S	5/14/13	10/3/13	86	5/14/14	10/3/14	78
6.2 (1)	E	7/6/14	8/7/14	25	7/6/15	8/7/15	18
6.2 (1)	W	9/20/14	9/25/14	5	9/20/15	9/25/15	6

Figure 14 shows all of the sensors used in this study; sensors with no data in the target time period have been excluded.
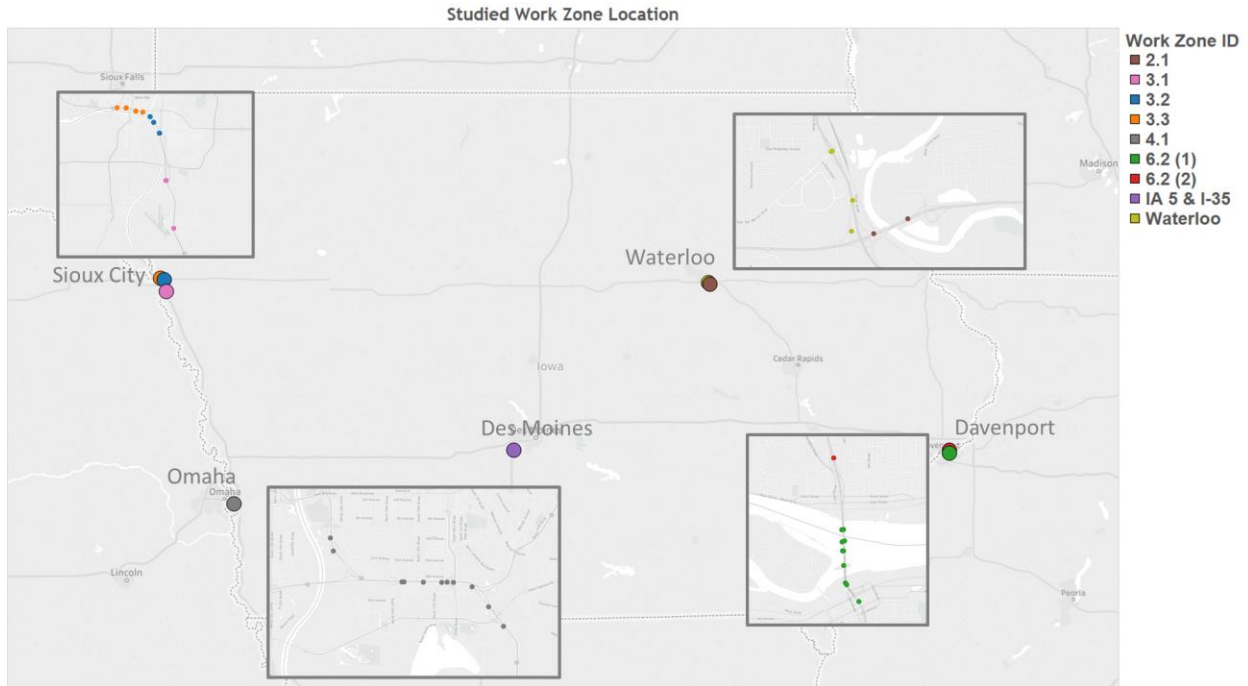
Figure 14. Studied work zones and sensors location

It is noteworthy that nearly all of the studied work zones are close to or within urban areas. Only work zone 3.1 and work zone IA 5 & I-35 are at the boundary of, and not strictly within, an urban area; therefore, they have relatively higher normal speed limits. Other work zones are located in urban areas. This situation may be due to the availability of sensors, in that sensors are intentionally installed more in high-volume urban areas to monitor critical traffic conditions than in low-volume rural areas. Although this study may thus represent urban work zone conditions more than rural conditions, the study nevertheless represents a general application of the analysis methods.

