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Identifying Effects and Applications of Fixed and Variable Speed Limits

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16. Abstract

In Indiana, distracted driving and unexpected queues have led to an increase in the amount of back-of-queue crashes, particularly on approach to work zones. This report presents new strategies for the assessment of both transportation safety and traffic operations using crowd-sourced probe vehicle data and a speed laser vehicle re-identification scheme. This report concludes by recommending strategies for the placement of variable speed limits (VSL) adjacent to work zones and suggestions for future research.

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EXECUTIVE SUMMARY

IDENTIFYING EFFECTS AND APPLICATIONS OF FIXED AND VARIABLE SPEED LIMITS

Introduction

In Indiana, distracted driving and unexpected queues have led to an increase in the amount of back-of-queue crashes, particularly on approach to work zones. This report presents new strategies for the assessment of both transportation safety and traffic operations using crowdsourced probe vehicle data and a speed laser vehicle re-identification scheme. This report concludes by recommending strategies for the placement of variable speed limits (VSL) adjacent to work zones and suggestions for future research.

The first portion of this study characterizes the back-of-queue concerns using a new assessment technique based on crash reduction factors. Crash reduction factors are widely used by engineers for prioritizing safety investments. Work zones are routinely analyzed by the length and duration of queues. Queue detection warning technology has been growing in availability and reliability in recent years. Three years of crash data and crowdsourced probe vehicle data were analyzed to classify crashes as being associated with queueing conditions or free-flow conditions. In 2014, only 1.2% of the distanced-weighted hours of operation of Indiana interstates operated at or under 45 MPH. A three-year study on Indiana interstates indicates that commercial vehicles were involved in 87% of back-of-queue fatal crashes compared to 39% of all fatal crashes during free-flow conditions. A new measure of crash rate was developed to account for the presence and duration of queues: crashes per mile-hour of congestion. The congested crash rate on all Indiana interstates in 2014 was found to be 24 times greater than the uncongested crash rate. Queues were found to be present for five minutes or longer prior to approximately 90% of congestion crashes in 2014. This information shows the importance of developing technology that can warn motorists of traffic queues.

Lastly, portable variable speed limit signs were deployed adjacent to a work zone in southern Indiana and an empirical analysis was done to develop best practices. This report presents a new methodology to evaluate the impact of variable speed limit signage based on individual vehicle-matching. The speeds and speed changes of these matched vehicles were used to analyze individual driver response to the variable speed limits. The new vehicle-matching methodology showed that after observing a 15 MPH speed drop on a single variable speed limit sign for cars (10 MPH for trucks) over three separate variable speed limit signs, cars reduced their speed by a median of 3.3 MPH (2.1 MPH for trucks). Overall, 3.5% of cars and 11.1% of trucks complied with the 55 MPH speed limit after observing three variable speed limit signs. Using a similar assessment strategy, variable speed limit signs were deployed in pairs and evaluated. Sign pairs consist of two portable variable speed limit signs in one location, one on each side of the roadway. When assessing a similar 15 MPH speed drop (10 MPH for trucks) it was discovered that three sets of paired signs are more effective in slowing down vehicles, with reductions of 4.7 MPH for passenger vehicles and 2.7 MPH for trucks relative to three individual signs. Compliance rates after the three sign locations were 3.3% and 9.1% for cars and trucks, respectively.

Findings

The final recommendations gathered for this study include:

- Paired variable speed limit signs outperform single signs when attempting to slow vehicles.
- Operators and managers should use at least three pairs of variable speed limit signs to obtain any tangible reduction in driver speeds.
- Variable speed limit signage should be placed upstream of the expected back-of-queue location.
- Placement of variable speed limit signage can be actively monitored using crowdsourced probe vehicle data.
- Future work should be considered including automating the speed limits on the variable speed limit signage.

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INTRODUCTION

This report focuses on the implementation and assessment of the first variable speed limit system in the State of Indiana. The report consists of three modules:

1. A study investigating back-of-queue crashes on Indiana interstates,
2. A study developing a systematic approach to investigate the placement of static speed limit signs and possible locations for variable speed limit signage, and
3. A study focusing on the implementation and assessment of a variable speed limit system adjacent to an active work zone on Interstate 65 south of Indianapolis.

The first study investigating back-of-queue crashes in Indiana serves as a motivation for the assessment of static and variable speed limit placement and effectiveness. The second study uses modern data sources to systematically investigate static speed limit locations. The third study uses a new vehicle-matching technique to determine the effectiveness of variable speed limit signs.

1. BACKGROUND

An extensive review of literature was done for each of the three studies outlined above. While there is vast research regarding crashes and road safety, research relating to the safety risks of congestion was the focus of the first study. The second study considered previous work concerning the placement and assessment of static speed limit signs. Lastly, the variable speed limit review focused on data collection and analysis strategies as well as previous variable speed limit studies.

1.1 Back-of-Queue Crashes (Motivation)

Congestion impacts both safety and mobility on the roadway. There is a debate whether congestion improves safety by causing lower speeds or degrades safety by increasing the number of potential opportunities for crashes. Part of this project included the study of historical crash data to determine crash rates during congested and uncongested traffic conditions on the interstates of Indiana. The purpose of this first study was to provide better understanding of safety risks due to congestion and help engineers prioritize and evaluate safety and mobility improvements.

There are two main types of crashes that occur in association with congestion. First, there are the low speed crashes that occur within a queue. It is generally accepted that these crashes are of low severity. The second type of congestion-related crash is the back-of-queue crash, which typically involves a vehicle traveling at a higher speed striking a vehicle traveling at a lower speed. These crashes are often high severity and most often occur along backward-forming shockwaves. As an example, Figure 1.1 is an image of a back-of-queue crash on I-70 Westbound on the evening of November 13, 2015. A little after 7 PM, construction crews began taking a lane in the westbound direction for a work zone at Exit 123, causing both forward- and backward-forming shockwaves. At 8:17 PM, a severe back-of-queue crash occurred at mile marker 127. The crash involved 14 vehicles and resulted in a fatality. The crash and smoke from a coal truck fire in the westbound direction caused queuing and corresponding crashes in the eastbound direction of I-70. The westbound direction was closed for clean-up and investigation purposes. As vehicles were diverted to Indiana State Route 1, a significant queue built upstream of Exit 137. The incident caused a full closure for about 12.5 hours, degradation of interstate mobility.

Agencies are concerned with the effect of the roadway and traffic conditions on safety since these are factors that can potentially be impacted via infrastructure improvements and operational changes. As such, there has been significant research and studies done on road safety. When safety is a concern, crash rates are the most common performance measure used by agencies and researchers. The *Highway Safety Manual* (AASHTO, 2010) defines crash frequency as the number of crashes over a period of time, usually a year. Crash rate is defined as the crash frequency of a period of time divided by the exposure in that same time period. Exposure is the total of all opportunities for a crash to occur, whether or not a crash actually occurs. The *Highway Safety Manual* refers to exposure as a measure of volume but, over the years, researchers have used a number of different ways to measure exposure, such as induced exposure (Carr, 1969; Chapman, 1973; Kirk & Stamatiadis, 2001; Stamatiadis & Deacon, 1997; Thorpe, 1964) and volume-based exposure (Brodsky & Hakkert, 1983; Elvik, Erke, & Christensen, 2009; Garber & Ehrhart, 2000; Harwood, Bauer, & Potts, 2013; Jovanis & Chang, 1986; Kononov, Reeves, Durso, & Allery, 2012; Martin, 2002; Mensah & Hauer, 1998; Pal & Sinha, 1996; Potts, Harwood, Fees, Bauer, & Kinzel, 2015; Quddus, Wang, & Ison, 2010; Shefer & Rietveld, 1997; Song & Yeo, 2012; Yeo, Jang, & Skabardonis, 2010). The volume-based exposure techniques and variations on those are the most relevant to this study.

A volume measure of some sort is the most common basis for exposure. Some studies use traffic counts recorded by infrastructure technology. Other studies use annual average daily traffic (AADT). Mensah and Hauer (1998) advise caution when using AADT as a measure of exposure. AADT is an aggregate measure and is not appropriate when considering the traffic conditions at the time of a crash. Specifically, when studying the effect of congestion on safety, an average measure of volume does not adequately represent the traffic conditions.

Regardless of the source of the volume data, there are three types of volume-based measures that are the most common in safety studies. One study used volume for calculated crash rates for different levels of severity, finding that property-damage-only and injury crash rates were highest when traffic was lightest (Martin, 2002). Another study used AADT-based hourly volumes to estimate the potential for conflicts (Elvik et al., 2009). A third study modeled crash severity using flow as a

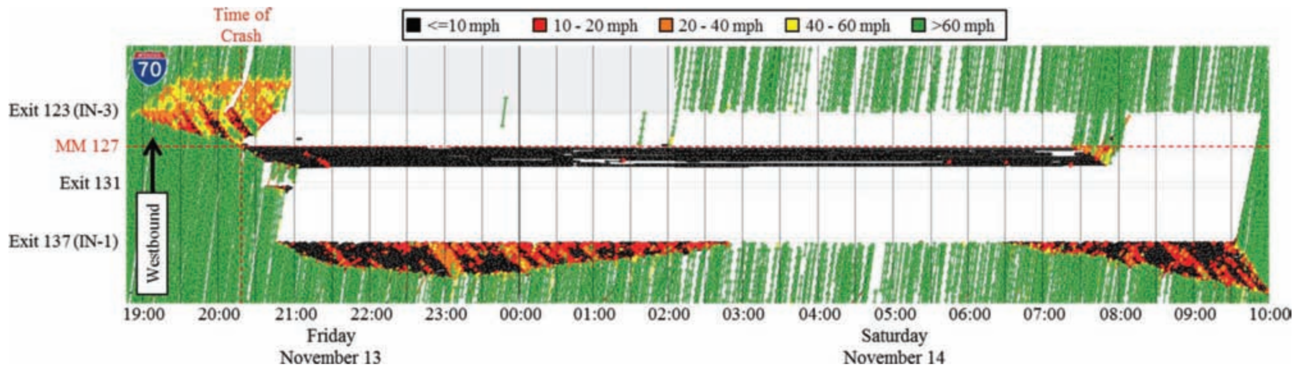


Figure 1.1 Probe vehicle trip trace diagram for the fatal, back-of-queue, work zone crash on I-70 westbound on November 13, 2015.

variable in addition to speed and delay caused by congestion (Quddus et al., 2010). Vehicle-miles traveled (VMT) is a widely accepted and often used measure of exposure when calculating crash rates longitudinally along corridors (Jovanis & Chang, 1986; Pal & Sinha, 1996; Potts et al., 2015; Song & Yeo, 2012; Yeo et al., 2010). Lastly, density (vehicles per mile), is frequently used in safety studies directly concerned with the effects of congestion on crash rates (Brodsky & Hakkert, 1983; Harwood et al., 2013; Kononov, Reeves, et al., 2012; Shefer & Rietveld, 1997). A common finding amongst safety studies using density as exposure is the parabolic, or U-shaped, relationship between density and crash rates, where the highest crash rates occur at low densities (mostly single vehicle crashes) and high densities (mostly multi-vehicle crashes). Some less common but no less viable measures of exposure are the standard deviation of speed between vehicles (Garber & Ehrhart, 2000) and the volume-to-capacity ratio at the time of the crash (Zhou & Sisiopiku, 1997).

Recently, with the greater availability and reliability of real-time traffic condition data, queue detection and alert systems are becoming more common. One system focused on specific highway sections designated as high-crash locations (Hourdos, Garg, Michalopoulos, & Davis, 2006). This detection system used a number of factors, such as average speed, different forms of traffic density, headway variability, acceleration noise, etc., to calculate the crash likelihood in real-time. The combination of crash likelihood model and detection algorithm succeeded in detecting 58% of crashes during the study. Another detection system was developed for the Indiana Department of Transportation (INDOT) and covered the entire interstate system instead of small sections (Li et al., 2015). This system uses only the difference between the space mean speeds of two adjacent roadway segments. If the average speed of an upstream segment is significantly higher than the average speed of the immediate downstream segment, an alert is made visible to dispatchers and emergency responders.

Of most relevance to the first study in this project is a study by University of California-Berkeley's Transportation Research and Education Center (Song & Yeo, 2012; Yeo et al., 2010). In this study, four different traffic states were considered. The four traffic states are based on speeds upstream and downstream of a crash and use 50 MPH as a threshold for congestion, using VMT and vehicle-hours traveled (VHT) as exposure. In this study, the researchers found that crash rates for the three different congestion states were about 5 times greater than the crash rate for the free flow state.

1.2 Static Speed Limits

Transportation engineers have limited mechanisms to influence traffic patterns on interstate highways. Capital projects, including reconstruction, lane widening, resurfacing, or adding intelligent transportation system (ITS) infrastructure, can be effective, but also costly. One low cost item that engineers can adjust is the placement and value of speed limit signs. This has led to numerous projects and research in the area of speed and speed limits. Many research projects have been designed to characterize the effect of speed limits, both in the driver behavior area as well as from a traffic safety perspective (Brewer, Pesti, & Schneider, 2006; Finley, 2011; Garber & Graham, 1990; Haglund & Aberg, 2000). Recently, much of the focus on speed limit studies has been encouraged by a rising interest in variable speed limit signs (Papageorgiou, Kosmatopolous, & Papamichail, 2008; USDOT, 2012). Variable speed limits have many theoretical advantages including increased traffic flow, less stop-and-go traffic during congested conditions, and safety benefits during adverse weather conditions (Jones et al., 2011). Ideal sign placement is currently one of the questions regarding the implementation of variable speed limits. Sign placement questions also exist for static speed limit signs. The motivation of the second study in this report is to propose a systematic approach using real-time crowdsourced probe vehicle data to analyze the placements of speed limit signs and to characterize drivers' responses to those placements.

In addition to typical posted speed limit changes, another interest to engineers is the effect of changes in posted speed limits on traffic entering and exiting a work zone. Heavy work zone police enforcement was shown to only reduce travel speeds by between 4 and 5 MPH (Wasson et al., 2011). A critical aspect of assigning variable or static speed limits in a work zone is understanding the impact that the sign will have on traffic.

1.3 Variable Speed Limits

When a speed study is evaluating a traffic control device, most often data are collected during free-flow conditions. Temporal (before and after) and spatial (upstream and downstream) variations in speed are often studied. Some common performance measures include average speed, 85th percentile speed, speed variance or standard deviation, and percentage of high speed vehicles. When evaluating a speed control or regulation device, the compliance rate is an important measure of effectiveness. Solomon (1964) found high compliance rates in his 1964 study of highways in the U.S. It is important to note that today's vehicles and drivers have different characteristics from those in 1964. Solomon's study considered 2-lane highways and 4-lane divided highways, only one of which had full access control like an interstate. For these reasons, the compliance rates found by Solomon do not match those found in this study. Various technologies and equipment have been used for data collection in speed studies. The most common include laser or radar speed measurement devices, various in-pavement detectors, Bluetooth detection technology, and pneumatic switches.

2. DATA SOURCES

2.1 Spot Speed vs. Space Mean Speed Data

One technique used in this study is vehicle-matching. Previous studies have developed and used methods for vehicle-matching using various technology (Abdukhai & Tabib, 2003; Bennett & Dunn, 1995; Coifman, 1998; Ernst, Krogmeier, & Bullock, 2011; Lin & Tong, 2011; Meyer, 2003; Oh, Ritchie, & Jeng, 2007; Wasson et al., 2011). The majority of these studies use space-mean-speeds or travel times along a roadway segment in their evaluations. However, one study used a vehicle-matching technique to develop deceleration curves for different vehicle classes on a ramp (Lin & Tong, 2011). No previous studies have used vehicle-matching to compare spot speeds and evaluate speed regulation devices. Some examples of the regulation devices evaluated in previous studies include speed radar cameras (Al-Ghamdi, 2006; Benekohal, Chitturi, Hajbabaje, Wang, & Medina, 2008; Oei, 1996), police presence (Al-Ghamdi, 2006; Wasson et al., 2011), speed-activated warning signs (Brewer et al., 2006; Mattox, Saradua, Ogle, Eckenrode, & Dunning, 2007; Oei, 1996; Santiago-Chaparro, Chitturi, Bill, & Noyce, 2012; Woo, Ho, & Chen, 2007), static speed limits (Agent, Pigman, & Weber, 1998; Finley, 2011; Binkowski, Maleck, Taylor, & Czewski, 1998; Remias, Mekker, McNamara, Sturdevant, & Bullock, 2015; Thornton & Lyles, 1996), and variable speed limits (Edara, Sun, & Hou, 2013; Habtemichael & de Picado Santos, 2013; Kononov, Durso, Reeves, & Allery, 2012; Lu & Shladover, 2014; Lu, Varaiya, Horowitz, Su, & Shladover, 2011; MDOT, 2004; Riffkin, McMurty, Heath, & Saito, 2008; Weikl, Bogenberger, & Bertini, 2013). These studies are evenly split between work zone and non-work zone speed regulation. Lu and Shladover (2014) provide a comprehensive review of the practice and theory of VSLs. Another study (Kononov, Durso, et al., 2012) proposes an algorithm for setting VSLs intended to slow traffic prior to reaching congestion. A number of studies have evaluated the use and operation of VSLs on urban highways (Habtemichael & de Picado Santos, 2013; Lu et al., 2011; Weikl et al., 2013) and in highway work zones (Edara et al., 2013; MDOT, 2004; Riffkin et al., 2008).