Speed Distribution

Representing a preliminary exploration of the speed distributions, Figure 14 shows a boxplot of speeds for each work zone in each direction by different work zone conditions and corresponding speed limits, indicated by red horizontal line. Further, the work zones are grouped by different speed limit reduction strategies. As shown at the bottom of Figure 15, each group name represents the normal speed limit/work zone speed limit.
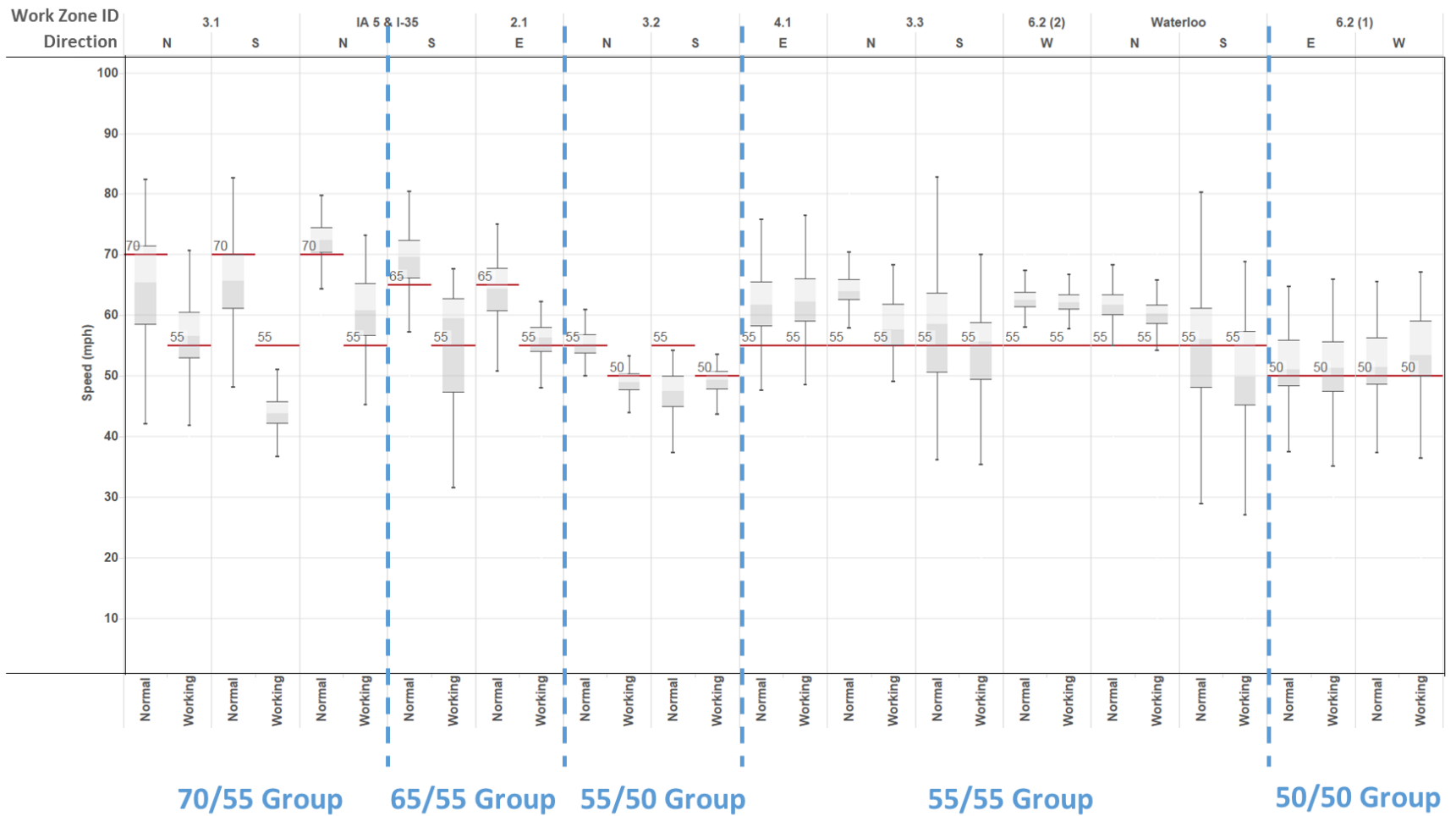
Figure 15. Exploratory analysis of speed distribution

Several insights can be discovered from Figure 15. In the 70/55 group (work zones 3.1 NB, 3.1 SB, and IA 5 & I-35 NB), the obvious drop in median speed from the normal condition to the work zone condition is observed for all work zones. However, the magnitudes of the changes resulting from the 15 mph reduction in the posted speed limit vary. In terms of speed variation, the changes caused by the work zones are not consistent within this group. Overall, when the work zone speed limit dropped from 70 mph to 55 mph, drivers tended to reduce their speed in response to the large speed limit reduction.

In the 65/55 group (work zones IA 5 & I-35 SB and 2.1 EB), the speed limit reduction is 10 mph. Drivers also responded to this speed limit reduction, evident in the downward shift in the speed distribution. The changes in speed variation between any two work zones within this group are still not the same, even though these work zones are in the same group. This indicates that speed variation might be impacted by other latent factors related to the sites.

In the 55/50 group (work zone 3.2 NB and SB), only one physical work zone used this speed limit reduction strategy. Thus, the speed distributions are similar in both directions and in both normal and work zone conditions. Because the segments in this group may have homogenous road characteristics, weather conditions, and other latent factors, the result of the analysis for this speed limit reduction strategy may be rather inconclusive.

In the 55/55 group (work zones 4.1 EB, 3.3 NB, 3.3 SB, 6.2 (2) WB, Waterloo NB and SB), six directional work zones were found not to have experienced large decreases in speed distribution when work zones were in place. It is reasonable to assume that because there was no speed limit reduction, drivers were not slowing down very much. However, drivers may nevertheless have been affected by other factors, such as work zone activities.

In the 50/50 group (work zone 6.2 (1) EB and WB), just as in the 55/50 group, only one physical work zone was present. The speed distributions are similar for both directions and both work zone conditions. The median drivers' speeds were slightly higher than the speed limit, and no change occurred when a work zone was in place.

Spatial Examination

In addition to examining each speed limit reduction strategy, a spatial examination was also conducted to explore the relationship between vehicle speed and vehicle position in work zones. Restricted by the availability of the sensor data, the relationship demonstrated here between speed and distance is discrete. Figure 16 shows how the average speed (darker colored lines) and standard deviation (lighter colored lines) change in a work zone.

As shown in Figure 16, the blue lines (normal condition) and red lines (work zone condition) interweave. Thus, both the average speed and standard deviation are not significantly impacted by work zones when only a vehicle's position within the work zone is considered.
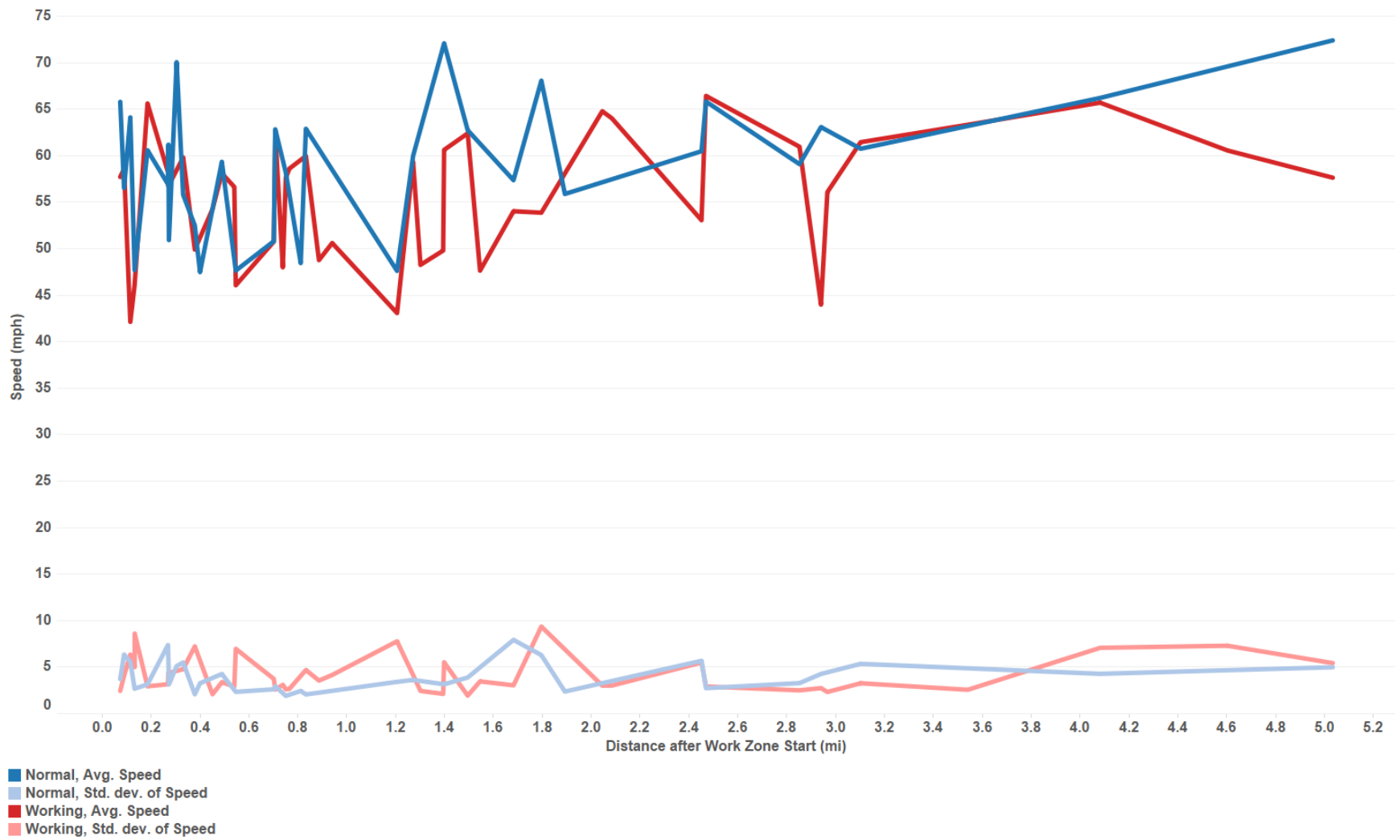
Figure 16. Average and standard deviation of speeds with distance after the start of a work zone

CHAPTER 5. STATISTICAL ASSESMENT OF SPEED DISTRIBUTION

Statistical Method

In previous research, numerous studies have focused on assessing the percentiles of traffic speed distribution, especially the 85th percentile, which is a key feature of speed profiles. The analysis described in this section examined the effects of reduced work zone speed limits by considering the speed distribution based on percentile data. Therefore, a quantile regression model was used.

The quantile regression model allows for the estimation of conditional quantile functions. As compared to the simple estimation of the mean of dependent variables in linear regression (such as in the ordinary least squares [OLS] method), quantile regression allows the distribution of the dependent variable to be estimated and is less sensitive to outliers than OLS. The basic form of the quantile regression model within the context of this study is as follows:

$$y_i = x_i'\beta_\theta + \mu_\theta, Quant_\theta(y_i|x_i) = x_i'\beta_\theta, \tag{2}$$

where $Quant_\theta(y_i|x_i)$ is a quantile of the distribution of vehicle speeds, y_i, conditional on the vector of variables included in the model, x_i. There are several ways to estimate the coefficient β_θ (Buchinsky 1998). In this study, the Frisch-Newton interior point method (Koenker and Ng 2005) was applied after preprocessing (Portnoy and Koenker 1997) using a package provided in R (Koenker 2016).