A number of different data sources were used for the various parts of this project. Crowdsourced probe vehicle data acted as the backbone and were supplemented with crash data and speed laser data where appropriate. All data sources have been subjected to quality control measures both in-house and by other parties.

2.2 Probe Vehicle Data

Commercially available crowdsourced probe vehicle data have introduced a new tool that engineers and planners can use to evaluate the road network. Crowdsourced data are speed information collected from GPS devices, cellular phones, or vehicle telematics. This information is then aggregated to predefined road segments and an average speed is given to preserve driver anonymity. These data are given as a minute-by-minute average speed over a predefined road segment. There are two possible segmentation schemes. The first is based on Traffic Message Channels (TMC) and is the older of the two. The TMC segments range from 0.5 to 15 miles in length. The second scheme, XD, is proprietary, with segment lengths ranging from 0.5 to 2 miles. The XD scheme has greater resolution but is only available from January, 1, 2014, and later. Using these data, performance measures have been created that visually depict the performance of an entire roadway over a period of time (Brennan et al., 2013; Lomax, Shrank, & Eisele, 2011, 2012; Remias, Brennan, Day, et al., 2013; Remias, Brennan, Grimmer, et al., 2012, 2013). Figure 2.1 shows an example speed profile from the 2012 Indiana Mobility report that characterizes speed on southbound I-65 over one year (Remias, Brennan, Grimmer, et al., 2013). Changes in the speed profile as a result of speed limit changes can be seen in numerous locations in this figure. Callouts 'i' and 'ii' in Figure 2.1 show two examples where the speed limit increases to 70 MPH. As a result of the speed limit change, an increase in the '65+' speed profile range can be seen. This visualization shows the concept of analyzing speed limit effectiveness, however there needs to be a clear approach to understanding driver tendencies during speed limit changes.

Speed data from crowdsourced probe vehicles were also used in a study to assess traffic conditions when a crash occurred. Figure 2.2a shows a sample of speed and trajectory data from probe vehicles before it is aggregated into space mean speeds. Specifically, these time-space diagrams are for probe vehicles passing through a section of I-65 northbound on February 2,

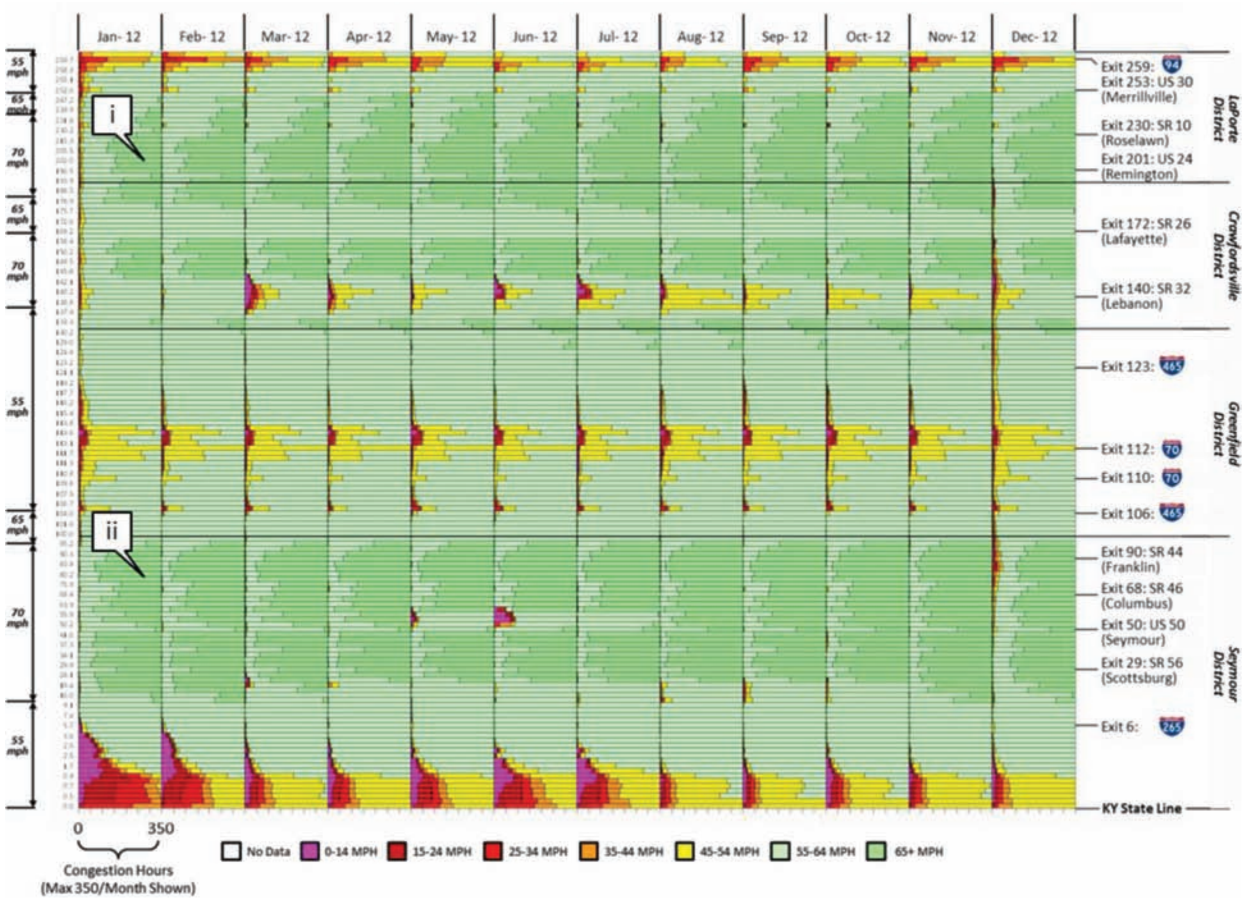


Figure 2.1 I-65 southbound speed profile diagram (Remias, Brennan, Grimmer, et al., 2013).

2015, before, during, and after a crash (Figure 2.3). The incident began when a trailer jackknifed due to slick road conditions at about 8:30 AM (labeled *i* in Figure 2.2). A queue began to form, with vehicles in the queue moving at 10 to 20 MPH until 9:40 AM when lanes were restricted to facilitate clean up. Within this queue, vehicles moved at less than 10 MPH, if at all. At approximately 9:55 AM, the queue began to dissipate quickly and was almost cleared when a passenger vehicle struck a trailer at the back of the queue at 10:16 AM (*ii*). Prior to and upstream of the crash, the queue existed for more than 90 minutes. The back-of-queue crash (*ii*) caused the queue to reform with speeds of less than 10 MPH lasting for more than 2 hours after the crash and extending nearly 10 miles behind the crash. Figure 2.2b shows the development of the queue using the real-time shockwave boundary detection tool on the INDOT web page (Li et al., 2015).

These new data sets provide the ability to precisely characterize traffic flow regimes with fidelity that has historically only been discussed in an academic context. Figure 2.4 depicts the shockwave diagram (Li et al., 2015) developed from the time-space diagram (Figure 2.2). Before the back-of-queue crash at 10:16 AM, the queue had a frontal stationary boundary, a backward-forming boundary propagating at approximately 1 MPH, and a backward-recovery boundary with a speed of 12 MPH. Just before the back-of-queue crash and because of the lane restrictions, the backward-forming boundary speed increased to 3.78 MPH. Before the first accident was cleared, the frontal-stationary boundary existed at mile marker 215, the site of the initial crash. However, with the back-of-queue crash, a new frontal-stationary boundary was formed at mile marker 213. In addition to backward-forming and backward-recovering boundaries, the queue from the secondary crash also had a rear-stationary boundary for a short time. Table 2.1 shows the duration and speeds of each of the 7 boundaries of the queue for this incident. In Figure 2.2 and Table 2.1, ω_n represents shockwave *n*.

2.3 Crash Database

Crash data were retrieved from the state crash database. Only crashes defined as being within the specified time frame (2012–2014) and as having occurred on an interstate were retrieved. Personal information, such as names and license plate numbers, were omitted. The crash data included the number of vehicles involved, the number of trailers involved, the number of injuries and deaths, whether or not construction was associated with the crash, the primary factor or cause, the manner of collision, information on the geometry of the road, etc. It should be noted that these crash

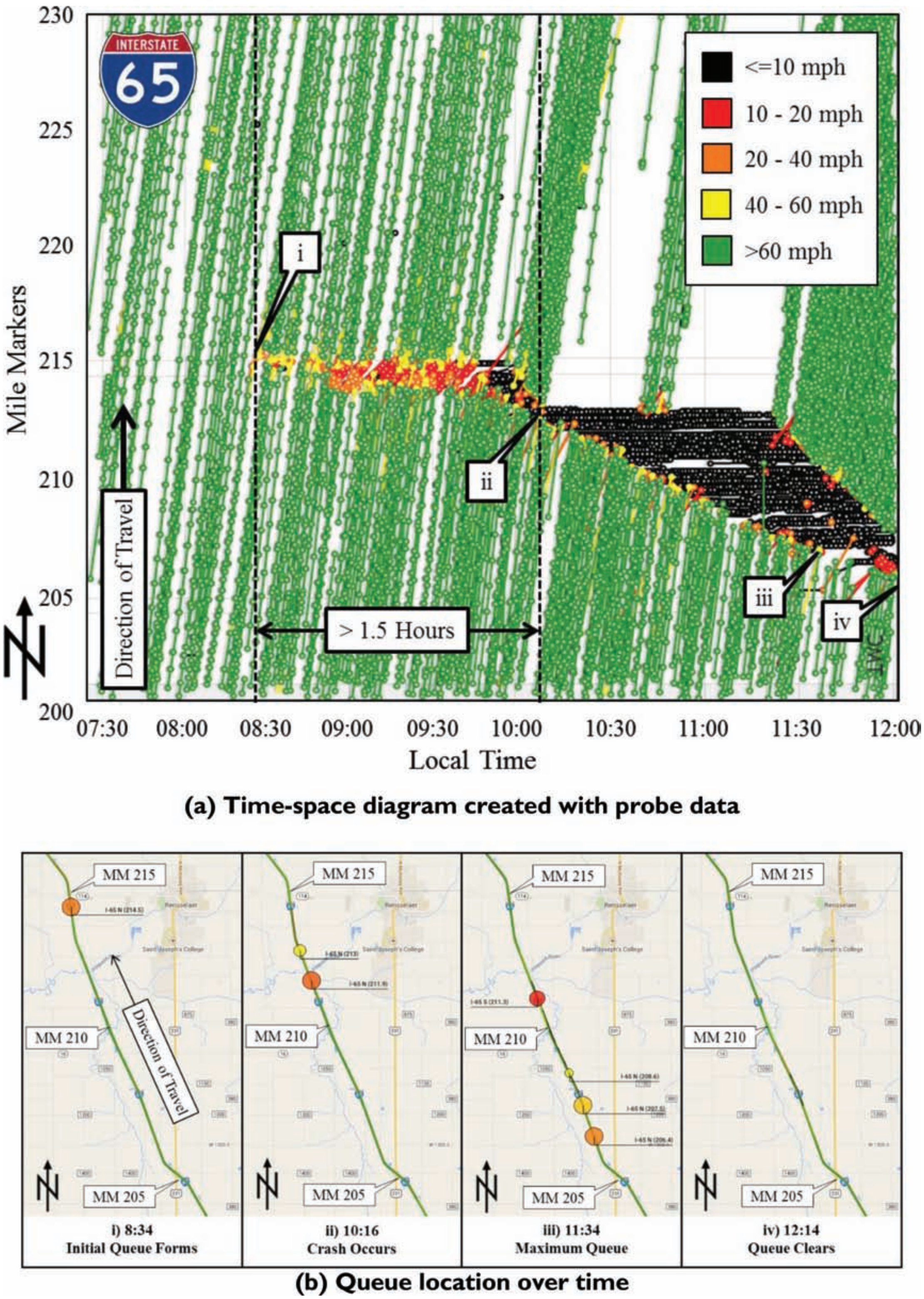


Figure 2.2 INRIX trip trace from February 2, 2015, crash on I-65.

data did not use the KABCO (K = fatal, A = incapacitating injury, B = non-incapacitating injury, C = possible injury, O = property damage only) scale of severity. The crash report data does not specify if the crash occurred during congested operations, if it was a secondary crash, or the cause of congestion. There are also no reliable data on concurrent roadside activities, such as stalled vehicles.

Figure 2.3 Back-of-queue crash on I-65 (February 2, 2015).

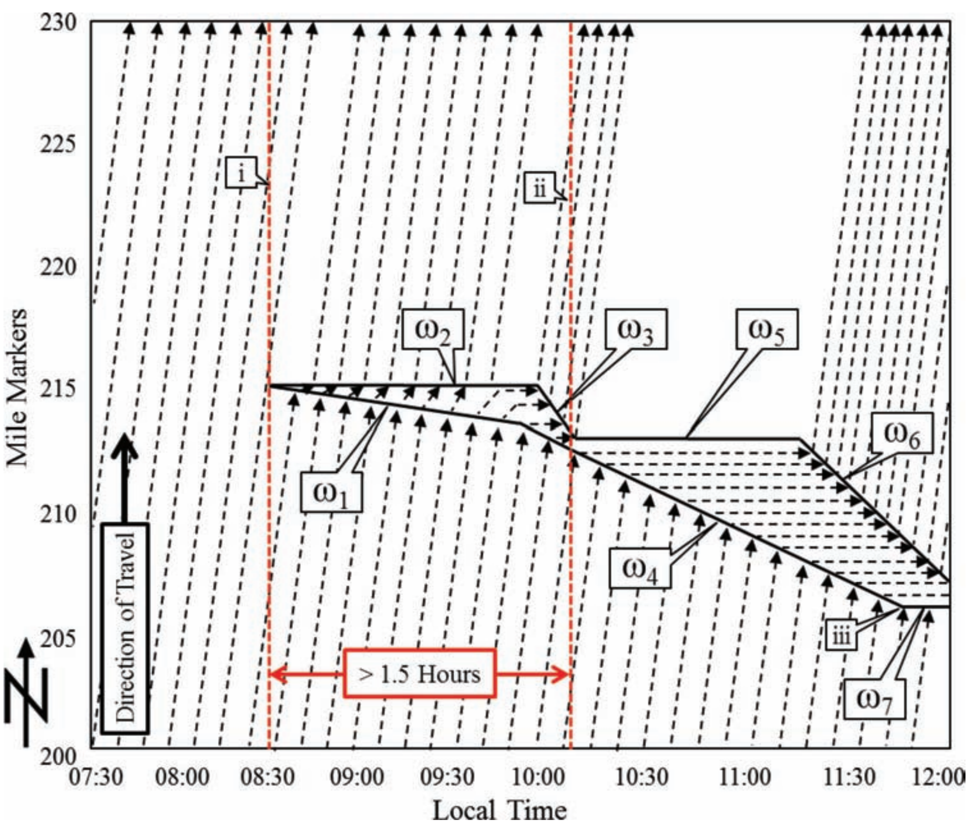


Figure 2.4 Shockwave diagram from February 2, 2015, crash on I-65.

Before being used in this study, the raw crash data had to be cleaned, which required extensive reading of the narrative to verify and correct database attributes. Any crash with an unknown or unreliable location was eliminated from the study data. Any crash that did not occur in the interstate travel lanes, such as on ramps, was also eliminated. Lastly, only crashes that occurred on interstates of the Interstate Highway System in Indiana were used, which includes I-265, I-465, I-469, I-64, I-65, I-69, I-70, I-74, I-80, I-865, I-90, and I-94. Interstate 275 was not included in this study due to lack of probe vehicle data and because its length in Indiana is only 3 miles.

2.4 Speed Laser Measurements

Two pieces of field equipment were used for the variable speed limit analysis. The VSL signs were used to set up different speed study scenarios upstream of the work zone. Laser speed measurement devices were used to collect spot speed data during those speed studies.