In this study, a model was estimated for the following three specific quantiles at each location: 15th percentile speed, 50th percentile (median) speed, and 85th percentile speed. The explanatory variables for these percentiles include the detector time occupancy (in percent) and the speed limit policy in effect when the speed measurements were obtained.

Empirical Settings

To implement the analysis, each work zone was classified into one of five categories based on the normal statutory speed limit and the work zone speed limit that was in place at each site. In Iowa, the maximum speed limit is 70 mph. According to our work zone examples, all speed limits within the work zones tended to be reduced to 50 or 55 mph. Table 5 provides details on the sample size (i.e., number of data bins) that were included in each speed limit combination. The table also provides the variable names (e.g., 55/55 Normal or 55/55 Work Zone) that are included in the subsequent statistical models.

Table 5. Indicator variables for different work zone groups

	Description			
Variable	**Statutory Speed Limit (mph)**	**Work Zone Speed Limit (mph)**	**Speed Limit Reduction (mph)**	**Sample Size**
70/55 Work Zone	70	55	15	5,259
70/55 Normal	70	N/A	N/A	7,290
65/55 Work Zone	65	55	10	4,689
65/55 Normal	65	N/A	N/A	2,164
50/50 Work Zone	50	50	0	6,140
50/50 Normal	50	N/A	N/A	8,421
55/50 Work Zone	55	50	5	465
55/50 Normal	55	N/A	N/A	463
55/55 Work Zone	55	55	0	40,388
55/55 Normal (base)	55	N/A	N/A	39,916

In addition to the indicators of each speed limit reduction strategy, occupancy was also added into the model as an explanatory variable. Due to the limitations in the data, more details about roadway segments, work zone activities, and weather conditions could not be obtained and included.

Because the basic assumption for using quantile regression is the independence of explanatory variables, before fitting the model, the correlations among the explanatory variables were calculated to examine the variables' independence. As Figure 17 shows, the strongest correlation between any of the pairs was only 0.44. Therefore, we assumed the independence of those variables and their suitability to fit the quantile regression model.
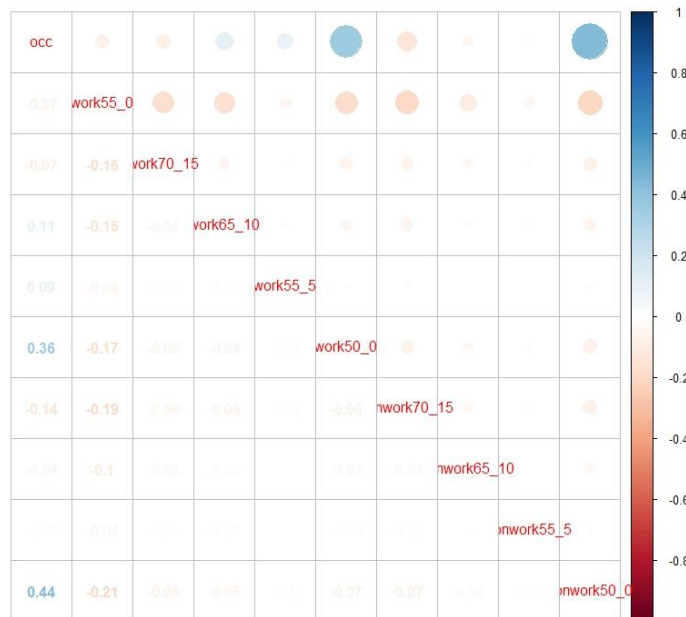
Figure 17. Correlation matrix among explanatory variables

Model Results and Discussions

Tables 6, 7, and 8 summarize the results of the quantile regression for the 15th, 50th, and 85th percentile speeds, respectively, for each work zone.

Table 6. Quantile regression results, 15th percentile speed

Variable	Estimate	Std. Error	t value
Constant (55/55 Normal)	54.62689	0.13619	41.1073
55/55 Work Zone	-0.46582	0.18763	-2.48263
70/55 Work Zone	-5.46549	-0.18128	30.14869
70/55 Normal	4.46576	0.17265	25.86557
65/55 Work Zone	-7.46082	-0.2519	29.61877
65/55 Normal	8.11793	0.3397	23.89726
55/50 Work Zone	-1.42437	0.23443	-6.076
55/50 Normal	-3.08581	0.32352	-9.53824
50/50 Work Zone	-1.69291	0.20123	-8.4127
50/50 Normal	-1.29895	0.17428	-7.45344
Occupancy (%)	-0.746	-0.01526	48.87439

Table 7. Quantile regression results, median speed

Variable	Estimate	Std. Error	t value
Constant (55/55 Normal)	62.05025	0.03206	1935.42459
55/55 Work Zone	-1.56855	0.03689	-42.52217
70/55 Work Zone	-5.47437	0.13197	-41.48264
70/55 Normal	6.42114	0.14062	45.66426
65/55 Work Zone	-4.79592	0.11917	-40.24455
65/55 Normal	7.33827	0.1936	37.9042
55/50 Work Zone	-9.61633	0.05525	-174.04951
55/50 Normal	-6.57938	0.13486	-48.78768
50/50 Work Zone	-6.06071	0.07783	-77.8701
50/50 Normal	-7.05343	0.07809	-90.32447
Occupancy (%)	-0.38128	0.00769	-49.58122