TABLE 2.1
Shockwave Boundaries from February 2, 2015, Crash on I-65

Shock-wave	Class	Duration (minutes)	Speed (MPH)
ω_1	Backward Forming	87	1.03
ω_2	Frontal Stationary	95	–
ω_3	Backward Recovery	10	12
ω_4	Backward Forming	115	3.78
ω_5	Frontal Stationary	40	–
ω_6	Backward Recovery	50+	7.2
ω_7	Rear Stationary	15+	–

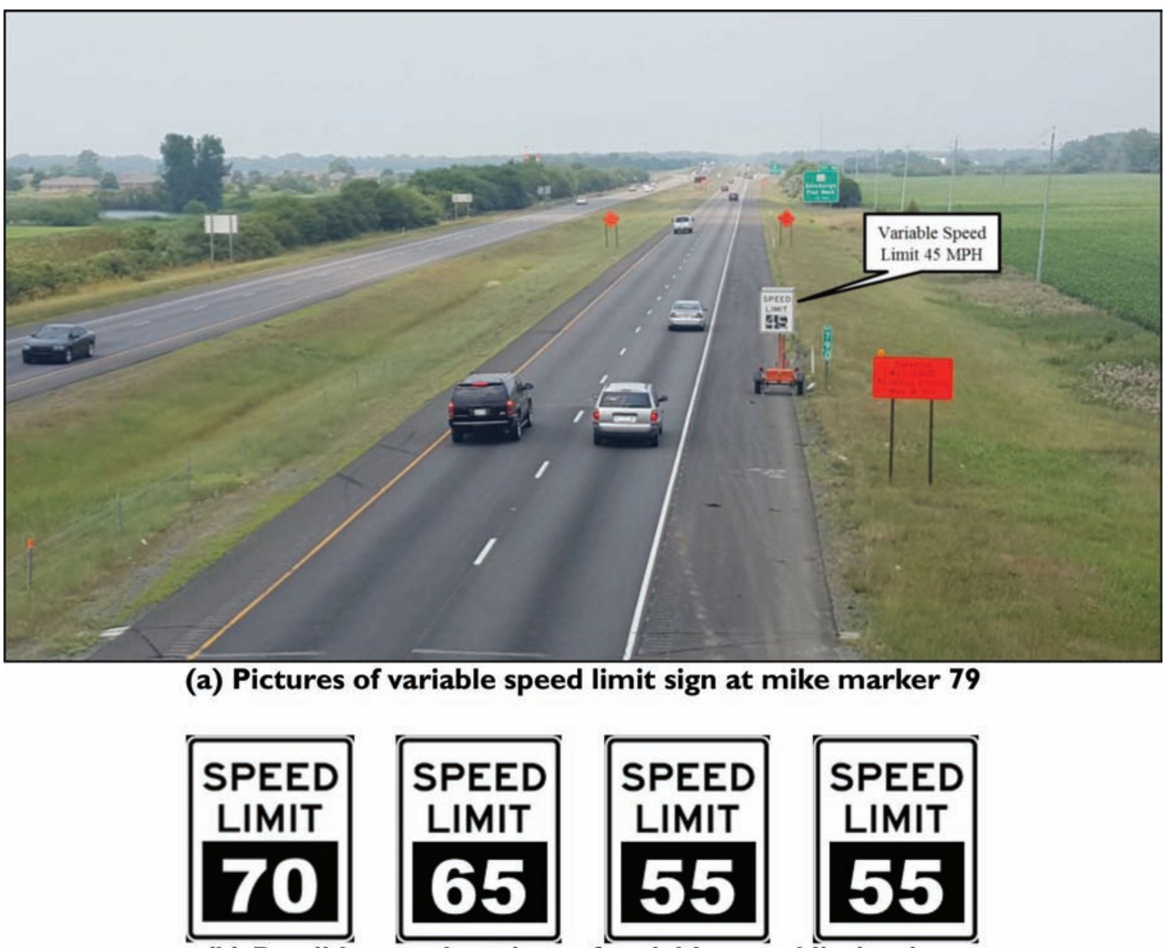
The sections below detail the features of the equipment and how they were used.

2.4.1 Variable Speed Limit Signs

For this project, eight VSL signs (Daktronics, 2007) were leased by INDOT. Each sign (Figure 2.5) has the capability to be programmed remotely. For the purpose of this study, the VSL signs were controlled manually. When data were not actively being collected, the signs were not set with any speed. When data were being collected, each sign could be individually programmed with short-term settings. This allowed researchers to collect data for a number of controlled study scenarios.

2.4.2 Laser Speed Measurement Devices

Spot speed measurements were collected with two speed measurement lasers. Each device has a sighting scope, transmit lens, camera lens, and receive lens. Each device also has a LCD touch screen that can be used to view captured vehicles and their corresponding speeds and distances or to view and change the



(a) Pictures of variable speed limit sign at mike marker 79

(b) Possible speed settings of variable speed limits signs

Figure 2.5 Variable speed limit signs deployed on I-65 northbound at mile markers 76.5, 77.5, and 79 in Indiana.

Figure 2.6 Sample photos of data collection.

device settings, such as location, user ID, and speed limits (Figure 2.6). Data for each capture are downloadable and include the vehicle's speed, distance, picture, video, timestamp, etc. These data can then be matched using the photos collected from the speed measurement lasers (Figure 2.7).

Figure 2.7 Example of vehicle-matching process.

3. STUDY 1: LONGITUDINAL INTERSTATE CRASH SUMMARY (MOTIVATION)

There is wide interest in and a need to understand crash rates associated with work zones and queued traffic. Historically, it has been very challenging to associate crash data with queued traffic. This study looks at opportunities to fuse crowdsourced probe data with crash reports to develop improved crash factors. This crash analysis was conducted in two parts. For the first part of this study, only fatal crashes that occurred in 2012 through 2014 were considered. The second part of the study looked in more detail at the 2014 crashes. This paper looked at the data in two cohorts. The longitudinal analysis of fatal crashes from 2012–2014 used the legacy TMC probe data that was available from 2012 onwards. Automated classification of 2014 crashes as occurring during congested or uncongested conditions was done using the newer, higher fidelity XD data with segment lengths approximately 1 mile in length.

3.1 Fatal Crashes

There were 230 fatal crashes total over the 3-year period of 2012–2014 on Indiana interstates. For each fatal crash, speed data from the crowdsourced probe vehicles prior to and downstream of the crash were analyzed to ascertain whether or not the crash occurred at the back of a queue. The probe data were augmented by the crash report narratives. Using this method, 30 of the fatal crashes were determined to be back-of-queue crashes. Figure 3.1 shows a Pareto chart of the durations of queues as seen in the probe vehicle data before each of the 30 fatal back-of-queue crashes. The durations range from not seen in the data at all (5 crashes) to 6 hours. The chart also shows which back-of-queue crashes were associated with construction and which involved commercial vehicles (trucks with trailers).

Figure 3.2 shows the total fatal crashes and number of fatal back-of-queue crashes by year. The number of back-of-queue crashes increases over the three-year period but the total number of fatal crashes does not. This could be attributed to the randomness in crash occurrence and there is insufficient data to reach a conclusion.

In this part of the study, different possible trends in back-of-queue fatal crashes were considered and evaluated. For example, a larger percentage of back-of-queue crashes than non-back-of-queue were associated with construction. This trend is perhaps influenced by the fact that work zones cause queueing more so than non-work zones. The most significant trend found in fatal back-of-queue crashes is the involvement of one or more trucks with trailers (Figure 3.3). Out of all fatal back-of queue crashes over the three-year period, 87% involved at least one truck. In comparison, only 39% of the non-back-of-queue fatal crashes involved at least one truck.

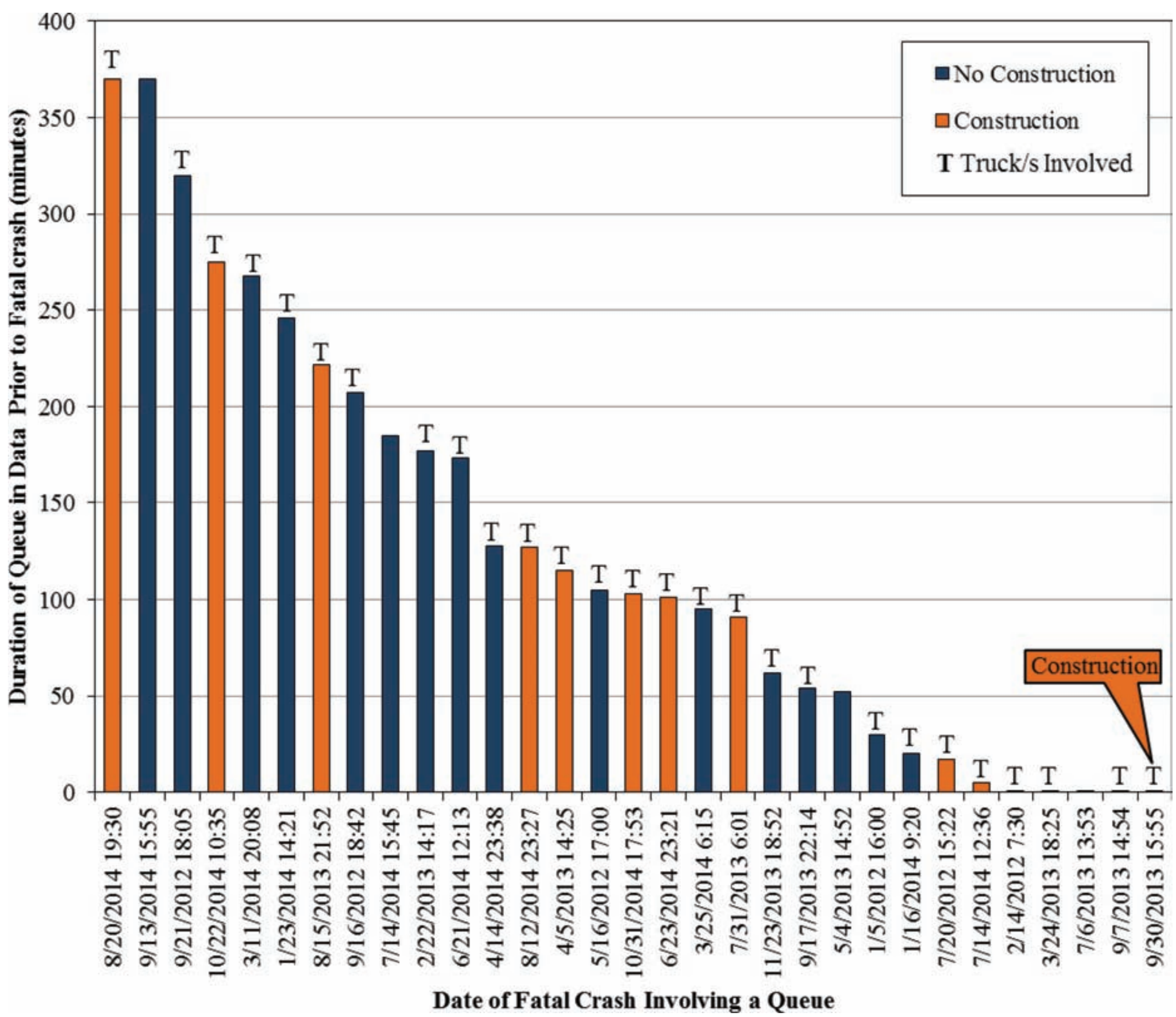


Figure 3.1 Duration of queue before fatal back-of-queue crash.

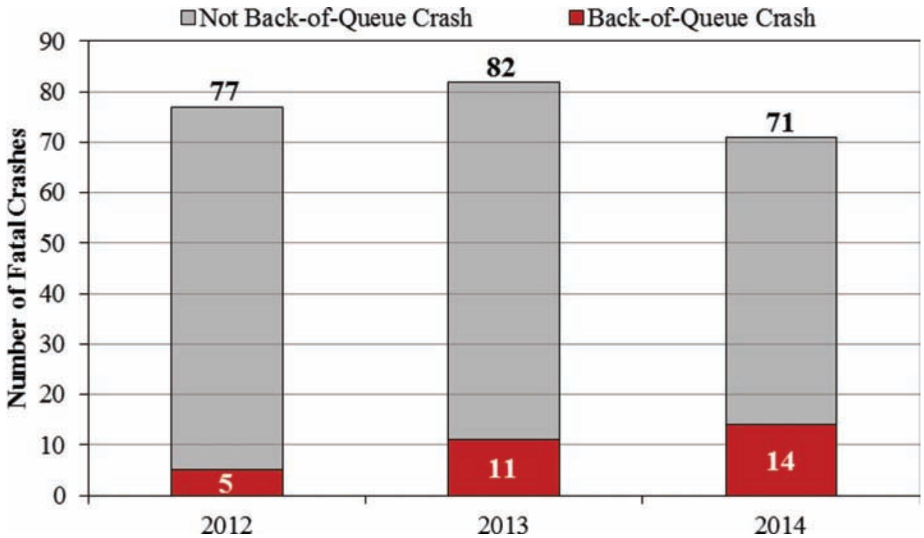


Figure 3.2 Number of fatal crashes on Indiana interstates by year.

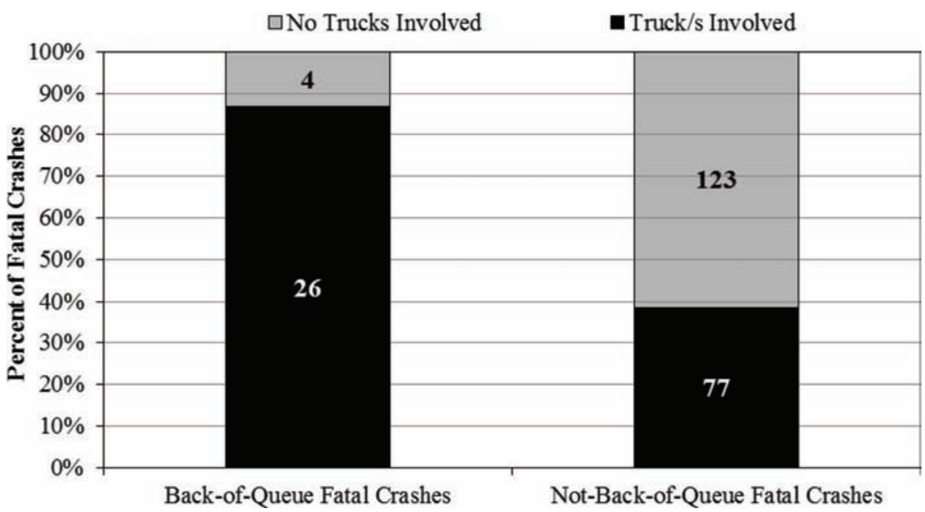


Figure 3.3 Percent of fatal crashes that involved trucks, 2012–2014.

3.2 Classifying Interstate Crashes in 2014

In the second portion of this study, crashes of all severities in 2014 were analyzed. Crash rates in congested and uncongested traffic conditions were the focus. In 2014, over 15,000 crashes occurred in the main lanes of travel on interstates in Indiana. Of these crashes, 3,448 were designated as having congestion involved, meaning the crashes occurred either at the back of or within queues. The following subsection will describe how a new unit of exposure was developed in order to define crash rate. Then, the process for determining whether a crash was associated with a queue is discussed. Lastly, the different crash rates will be discussed.

With the fatal crashes discussed in the section above, back-of-queue crashes were the primary focus. However, due to the large sample size when considering crashes of all severities, a secondary focus on crashes within the queue was added. It should be noted that there may be multiple shockwaves (i.e. multiple "backs" of queues) within a single congestion incident. Therefore, crashes that seemingly occur within the queue may have actually occurred at a shockwave boundary (a back of queue) that may not be readily visible without extensive analysis of the data. Due to time constraints and the quantity of data, this type of analysis was not feasible when considering all crashes in 2014.

3.2.1 Mile-Hours as Unit of Exposure

As discussed earlier, the vast majority of crash rates use volume, or some form of volume, as the unit of exposure. Many safety studies use AADT to derive volume. However, an aggregate measure of volume would be insufficient in this case since congested conditions are not adequately represented by average measures. Some safety studies use count data as measured by ITS infrastructure, such as detector loops. However, no agencies have statewide coverage, particularly in work zones or rural areas. Count stations are located infrequently enough that any volume measure would still be too aggregated. Also, even if ITS devices are installed near work zones, the temporary lane use patterns often degrade the quality of data. Therefore, a new unit of exposure was developed for this study that uses crowdsourced probe data.

A mile-hour of congestion is a measure of exposure that combines the duration of a condition with the length of roadway that the condition covered. For this study, the probe vehicle data were used in calculations of mile-hours of exposure. As described above, each segment has a length and an average speed every minute. A threshold of 45 MPH was chosen for defining congestion as this threshold has been used extensively in interstate-based studies in Indiana. The sum of hours when the segment operated at or under 45 MPH multiplied by the segment's length is defined as the exposure of that segment to congestion. For example, a queue of 1 mile in length that lasted for 1 hour would equate to 1 mile-hour of congestion.

Following this idea, the crash rate is defined by the number of crashes that occurred during a certain condition and the mile-hours of exposure to that condition. In this case, the uncongested crash rate (Equation 3.1) uses mile-hours of uncongested conditions and the congested crash rate (Equation 3.2) uses mile-hours of congested conditions.

$$\text{Uncongested crash rate} = \frac{\text{Number of crashes in uncongested traffic conditions}}{\sum_{n=1}^{N} \text{Segment length} \times \text{Number of uncongested hours}} \quad (3.1)$$

$$\text{Congested crash rate} = \frac{\text{Number of crashes in congested conditions}}{\sum_{n=1}^{N} \text{Segment length} \times \text{Number of congested hours}} \quad (3.2)$$

Figure 3.4a shows the total number of congested mile-hours on Indiana interstates in 2014. Congested conditions make up only 1.2% of the total possible mile-hours of operation. Interstates in Indiana experience congested conditions for a very small portion of yearly operation. Differences between rural and urban crash rates and traffic conditions were also considered. Using the metropolitan statistical areas, based on the United States Census, of Chicago, Indianapolis, and Louisville, the interstate segments and crashes were designated as either rural or urban. Four interstates were contained entirely in urban areas: I-265, I-465, I-865, and I-90. Interstate 469 was the only interstate that was entirely defined as rural.