**Table 8. Quantile regression results, 85th percentile speed**

Variable	Estimate	Std. Error	t value
Constant (55/55 Normal)	65.61628	0.04031	1627.87506
55/55 Work Zone	-1.42767	0.05834	-24.46952
70/55 Work Zone	-1.53253	0.18394	-8.33146
70/55 Normal	9.15399	0.10098	90.64988
65/55 Work Zone	-4.63846	0.10095	-45.94906
65/55 Normal	8.12294	0.11373	71.4214
55/50 Work Zone	-12.62979	0.08029	-157.29945
55/50 Normal	-7.02516	0.12327	-56.99167
50/50 Work Zone	-4.66006	0.10974	-42.46271
50/50 Normal	-5.61935	0.08245	-68.15517
Occupancy (%)	-0.28018	0.00817	-34.28274

The constant in the tables represents the base group, that is, the group with 55 mph as the normal speed limit and without a reduced speed limit in the work zone. The estimates are the coefficients from the regression, which reflect the difference between the target group and the base group. For example, in Table 6, the estimate for the 55/55 Work Zone variable is -0.46582, which means that the 15th percentile speed at site 55/55 Work Zone is 0.46582 mph lower under working conditions than under normal conditions when all other variables are set to zero.

The standard error and t value are used to indicate whether the estimate for that variable is significantly different from zero. The standard error provides a 95% confidence interval for the estimates, and the corresponding t value would be large (or small, if negative) when that interval does not include zero. In Tables 6, 7, and 8, the t values indicate that all estimates are statistically significant at the 95% confidence level. All of the variables have significant impacts on speed percentiles.

To more clearly show how the speed limit reductions impact the speed distributions, Figure 18 provides plots of the normal and work zone speed profiles as they relate to the posted statutory and work zone speed limits.
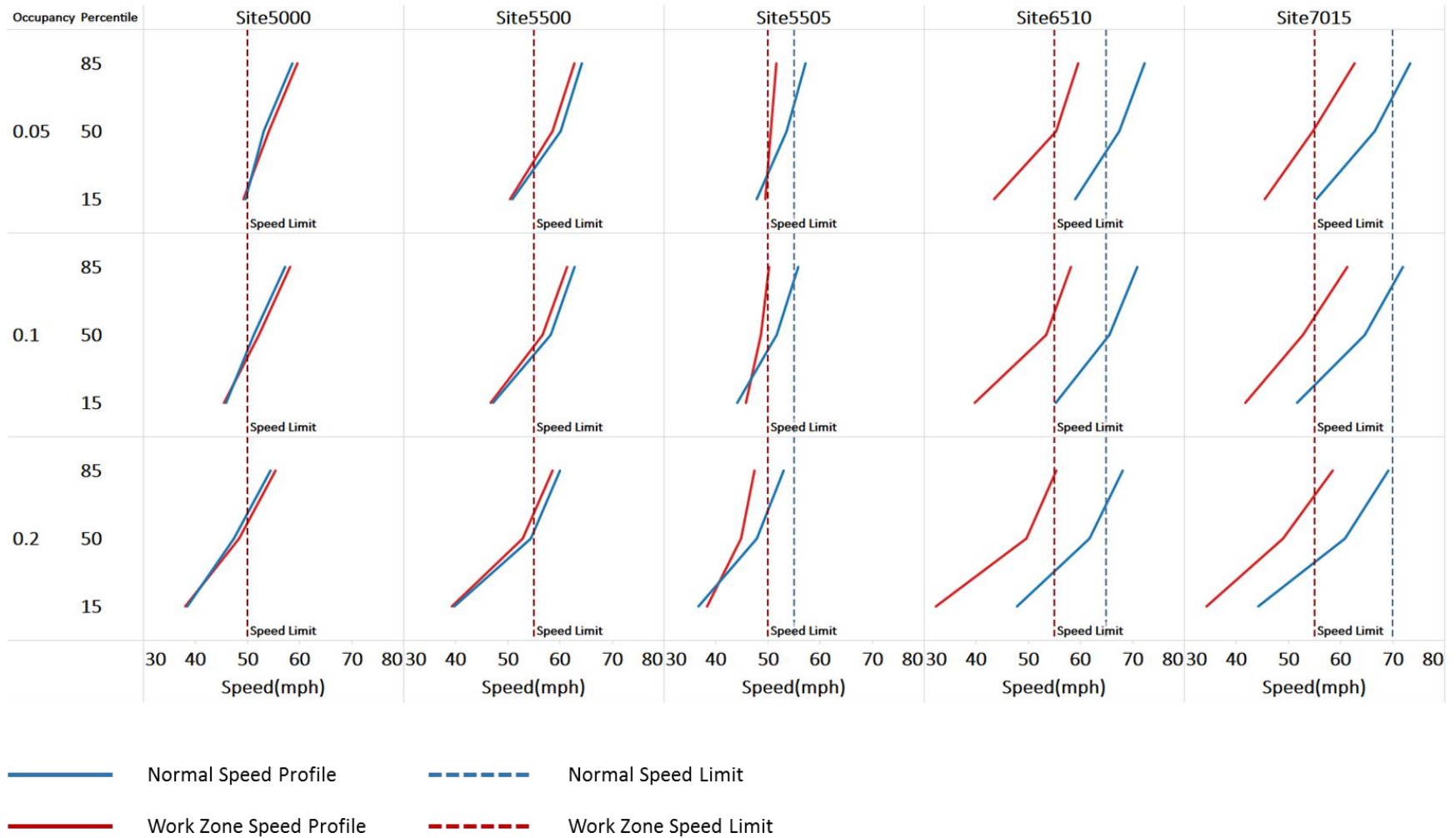
Figure 18. Impacts of speed limit reduction on estimated speed percentiles under different occupancy conditions