Figure 3.4b shows the mile-hours of congestion as seen in Figure 3.4a split between rural and urban interstate segments.

3.2.2 Queue Duration Algorithm

In the first part of this study, the speed data and crash reports were analyzed in-depth manually. However, this process proved to be time-consuming and would not be feasible for the 15,000+ crashes that were considered for the second part of the study. Therefore, an algorithm was developed that would analyze the speed data from a large number of crashes and provide the duration of a queue in the data as an output.

The algorithm pulls archived speed data corresponding to the date, time, and location (roadway, direction, and mile marker) of a crash and checks for speeds below the threshold of 45 MPH both prior to and downstream of that crash. The movement of a shockwave boundary between interstate segments, which may cause minor fluctuations in the average speed was taken into account when designing the algorithm. For example, as a shockwave enters a segment, the average speed of that segment could vary between 50 MPH and 40 MPH. While 50 MPH is above the congestion threshold, it does not mean that the queue has disappeared. A buffer period of 10 minutes is used to account for shockwaves passing between segments and allows the algorithm to see a queue that existed across several segments. In summary, the algorithm evaluates the speeds prior to the occurrence of the crash in the segment that the crash occurred. If the segment had average speeds below 45 MPH immediately before a crash occurred, it is concluded that a queue existed prior to that crash. The algorithm then evaluates consecutive roadway segments downstream of the crash until the origin time and location is found. The difference between the origin time of the queue and the time of the crash is taken as the queue duration.

As stated above, 3,448 crashes were found to have been involved in a queue.

Figure 3.5a shows a Pareto chart of the queue durations for all crashes in 2014, similar to Figure 3.1 for the fatal back-of-queue crashes. Of the 15,117 total crashes, 3,448 or 22.8% were associated with congestion prior to the crash itself. Figure 3.1b is a cumulative frequency diagram of the duration of congestion prior to crash for each of the 3,448 congestion crashes. Approximately 90% of congestion crashes have a queue duration of 5 minutes or longer and 75% have a queue duration of 14 minutes or longer.

3.2.3 Crash Rates

Using Equations 1 and 2, uncongested and congested crash rates were calculated for each interstate and overall in 2014. Figure 3.6a shows both crash rates side-by-side for each interstate. The dotted lines represent the overall crash rates. Figure 3.6b and Figure 3.6c show the crash rates segmented by rural and urban interstate segments, respectively.

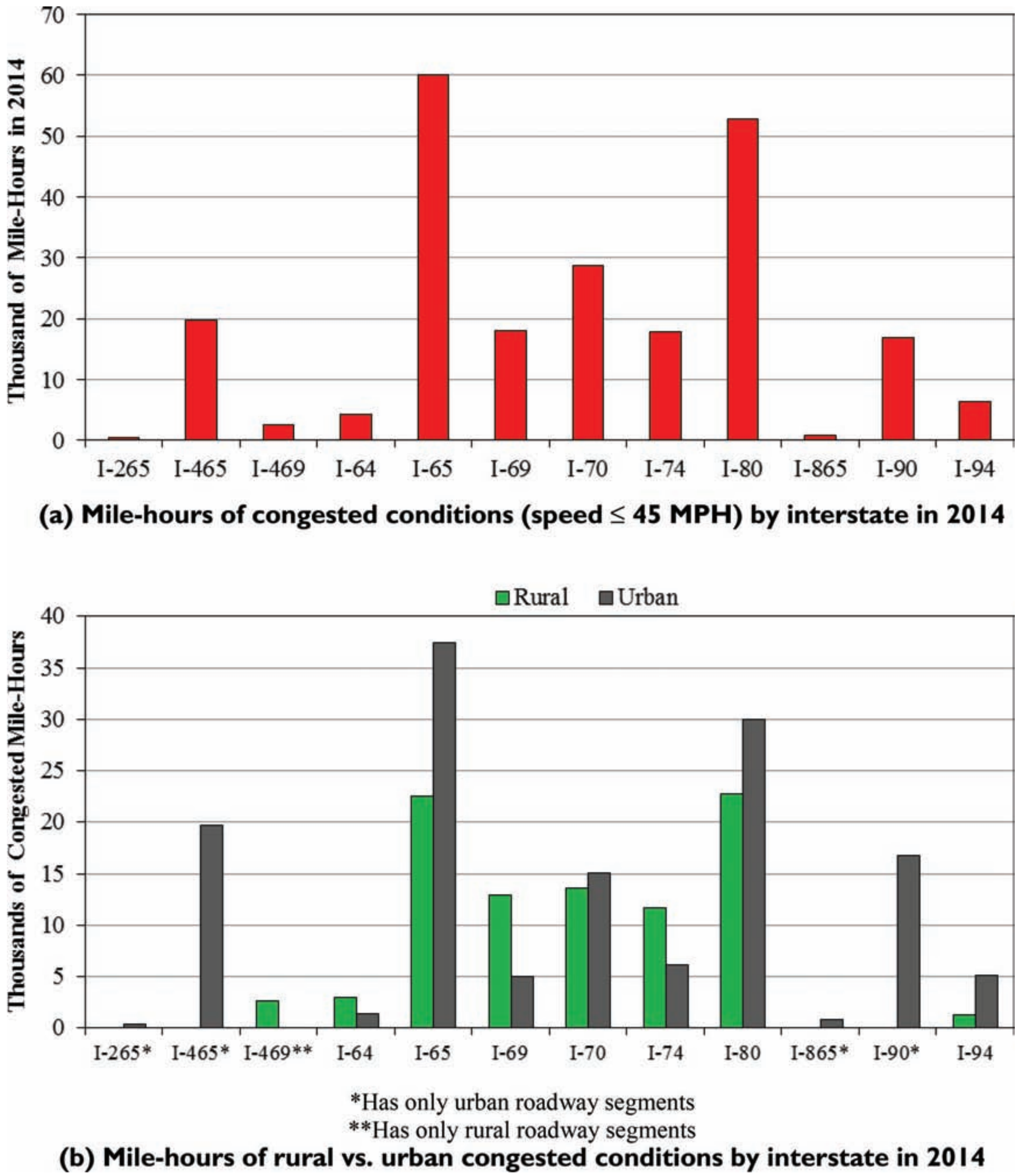


Figure 3.4 Summary of congested conditions by interstate in 2014.

The ratios between the uncongested and congested crash rates are significant. In this paper, the crash rate ratio is defined as the congested crash rate divided by the uncongested crash rate. Figure 3.7a shows the crash rate ratios for each interstate in 2014. The ratios range from 6 for I-865 to 69 for I-265. The overall congested crash rate is 24.1 times the overall uncongested crash rate. Figure 3.7b and Figure 3.7c show the crash rate ratios for rural and urban segments, respectively. For rural interstate segments, the congested crash rate is 23.8 times the uncongested crash rate. For urban interstate segment, the congested crash rate is 20.7 times the uncongested crash rate. The total crash rate ratio is higher than both the urban and rural crash ratios due to the congested crash rate being influenced heavily by urban conditions, while the uncongested crash rate is equally influenced by urban and rural conditions. This is expected because congested conditions are primarily located in urban environments, while uncongested conditions are shared in both urban and rural environments.

These findings are different from those of the Potts et al. (2015) SHRP 2 Report and the Kononov, Reeves, et. al. (2012) study, where the different crash rates were not found to be so drastically different. First, in the SHRP 2 Report, only metropolitan areas were studied and segments with reliable, non-aggregate volume measurements were used. This study, instead, considers both rural and urban interstate segments and did not

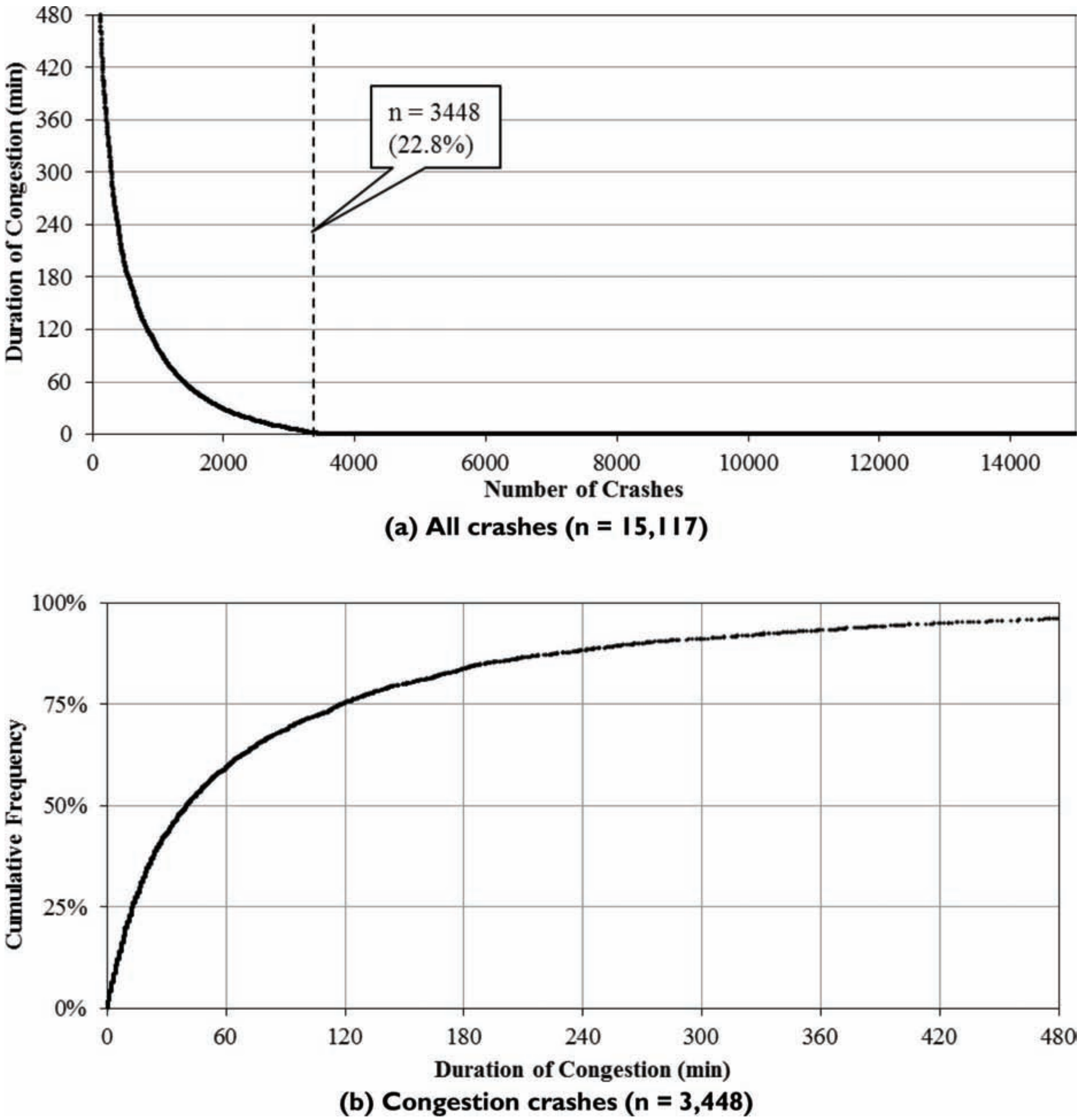


Figure 3.5 Distribution of congestion duration before crashes on all Interstates in 2014.

have access to reliable volume data. The crash rates found in this study are state-wide rates, not segment-specific. Second, both of the above mentioned studies considered multiple states of traffic congestion whereas this study only considered two: congested and uncongested. Third, the measure of exposure used in this study, mile-hours of congestion, is different from the traditional measures of exposure used in the above mentioned papers. However, the authors of this paper believe the results of this study are reliable, understandable, and applicable, especially in situations where volume data is not available or reliable. The speed data used in this study instead of volume data has been used extensively in Indiana interstate studies and its reliability has been vetted extensively.

3.3 Back-of-Queue Crash Conclusions

The impact of congestion on crashes is quite evident from the data presented in this study. Using crash and probe vehicle data, the following trends were found:

- Over the 3 years studied, 13% of fatal crashes occurred at the back of a queue.
- 87% of fatal back-of-queue crashes involved at least one commercial vehicle.

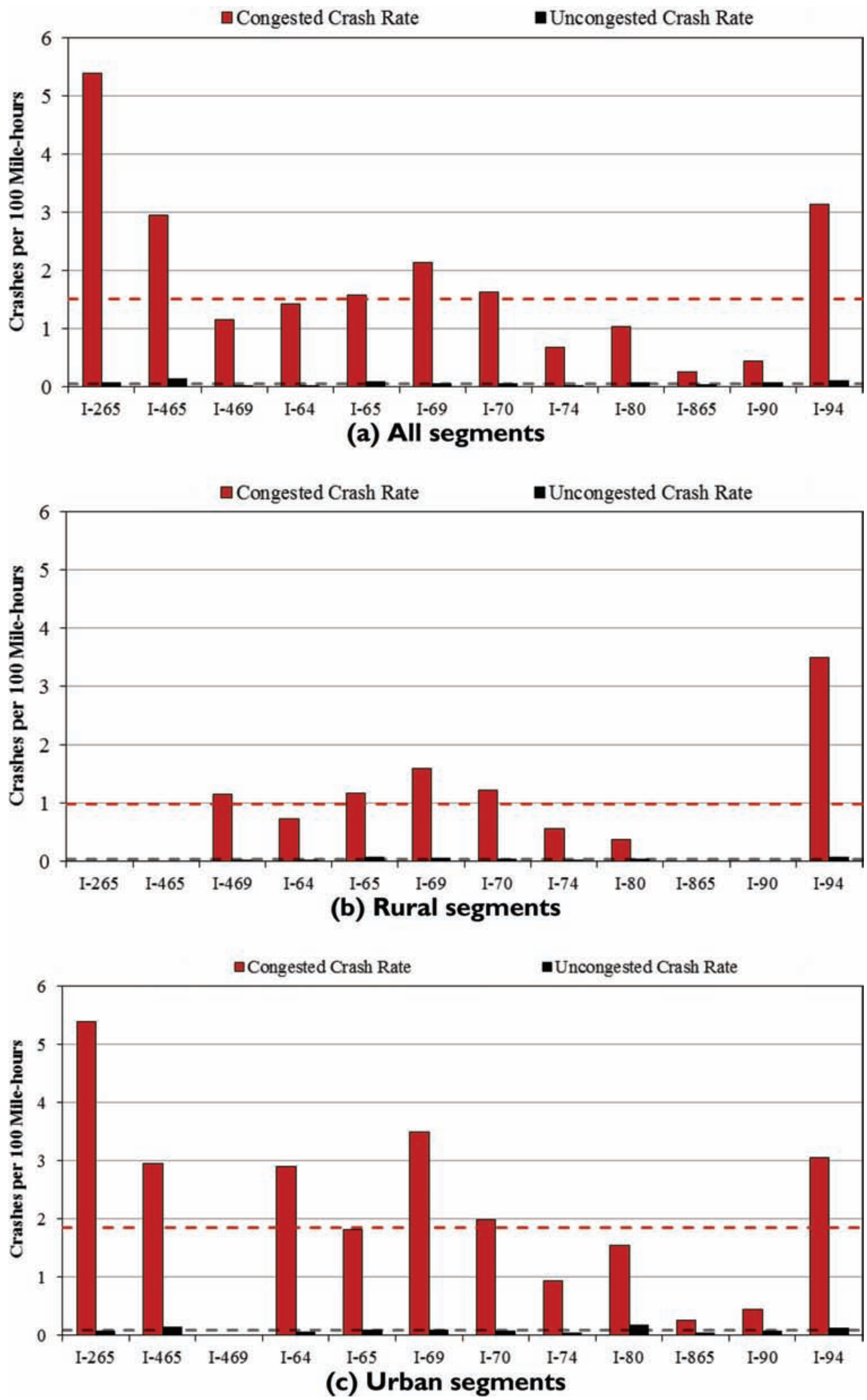


Figure 3.6 Uncongested vs. congested crash rates by interstate in 2014.

- Only 1.2% of the total mile-hours of interstate operated under congested conditions.
- 90% of congested crashes in 2014 had a queue duration ≥ 5 minutes.
- 75% of congested crashes in 2014 had a queue duration ≥ 14 minutes.
- Overall congested crash rate was 24.1 times greater than the uncongested crash rate.

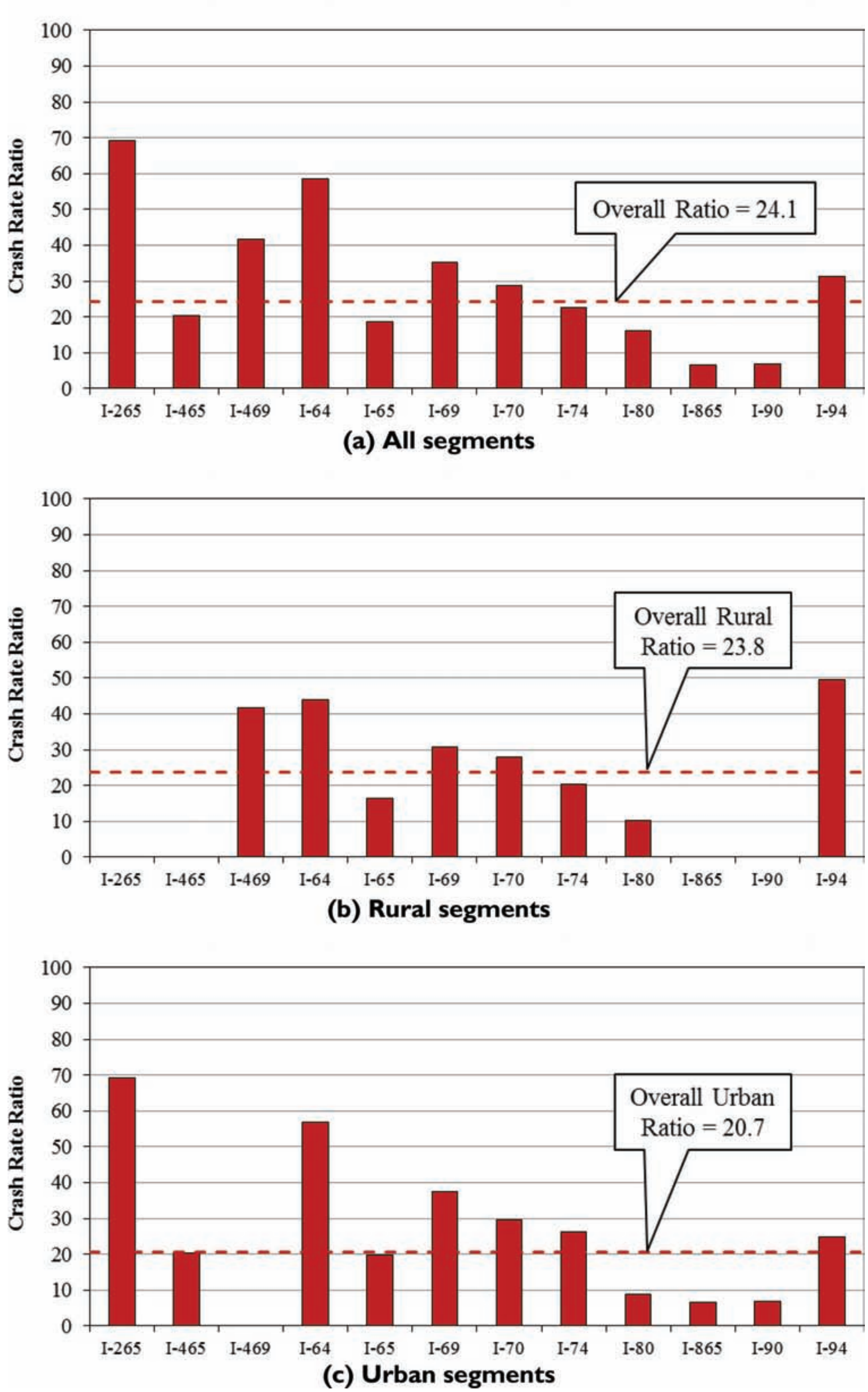


Figure 3.7 Congested/uncongested crash rate ratios by interstate in 2014.

- Rural congested crash rate was 23.8 times greater than the rural uncongested crash rate.
- Urban congested crash rate was 20.7 times greater than the urban uncongested crash rate.

The data reported here may be useful to designers in performing alternative analysis of mobility enhancements and work zone traffic management designs. It can also be useful for incident management professionals to quantify the impact of shoulder activities, such as crash investigation and tire changes. Special consideration should also be given to congestion- and queue-management in the design of work zones. Though this study is specific to interstates in Indiana, it can be assumed that similar results would be found for interstates across the country. These findings support increased use of either roadside or in-vehicle back-of-queue warning equipment. Longer term, this information is important to communicate to decision makers on the importance of advancing connected vehicle technology that warn motorists of queued traffic on the interstate.

4. STUDY 2: STATIC SPEED LIMIT ASSESSMENT ON INTERSTATES

Interstate 65 through Indiana is a 261-mile interstate corridor that currently has both urban and rural sections. The transition between urban and rural characteristics on the interstate leads to numerous speed limit changes, providing a reasonable test corridor to understand speed limit changes. A portable GPS unit was used to geo-locate every posted speed limit sign on I-65 in both directions. Figure 4.1 shows the locations of the northbound speed limit signs (n = 105) on the interstate. Both work zone and non-work zone speed limit posts were recorded for the purposes of this study. The same methodology was used to record the geo-location of the posted speed limit signs in the southbound direction (n = 115).

Using the known location of the speed limit signs, a week of crowdsourced data were used from July 21 to July 26, 2014. This period was selected because the temporary work zone speed limits that moved throughout the summer were consistent during that week.

The sign location and crowdsourced probe data were fused to create a series of case studies characterizing the spatial changes in probe vehicle speeds just upstream of and just downstream of various speed limit changes. The case studies were then expanded to develop a statewide visual performance measure of speed limit placement and effect. Typical statistical measures including mean, median, standard deviation, and interquartile range were used to assess the change in speeds. The entire I-65 corridor was then evaluated to determine typical expected values of speed reduction and speed increase after a speed limit change.

4.1 Case Studies

4.1.1 Case Study 1: Speed Limit Increase from 55 MPH to 70 MPH

The first case study demonstrates the effect of a typical increase from an urban speed limit of 55 MPH to a rural speed limit of 70 MPH. The area selected was the southern-most portion of I-65 near Louisville, KY. Figure 4.2 illustrates the northbound corridor. On the right-hand side of the figure are the precise locations of the posted speed limit signs in the area. On the left-hand side are the crowdsourced speed segments that were used for analysis. Segment 1 is the last segment where 55 MPH was the posted speed limit. Segment 2 is the segment where the speed limit changes from 55 MPH to 70 MPH, which will be referred to as the transitional, or transition, segment. Segment 3 through segment 8 are the segments after the speed limit has changed; in this example, the posted speed limit remained constant at 70 MPH throughout these segments. The segments are numbered in geographic order, where a driver would travel through the corridor in chronological order (segment 1 to segment 8).

Visualizing the trends in the data are critical to provide engineers a useful performance metric to evaluate the impact of speed limits. Figure 4.3 shows the raw speed data over the course of the week for segment 1 (Figure 4.3a), 2 (Figure 4.3b), and 3 (Figure 4.3c). The slight stratification of the images is a result of the speeds being reported to the nearest whole MPH. It is important to realize a single number cannot accurately represent the speeds on a segment, however a distribution is needed to visualize trends. Figure 4.4a is the distribution representation of the segments in the form of a cumulative frequency diagram (CFD). Once again the stepwise appearance of the curves is a result of the speed delivery to the nearest integral. Figure 4.4a shows segment 1 having the lowest speed distribution (furthest to the left). This is expected as segment 1 has the lowest speed limit. It is interesting to see that the entire distribution is well above the 55 MPH posted speed limit of the segment. Segment 2, represented by the gray line in Figure 4.4a, is the transition segment where the speed increases from 55 MPH to 75 MPH. As expected, this segment's speed distribution falls between segment 1 and a cluster of distributions representing segments 3 through segment 8. Segment 3 is represented with an orange line in Figure 4.4a.

Another approach to visualizing this data is using a box and whisker plot to characterize the speed transition. Figure 4.4b shows the distribution trends from segment 1 to segment 8. The mean, standard deviation, and interquartile range are visualized in this approach. Callout 'i' shows the segment where the speed limit transition takes place, or segment 2. A moderate change in speed is seen in this segment and the speed stabilizes by the next segment (segment 3).

4.1.2 Case Study 2: Speed Limit Decrease from 70 MPH to 55 MPH

The second case study uses the same approach as the first, except a decrease in speed limit from 70 MPH to 55 MPH is used. Figure 4.5a shows the corridor used, which is the same corridor as case study 1, only in the opposite direction of travel. The speed limit changes from 70 MPH to 55 MPH and a slowdown is seen in the crowdsourced data. Figure 4.5b shows the distributions of segments 1 through 8. Segment 1 is the last segment the speed limit is 70 MPH and segment 2 is the transition segment. Segment 3 is the segment after the

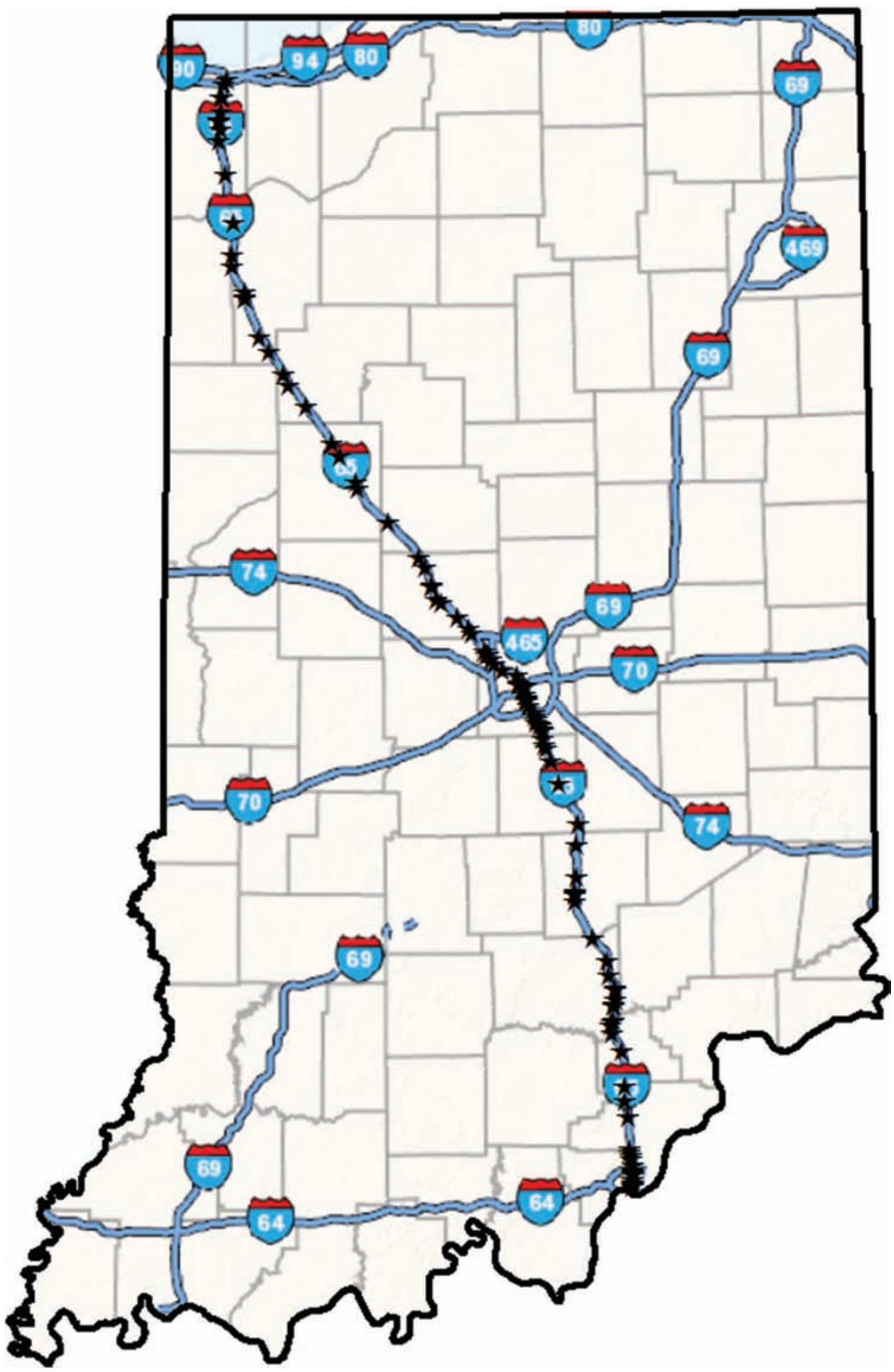


Figure 4.1 Geo-located speed limit signs on northbound I-65 in Indiana (105 northbound, 115 southbound).

transition and is the first whole segment where the speed limit is 55 MPH. Segment 3 in Figure 4.5b, is still to the right of the cluster of distributions for segments 4 through 8. This means that the speed transition is still occurring in segment 3. Figure 4.5c illustrates a similar concept where the distribution of segment speeds does not normalize until the beginning of segment 4.

4.1.3 Case Study 3: Speeds through an inactive work zone (55 MPH posted speed)

Case Study 3 investigates the speed through an inactive work zone. The southbound direction of a work zone along I-65 in northern Indiana (Figure 4.6a, Figure 4.6b) was used to evaluate the effect of posted speeds in

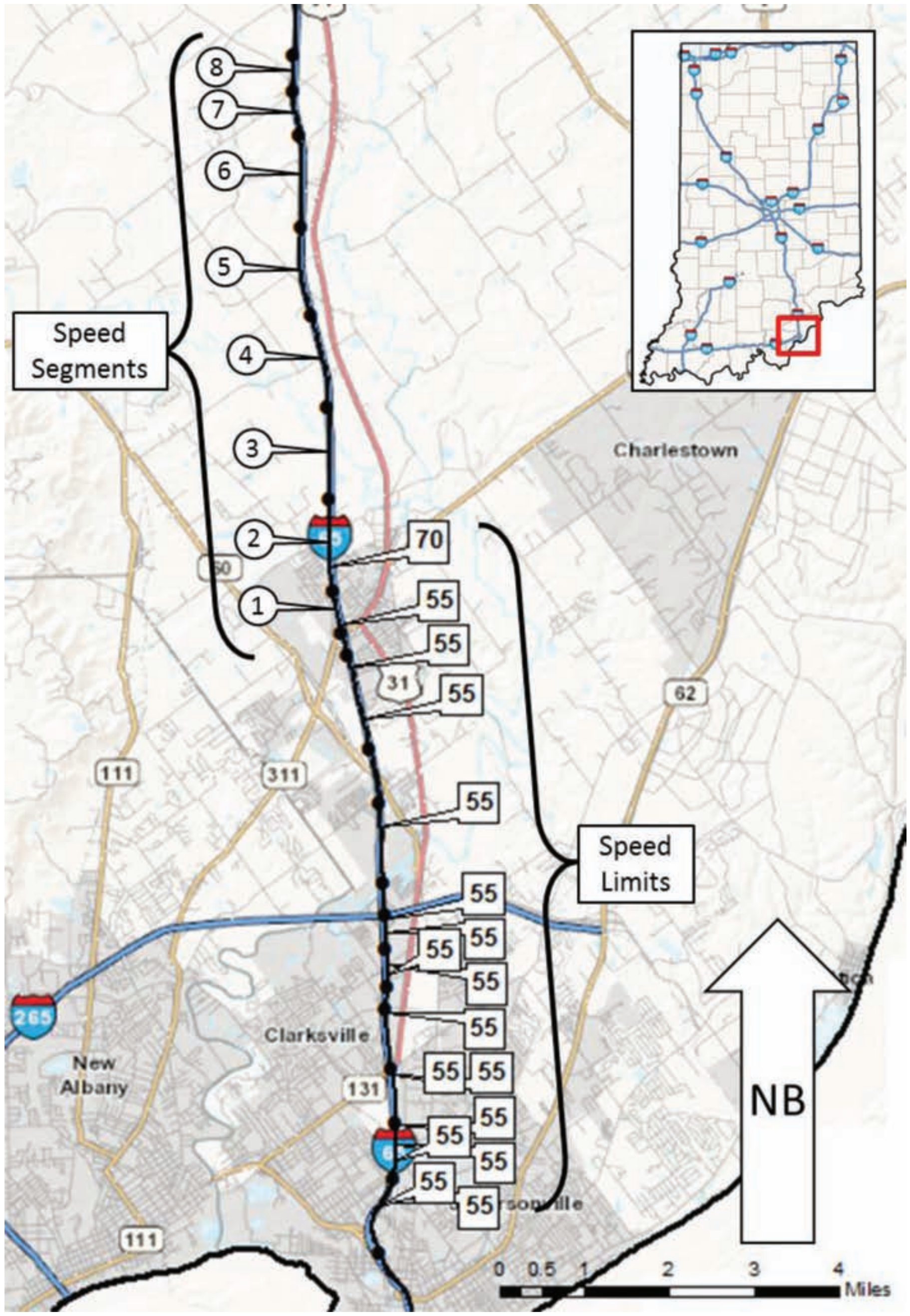


Figure 4.2 I-65 northbound corridor near Louisville, Kentucky.

an inactive work zone. The work zone was posted at 55 MPH, however there were no lane restrictions or workers present in the zone. Figure 4.6c shows the speed distributions for 25 segments: 7 before the work zone, 12 during the work zone, and 6 after the work zone. The speed distributions show that vehicles slowed down 1 to 2 MPH when proceeding through the inactive zone.