Figure 18 shows that, overall, as the magnitude of the speed limit reduction increases (from left to right in Figure 18), the speed curves generally show larger gaps between the work zone and non–work zone conditions. This result further indicates that drivers are reacting to the work zone speed limits and reducing their speeds accordingly.

As Figure 18 shows, the shapes of the speed distributions are quite similar, which suggests that drivers tend to behave similarly overall. The one exception was the location with a posted statutory speed limit of 55 mph and a work zone speed limit of 50 mph (column 3 in Figure 18). At this site, there was a greater reduction in speeds among the fastest drivers than the slowest drivers. This site also showed behavior at the 15th percentile that was inverse to the behavior observed at the other percentiles. This slowest group of drivers tended to maintain a certain speed regardless of whether a work zone was in place. This may be due to the fact that this group had the smallest sample size among all the groups; because there is only one case in this group, the results may be site specific rather than general for all the work zones with this speed limit reduction strategy.

It is also noteworthy that the site where speeds were reduced from 65 to 55 mph (column 4 in Figure 18) exhibited larger differences than the site where speeds were reduced from 70 to 55 mph (column 5 in Figure 18). The reason may be the high driving speeds under normal conditions at Site 65/55. From Figure 18, we can observe that the estimated normal speed profile of Site 65/55 is already larger than that of Site 70/55, but the estimated work zone speed profiles are similar between the two sites. Thus, the gap between the normal and work zone speed profiles appears larger for Site 65/55. This can also be seen in Figure 15, where one work zone in the 65/55 group has much higher normal speeds than the other groups, while one work zone in the 70/55 group has much lower work zone speeds than the other groups. Uncommon driving behavior in one or two cases may have influenced the overall results due to the lack of cases in each category.

Regarding the impact of occupancy on speeds, Figure 18 shows the different speed profiles under 5%, 10%, and 20% occupancy conditions. By comparing each row in Figure 18, it can be seen that all speed profiles for each site have the same shape as occupancy increases. This result indicates that the overall speed variation may be not affected by changes in occupancy when the occupancy is less than 20%. However, the estimated speed percentiles also shift a little to the left as occupancy increases, which means that drivers slow down a little to respond to the increasing traffic density.

CHAPTER 6. SUMMARY AND RECOMMENDATIONS

Work zone safety continues to be an important concern for transportation agencies, particularly as an increasing emphasis is placed on improving the sustainability and lifespan of the transportation infrastructure. Historically, speed control in work zones has been an area of great concern because speeds have been shown to impact both the frequency and severity of crashes involving both motorists and workers. To improve work zone safety, many transportation agencies have established temporary reduced work zone speed limits on select high-speed segments. This project examined the impacts of work zone speed limit policy on driver speed selection in work zones.

Conclusions

In this project, speed data from nine study locations were compared at various levels of fidelity using data for both the work zone and normal periods. Data reduction and quality assurance/quality control techniques were utilized to extract and reduce very large databases. Quantile regression models were estimated to examine how speed distributions varied depending on whether a work zone was in place and what the posted statutory and work zone speed limits were. Separate models were estimated for 15th, 50th, and 85th percentile speeds.

The results from the regression showed that, in general, drivers maintained good compliance with both the original speed limit and the work zone speed limit. However, compliance was found to vary from site to site, which is likely reflective of important unobserved factors related to the work zone's characteristics or to the specific road segments. Overall, reduced work zone speed limits helped to reduce drivers' speeds when they were traveling through a work zone.

Limitations

There are also some limitations to this analysis that warrant noting. One is the lack of data for every permutation and combination of speed limit reduction. Data were collected at only a finite number of work zones, resulting in only one work zone for several speed limit combinations and no work zones for some combinations. For example, there were no work zones with a normal speed limit of 70 mph and a reduced speed limit of 65 mph, 60 mph, and so on. The different speed limit reduction strategies could not all be practiced in one work zone in the real world, so therefore the effects identified in this project are site-specific. Given that extensive data are collected on an annual basis in a series of high-priority work zones, subsequent research that considers additional work zones can provide further information to help inform work zone speed limit policy decisions.

Another limitation is that this project only assumed the most conservative normal and work zone time periods by utilizing all the available data sources. There is a need to consistently mark the location, time, and type of work zone activities to successfully conduct any large-scale impact analysis. Nevertheless, this project indicated some effects of speed limit reduction, even if the

findings could not generally be applied to all situations. Improvements in data resolution and availability, especially in terms of a traffic control diary, will make future studies more precise.

Moreover, high-resolution historical weather data were not fully available for this project. Because weather is usually considered to be an important factor in drivers' speed choice, including weather variables in the modeling could improve the model.

It should also be noted the present research couldn't include the exact type of work activity due to data inconsistencies. This affects the transferability of results to other sites, and it is highly recommended that work zone activity type should be included in future research to further corroborate the above results.

Recommendations

Overall, this project proposed a methodology for developing a set of guidelines for fixing work zone speed limits based on a work zone's unique characteristics and the trends observed in the speed limit reduction strategies examined in this research. After combining the results obtained from all the analyses, in general we recommend that speed limits be reduced in work zones with high speed limits, while the speed limit should be kept to at least 55 mph to avoid affecting the capacity.

In addition to the statistical analysis for setting speed limit reduction strategies, this study could also be extended to include real-time data. Figure 19 demonstrates a near-real-time work zone performance analysis tool created to analyze 2016 work zones for the Iowa DOT. This tool could utilize speed data updated every 20 seconds and video images updated every 5 minutes to show the near-real-time speeds.

In addition to the speed heat map shown in Figure 19, Figure 20 demonstrates another function of the analysis tool: generating daily slowness cumulative distribution functions (CDFs), i.e., cumulative frequency curves of 1/speed.