4.1.4 Case Study 4: Speed limit decrease into an active work zone (70 MPH to 45 MPH)

The last case study evaluates traveling into an active work zone where the posted speed limit is reduced from 70 MPH to 55 MPH to 45 MPH. The work zone is located near Seymour, Indiana in southern Indiana (Figure 4.7a and Figure 4.7b). Callout 'i' indicates the speed limit reduction to 55 MPH prior to the 45 MPH reduction The southbound direction of travel had been experiencing significant amount of congestion in and around the work zone. Figure 4.7c shows the speed distributions for segments before, during, and after the zone. The ideal placement of a work zone speed limit sign would be upstream of any queuing. This will provide drivers a warning to slow down before reaching the back of any queue caused by the work zone. In this example, there are long queues approaching the work

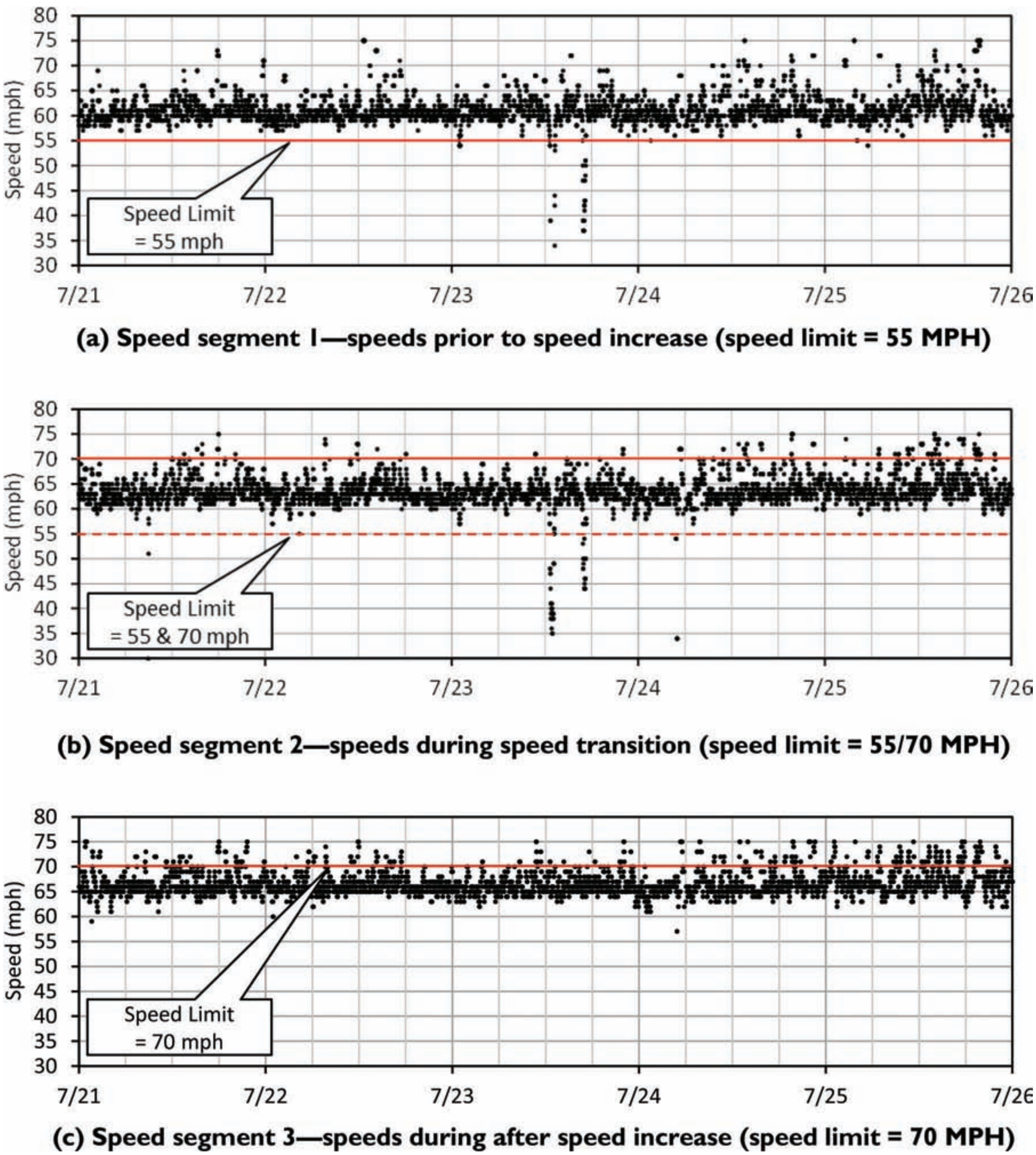


Figure 4.3 Scatter plot of speeds before, during, and after speed transition.

zone and slow speeds begin approximately 5 miles prior to the work zone speed limit (Figure 4.7c callout 'ii'). There are clearly slower than normal speeds 3 miles ahead of the work zone (Figure 4.7c callout 'iii'). In this particular example, there appears to be an opportunity to move the work zone speed limit sign ahead of any queues. This would provide a potential safety improvement by slowing vehicles ahead of a queue.

4.2 Statewide Analysis

The case studies provided above allow traffic engineers to view the impact of speed limit sign placement and determine the effect the sign has on travel speeds. From a statewide perspective, it is desirable to have a simple visual tool to understand where all of the speed changes are in the state, as well as the influence these speed changes have on traffic. Figure 4.8 is a proposed visual performance measure that allows an agency to evaluate the placement of speed limit signs and understand the effect of those placements. Figure 4.8 shows the southbound direction of Interstate 65 from Gary, IN, to Louisville, KY, over the week of July 21–26, 2014. The green line represents static posted speed limits and the red line represents moveable work zone speed limits. Overall, when the posted speed limit is 70 MPH, typical traffic is adhering to the speed limit. However, when speed limits are posted lower (65 MPH,

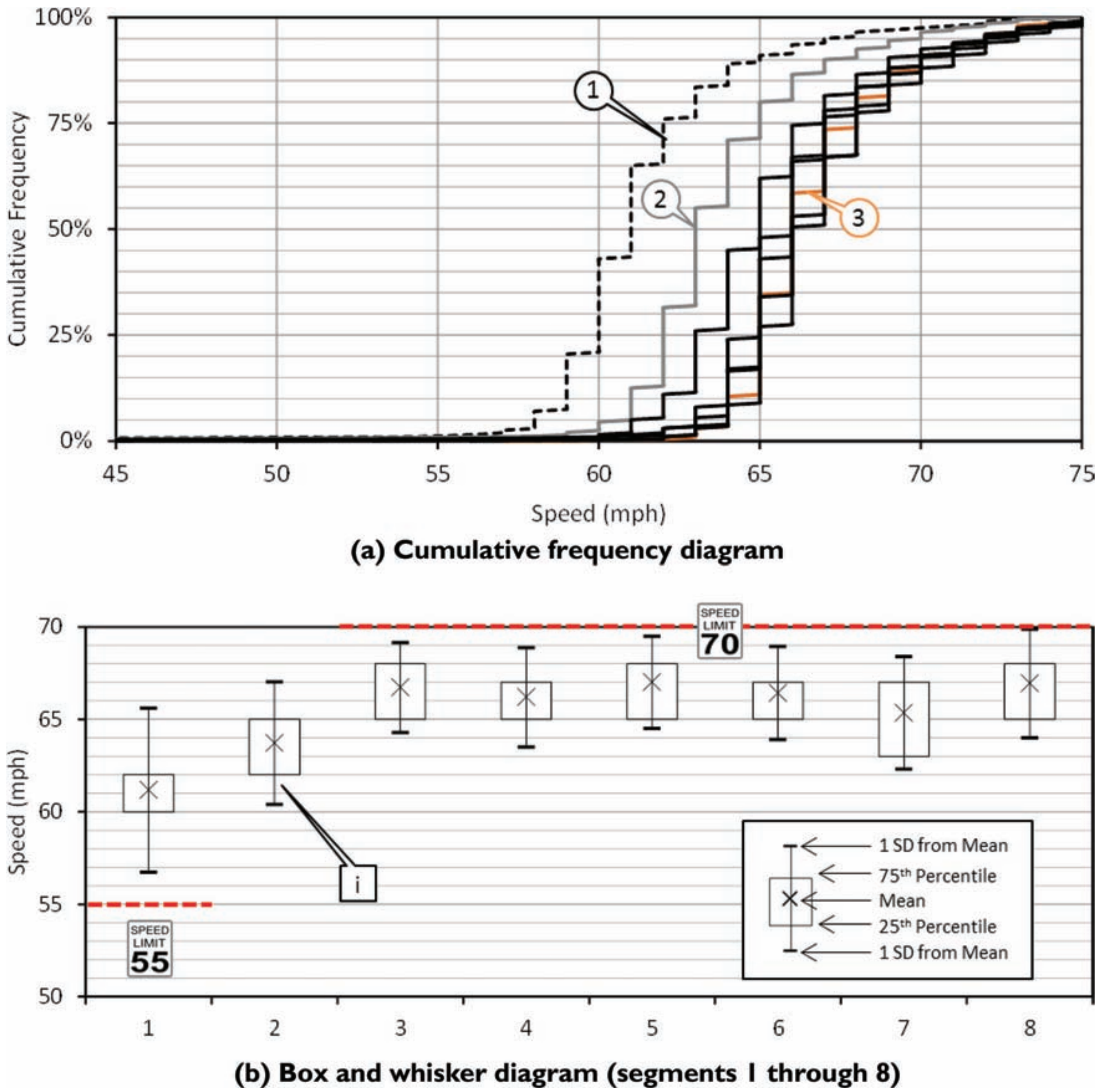


Figure 4.4 Analysis of 8 segments during a speed limit increase.

55 MPH, and 45 MPH), the trend of typical traffic is to travel faster than the posted speed. This trend of traveling faster than the posted speed remains true when the lower speed limit is in a work zone. Case study 3 discussed an example where the posted work zone speed limit of 55 MPH was almost completely ignored by traffic. This example can be seen in callout 'i' of Figure 4.8. Callout 'ii' of Figure 4.8 shows an area in Indianapolis, Indiana where the speed limit on the interstate is reduced to 50 MPH. This reduction is one of the few on Interstate I-65 where adherence seems to be reflected in the probe vehicle speed data. Callout 'iii' shows the section discussed in case study 3, where there is an opportunity to move the work zone speed limits upstream, ahead of any queuing seen in the crowd-sourced probe data. Callout 'iv' in Figure 4.8 shows the corridor of I-65 discussed in case study 2, which is a typical rural to urban speed limit transition.

Figure 4.9 represents the same visual performance measure, except in the northbound direction. Similar overall trends can be visualized in the opposite direction. Posted speed limits of 70 MPH are seeing compliance, while lower speed limits are being violated. Callout 'i' in Figure 4.9 represents the opposite direction of case study 3, in this direction the work zone has more activity, but is still not completely active. The speeds in this area do see a minor reduction, but still are nearly 10 MPH above the posted speeds. Callout 'ii' represents the downtown Indianapolis area where speeds are reduced to 55 MPH. Callout 'iii' represents the opposite direction of the work zone discussed in case study 4. Similar to the southbound direction, there is an opportunity to move the reduced speed limits upstream to be ahead of the queuing from the work zone. Callout 'iv' represents the instantaneous speed increase shown in case study 1.

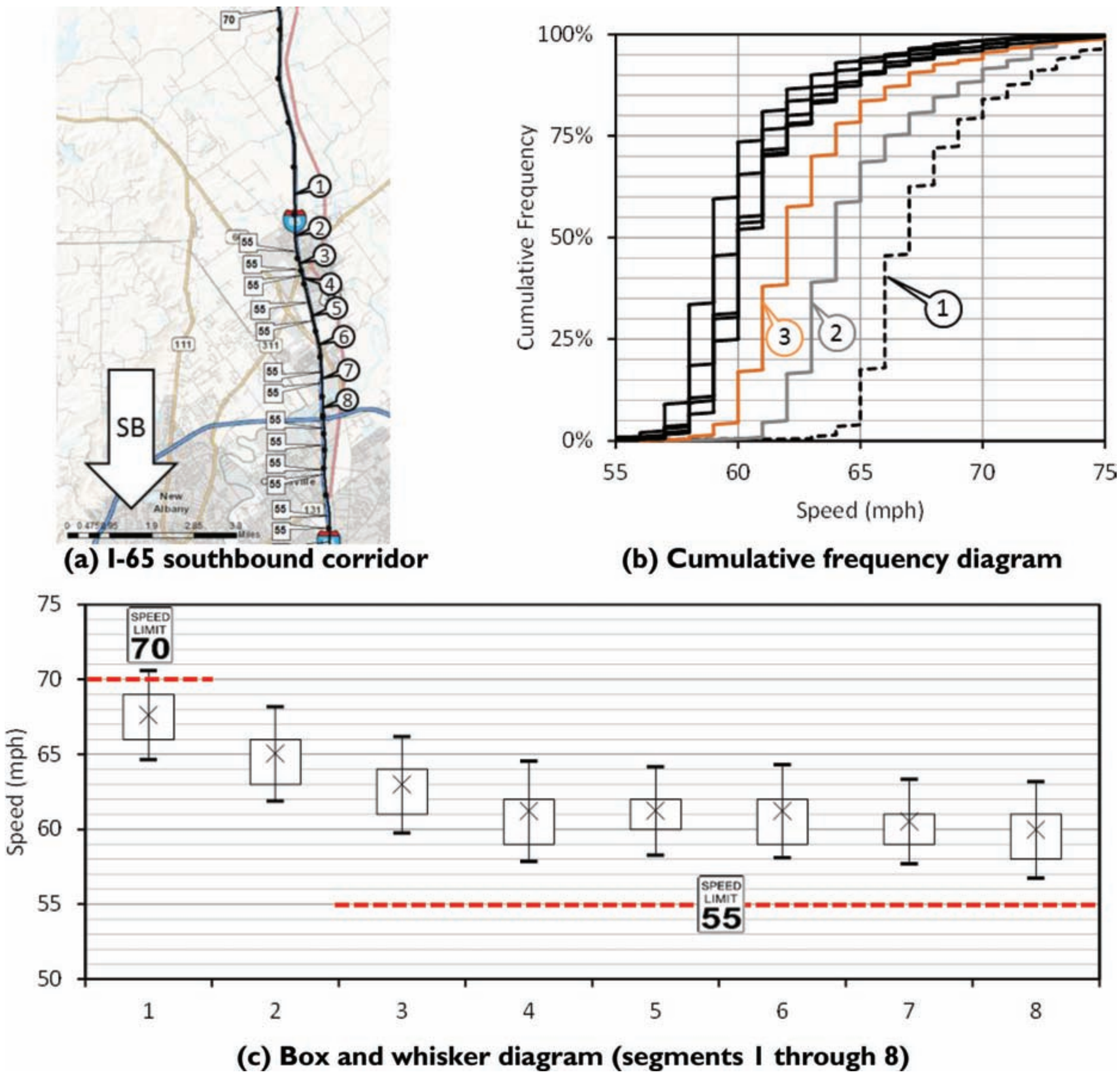


Figure 4.5 Analysis of 8 segments during a speed limit decrease.

Figure 4.8 and Figure 4.9 provide a statewide visual performance characterization of speed limits as well as actual speeds. These graphics give decision makers a tool to understand where they are having an impact on speeds and where there may be an opportunity to have an impact by changing the location or value of speed limits. Currently, in the state of Indiana there are 20 static speed limit changes (10 in each direction) that are not located in work zones. Using a similar approach to the case studies above, each of these 20 speed limit changes were analyzed for two 3-hour time periods during the week (0900–1200 and 2100–2400). Figure 4.10 and Figure 4.11 represent the speed limit changes and the corresponding average speeds for the last segment of the upstream speed limit segment (segment 1), the transition segment (segment 2), and the first three segments of the new speed limit (segment 3). Figure 4.10 represents a midday period from 9 AM to 12 PM. Figure 4.11 represents a night time period from 9 PM to 12 AM.

Figure 4.10 illustrates both expected and unexpected trends in average speed changes as a result of changing speed limits:

- Figure 4.10a callout 'i' represents an increase in speed limit, however there is a decreasing trend of average speeds in the southbound direction at MM 109.1. This is likely due to the proximity of this segment to downtown Indianapolis and the impact of an urban freeway environment has a stronger impact on vehicle speed than the signs.
- Figure 4.10b shows a section of I-65 where there is a 5 MPH reduction in speed limit (55 MPH to 50 MPH) and there is a corresponding 5 MPH reduction in average speed.
- Figure 4.10c shows an increase in speed limit from 55 MPH to 70 MPH and a 5 MPH increase in average speed.

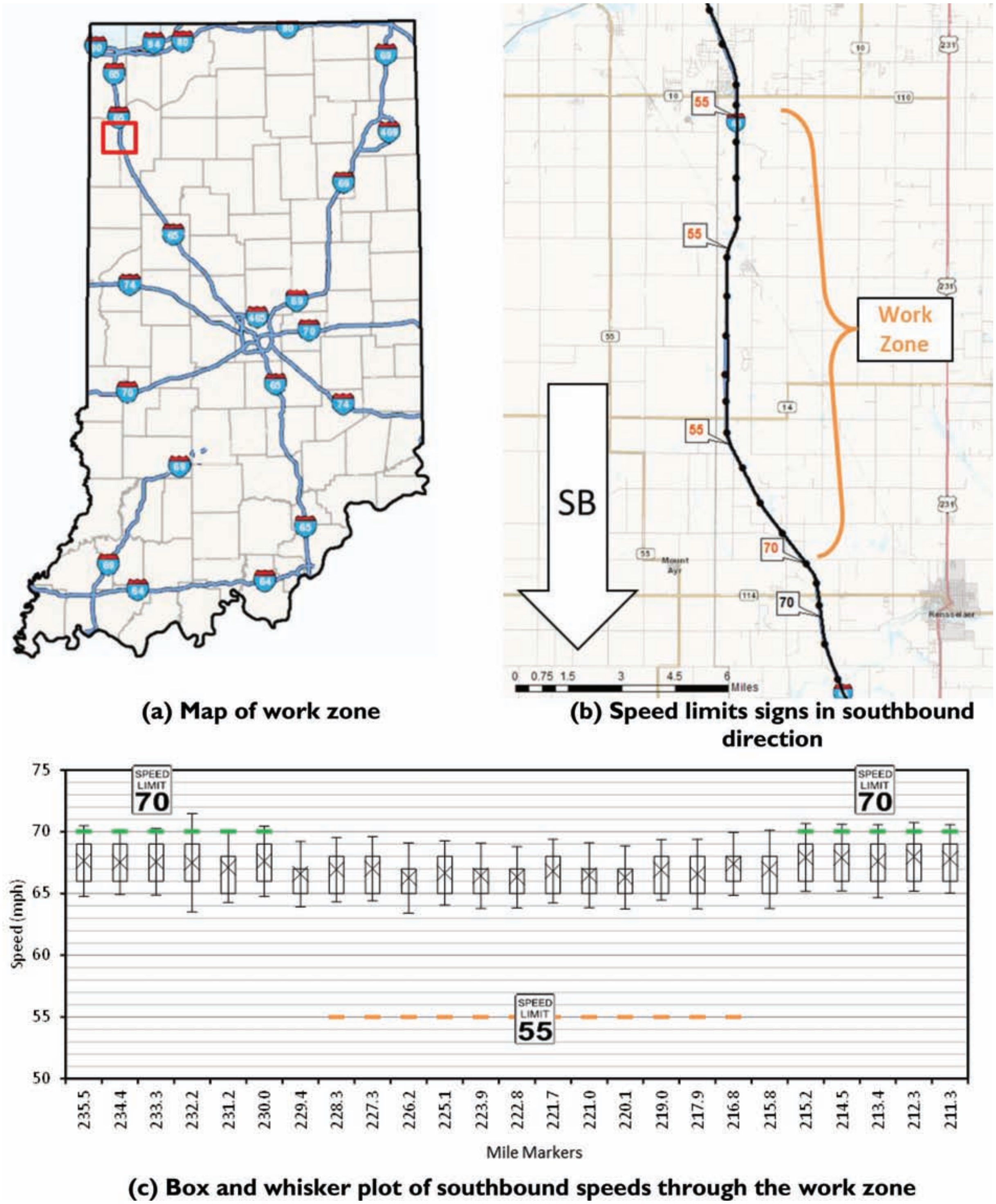


Figure 4.6 Example of work zone speed limits being ignored by drivers.

- Figure 4.10d illustrates a 10 MPH reduction in speed limit (65 MPH to 55 MPH). The four points on I-65 where this occurs have significantly different trends. Callout 'ii' represents a section a northbound section of I-65, which is a typical commuter route to Chicago. The average speed trend increases here, even though the speed limit is reduced. Callout 'iii' represents a northbound segment of I-65 near Indianapolis, just downstream of this segment is a work zone that is causing vehicles to queue. There is another opportunity here to move work zone speed limit signs upstream of the queues detected using crowdsourced probe vehicle data.
- Figure 4.10e represents the four locations on I-65 where the speed limit increases from 65 MPH to 70 MPH. The crowdsourced speed data shows an increase in average speeds between 1 and 5 MPH.

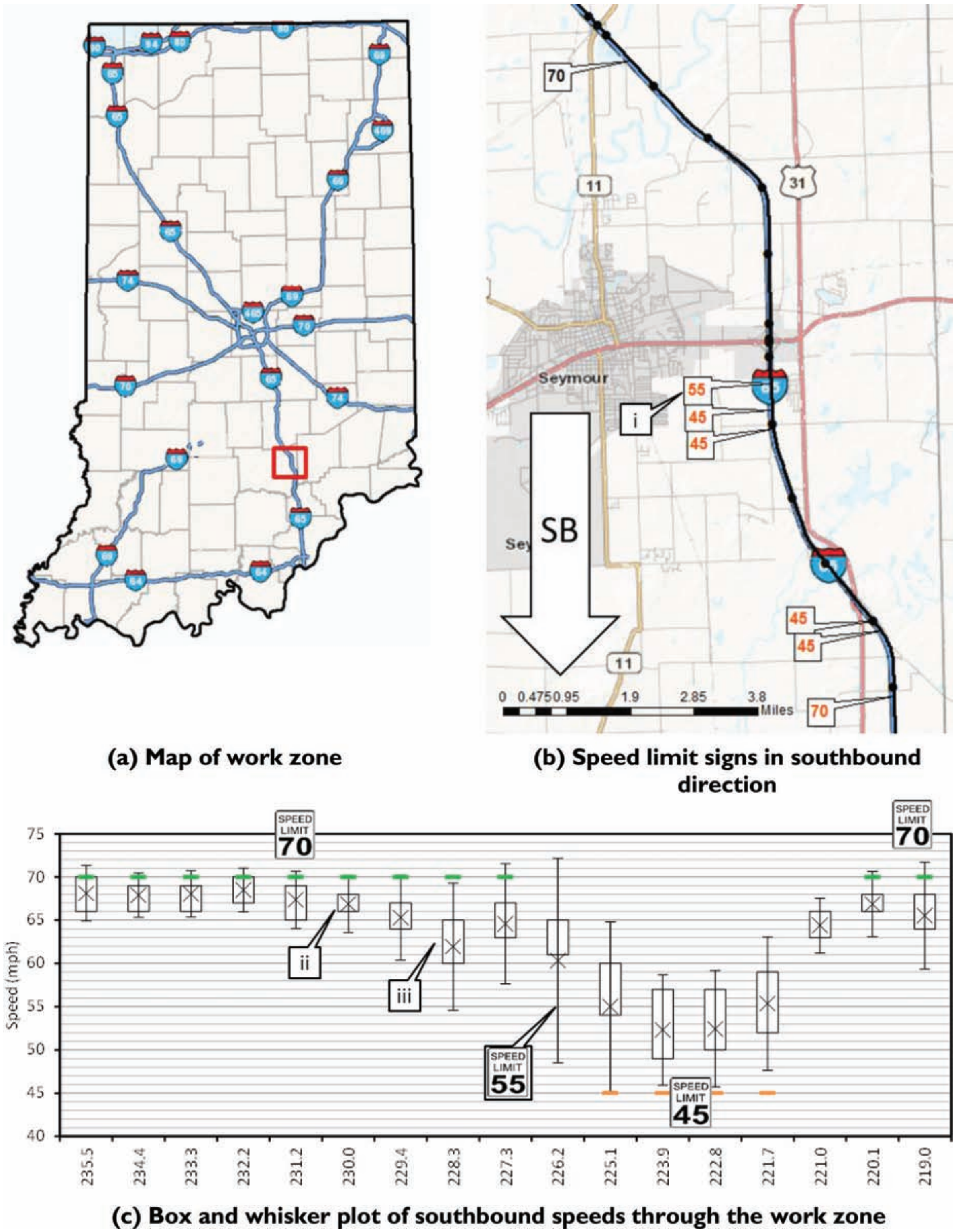


Figure 4.7 Example of work zone speed limit sign that requires movement.

- Figure 4.10f shows the four locations where speed is reduced from 70 MPH to 65 MPH on the interstate. A slight reduction in speeds is seen for these segments.
- Figure 4.10g illustrates the only location on I-65 where the speed limit reduces from 70 MPH to 55 MPH. The average speed reduction as a result of this was 7 MPH.

Figure 4.11 illustrates the same sections of roadway as Figure 4.10 during the 2100–2400 hours. Most of the speed trends remain the same between the daytime and night time periods. One segment to note is the NB I-65 segment near the 100th mile marker south of

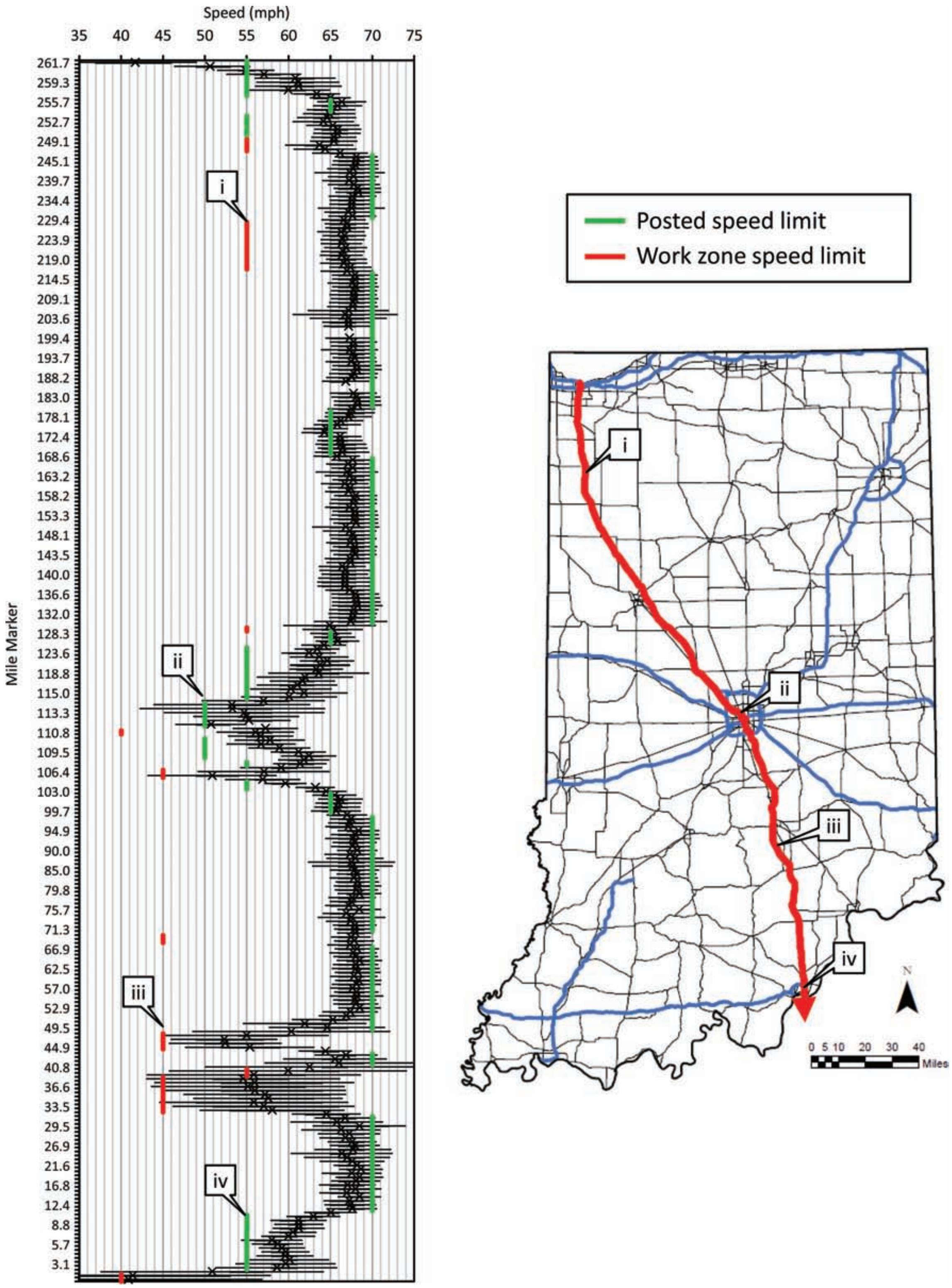


Figure 4.8 I-65 southbound statewide speed limit summary (week of July 21–26).

Indianapolis (Figure 4.11 callout 'i'). The speed declines at a much more rapid rate approaching the work zone. This is indicative of nighttime construction activities, and once again may warrant the movement of speed limit signs upstream of queueing. Figure 4.10 and Figure 4.11 illustrate an effective approach for determining if static speed limit changes are having the desired spatial impact.

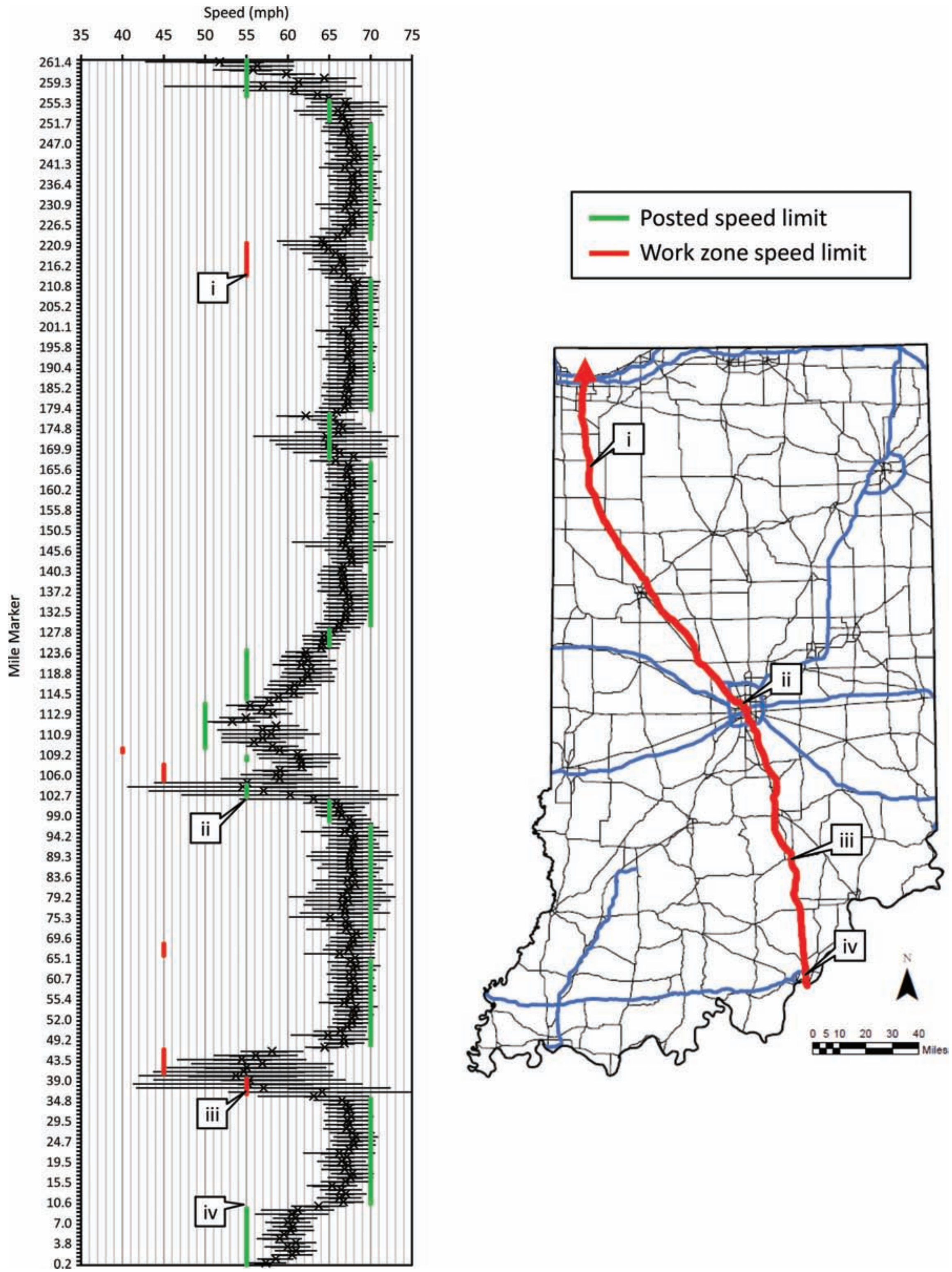


Figure 4.9 I-65 northbound statewide speed limit summary (week of July 21–26).