It can be observed that, for all sensors, slowness on December 4 (a snow day) had a different pattern than on any of the other days. This pattern can be confirmed by Figure 19, where the red cluster on the speed heat map indicates a slowdown situation and the corresponding video image shows snow on the road. Thus, these curves provide a more straightforward, quicker way than statistics to discern latent impacts on speeds. Furthermore, when the exact working dates are available, the impacts of speed limit reductions on slowness can be examined more quickly and directly by observing the changes to these curves.
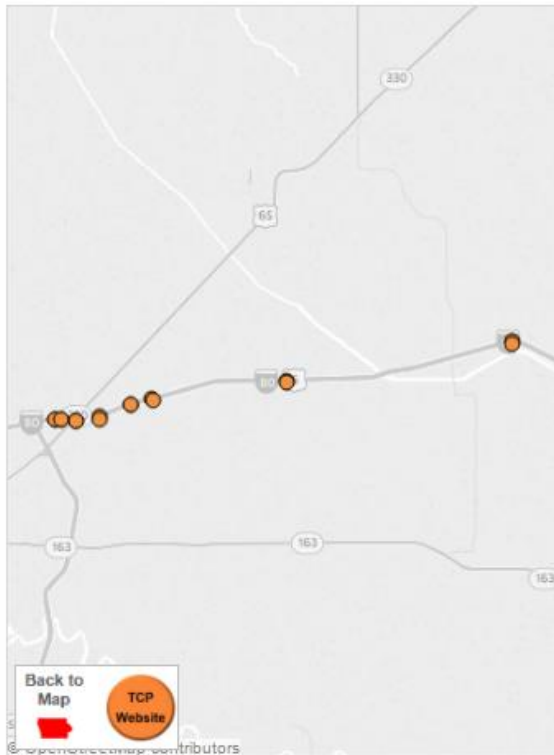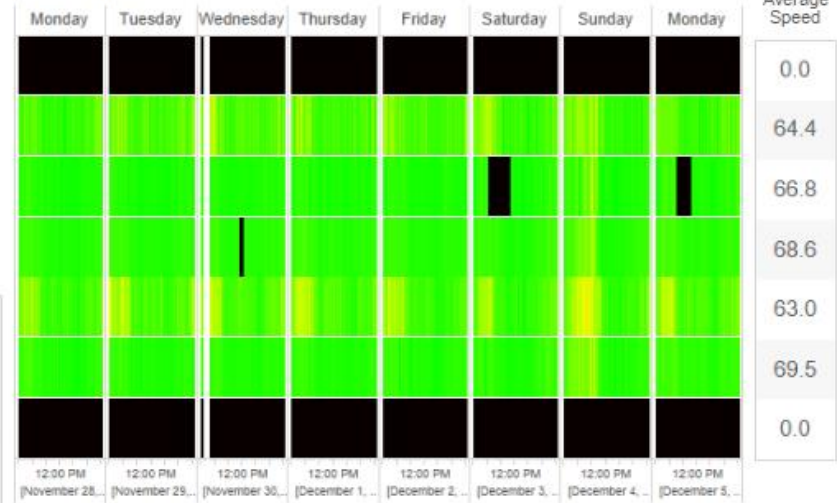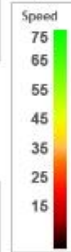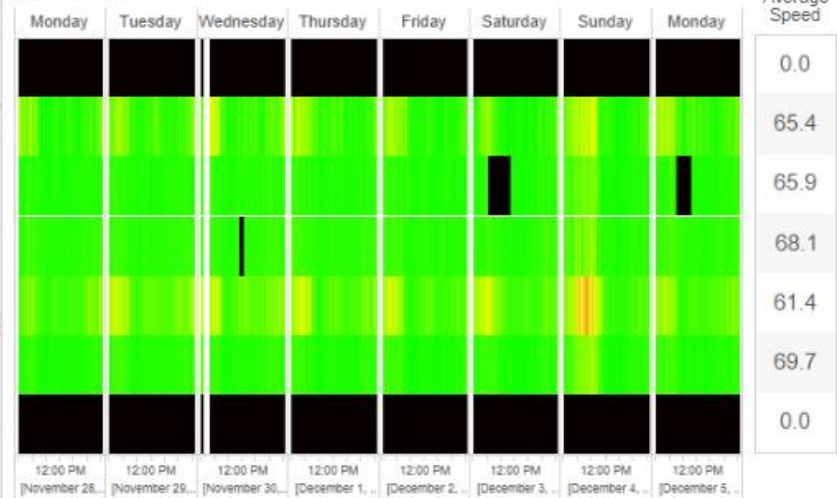
Figure 19. Near-real-time speed heat map in one work zone
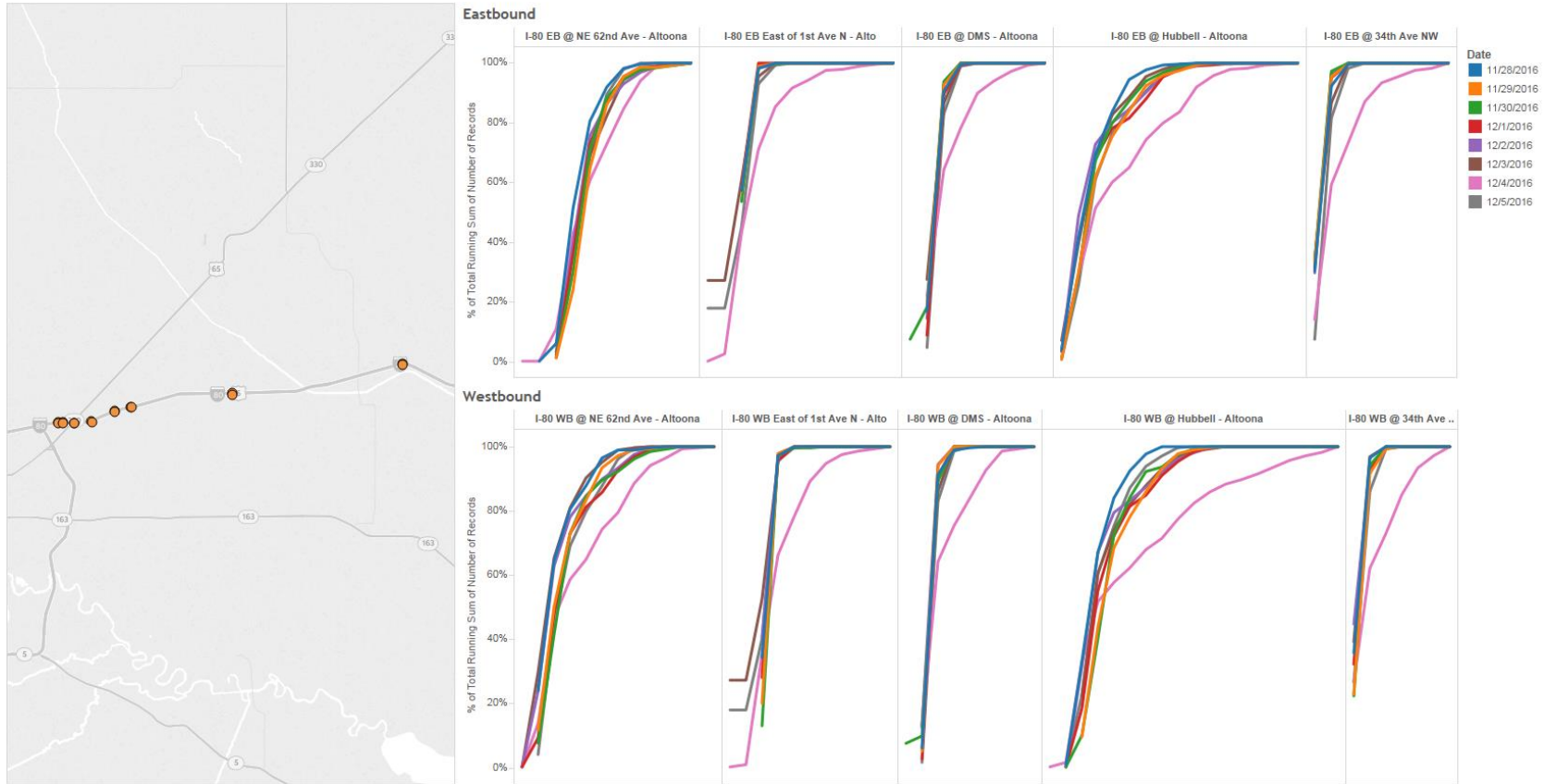
Figure 20. Daily cumulative density curves of slowness in one work zone

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