4.3 Static Speed Study Conclusions

Signage, especially speed limits, are one of the quick and easy changes that decision makers can utilize to directly impact driver behavior. Historically, speed limit signs, particularly for construction zones, have been deployed with virtually no outcome assessment to characterize their impact. This report used four case studies

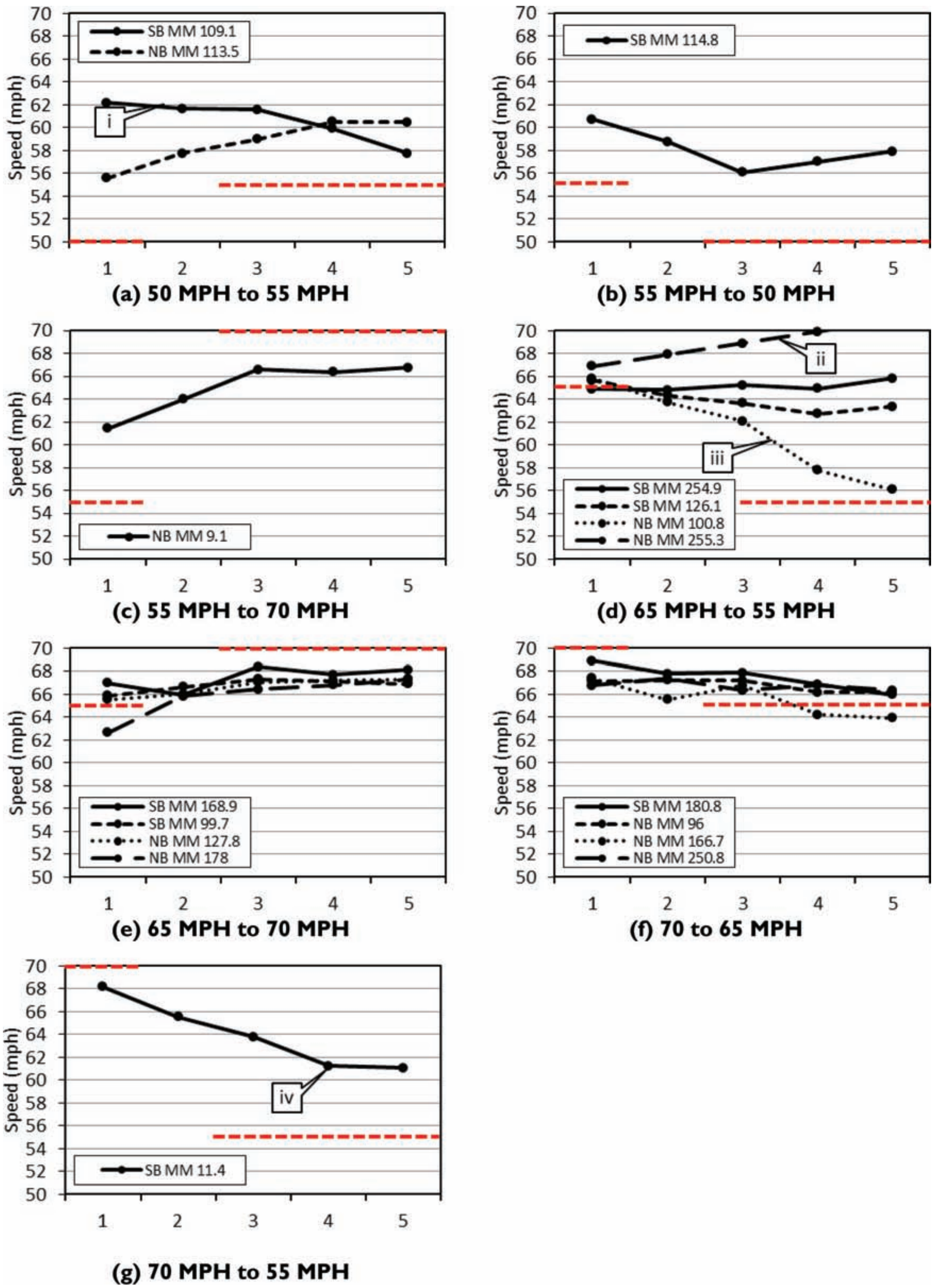


Figure 4.10 Non-work zone static speed limit changes on I-65 in Indiana (0900–1200 hours).

to describe a scalable technique for assessing the impact of speed limit signs. This technique could be deployed on virtually any freeway in the country to continually assess speeds adjacent to static and variable speed limit changes.

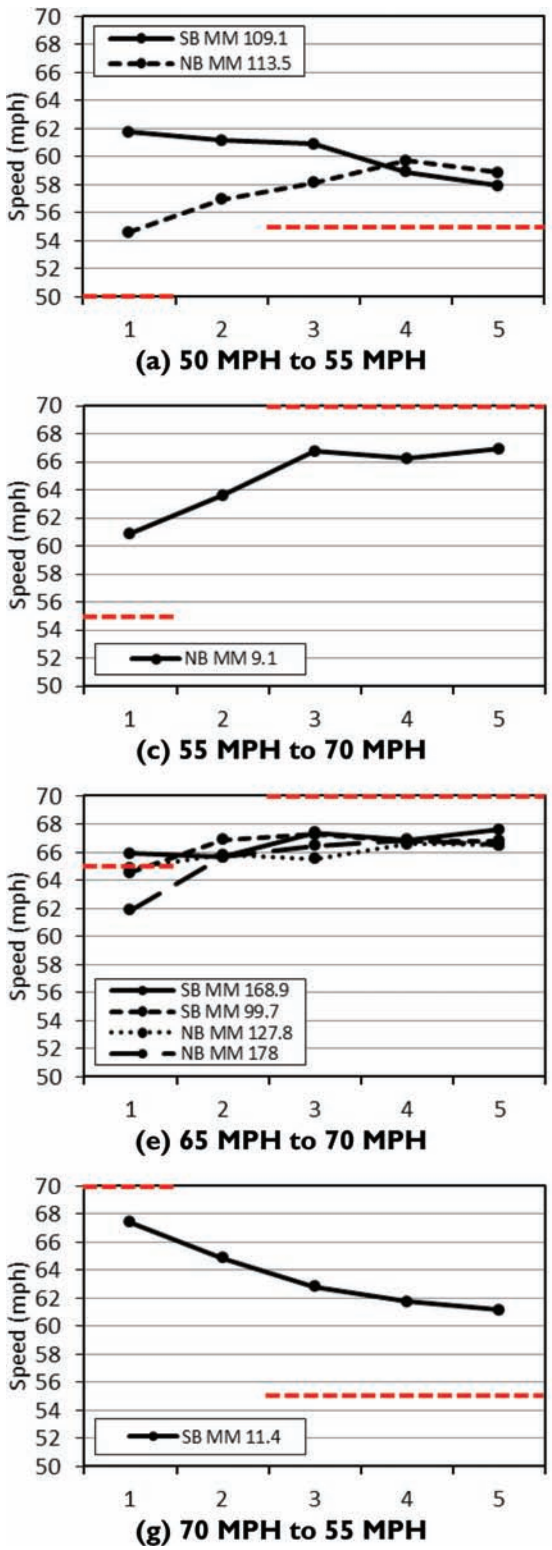


Figure 4.11 Non-work zone static speed limit changes on I-65 in Indiana (2100–2400 hours).

5. STUDY 3: VARIABLE SPEED LIMIT ASSESSMENT IN A WORK ZONE

The main purpose of this project was to evaluate the use of variable speed limit (VSL) signs on interstates in Indiana. A new speed study methodology, which involved vehicle-matching, was developed for this purpose. Figure 2.5 shows one of six signs that were deployed on Interstate 65 south of Indianapolis and the four possible speed settings. In this study, the VSL signs used were speed limit signs with a variable speed limit display, not a variable message sign displaying a speed limit. The INDOT expressed interest in utilizing VSLs on both urban interstate segments and in interstate work zones for traffic management purposes. VSLs will potentially allow for higher speeds during periods with low traffic volume and no work zone activity but would be set to slower speeds when work is occurring or there are queues present. This study focuses on the impact of VSLs on free-flowing traffic.

The six VSL signs were deployed upstream of a work zone on Interstate 65 between mile markers 80 and 90. Figure 5.1 shows the configuration of the work zone at the beginning of the study with three VSL signs in each direction. At mile marker 80, the passing lane of the northbound travel lanes (long-dotted lines) crossed over the median to the shoulder of the southbound roadway and was separated from the southbound travel lanes (short-dotted lines) by a concrete barrier. The slower right lane of the northbound roadway was shifted to the left lane and was separated from construction in the right lane by construction barrels and concrete barriers. Three VSL signs were located north of the work zone to regulate the speeds of southbound traffic. Three signs were also located south of the work zone for northbound traffic. The speed limit inside the work zone was set to 45 MPH with typical static work zone signage. A few months after the start of this study, the three signs north of the work zone were moved and paired with the three signs south of the work zone. This configuration change will be discussed in more detail later in this report. This study focused on the VSL signs servicing northbound traffic, placed at the south end of the work zone, to evaluate their impact on free-flowing traffic.

Figure 5.2 shows segment speed data obtained from northbound crowdsourced probe vehicle data with and without individual variable speed signs active at mile markers 76.5, 77.5, and 79.0. The fixed 45 MPH speed limit is at mile marker 79.5. The posted speed limit upstream of the first VSL sign is 70 MPH for passenger vehicles and 65 MPH for trucks. The segment speeds

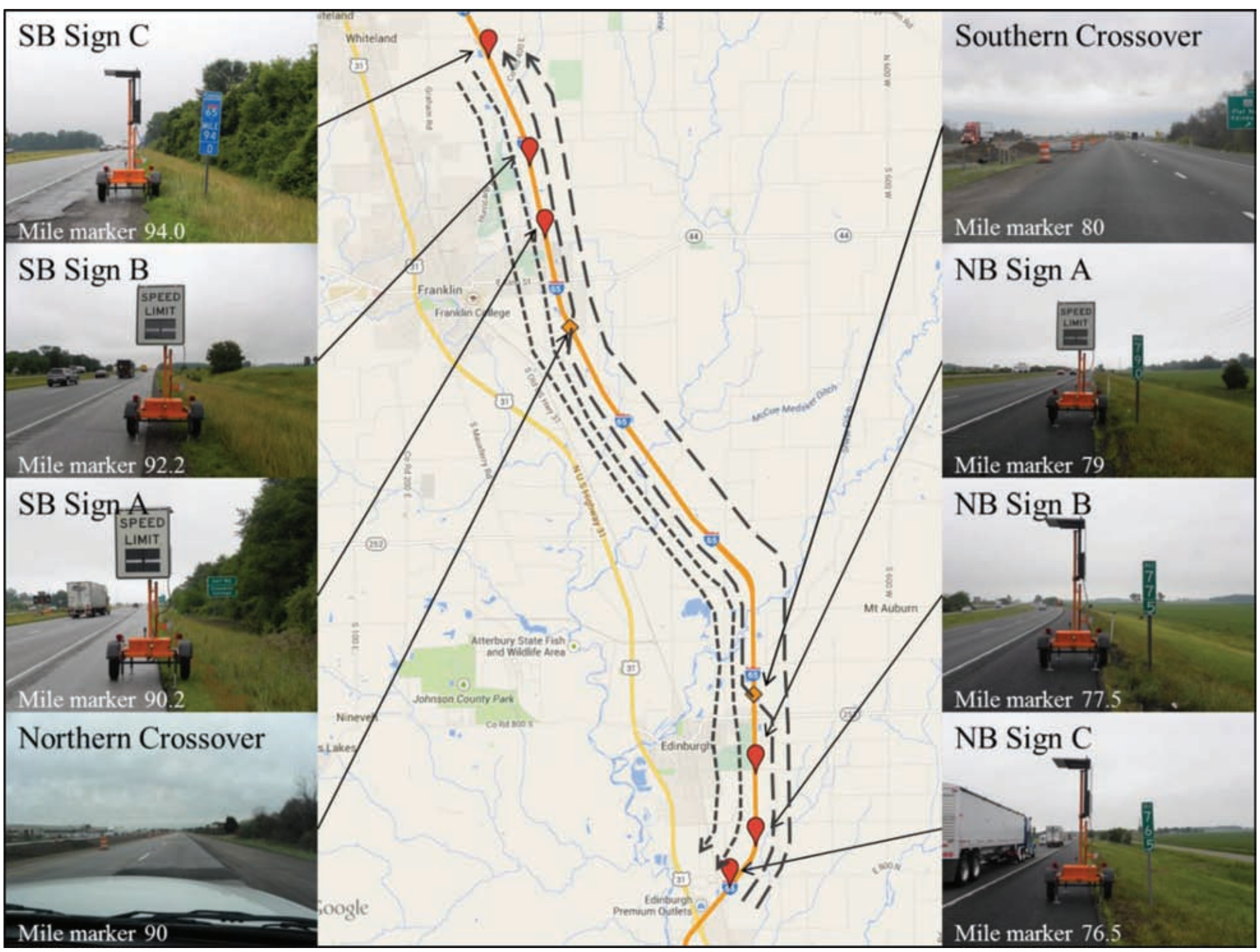


Figure 5.1 Locations of variable speed limit signs and basic work zone layout.

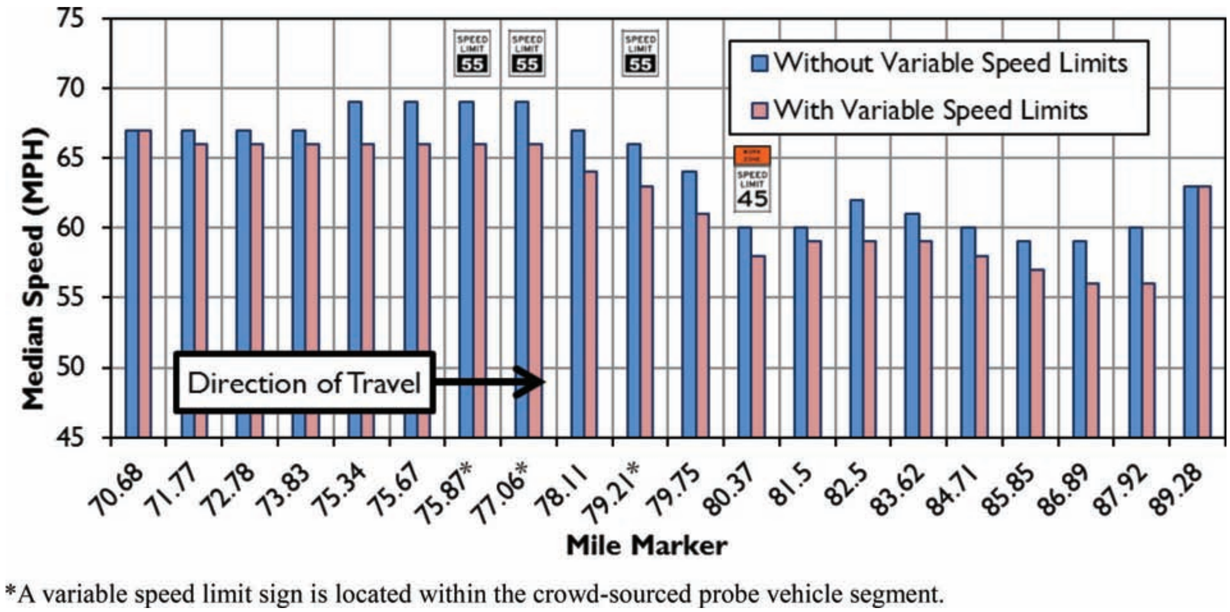


Figure 5.2 Spatial comparison of crowdsourced probe vehicle median speeds with and without variable speed limits on I-65 between mile markers 70 and 90.

show that speeds are slower both approaching the work zone and in the work zone when the variable speed signs are used in advance. However, this only provides average data and does not provide any information on how individual vehicles respond to changes in posted speed limit. There is limited literature on the area of influence of a speed limit zone. This study helps clarify this on a vehicle-by-vehicle bases.

There have been no published studies of variable speed limit signs used to slow traffic prior to a work zone using data from matched vehicles. The first objective of this study was to develop a new speed study methodology involving the matching of vehicles to evaluate individual driver behavior. The second objective was to use this new methodology to evaluate the effect of VSLs signs on vehicle speeds upstream of a work zone. The scope of this study does not include a comparison of the VSL signs to other traffic control devices.

5.1 Methodology

Crowdsourced probe vehicle data provide average speeds but do not allow for the analysis of individual vehicle behavior (Figure 5.2). An advantage of using the laser speed measurement devices is the ability to match vehicles and look at individual driver behavior. Oftentimes, it is the difference in vehicle speeds that is more dangerous than the speeds themselves. Therefore, spot speed measurements were collected simultaneously at locations upstream and downstream from the speed limit sign of interest. Figure 2.6a and Figure 2.6b show examples of researchers at upstream and downstream data collection locations. An example vehicle-capture as seen through the sight scope is shown in Figure 2.6c.

Figure 5.3 shows all sign and data collection locations. Data collection locations were chosen based on the safety of the researcher and visibility of the researcher by drivers. In order to have the least amount of influence on chosen speeds, researchers were hidden as much as possible from driver view. Care was also taken to select locations that would have a cosine correction of less than 2% (about 1 MPH). Figure 5.4 shows close-up aerial views and street views of each data collection location. On each image, the star represents where a researcher would be stationed.

5.1.1 Vehicle-Matching

The vehicle-matching process was performed after the data collection was completed. Researchers compared upstream vehicle photos to downstream vehicle photos. In the initial stages of the project, vehicle-matching was performed manually by comparing only two images at a time (one from upstream (Figure 2.7a) and one from downstream (Figure 2.7b, Figure 2.7c)). It was time-consuming even for smaller samples of less than 100 vehicles. Subsequently, a semi-automated process was developed to make the process more efficient. This method provided automated sorting of likely matches with the researcher making the final match decision (Figure 2.7c). Matching vehicles after the data was collected rather than in real-time during the data collection process allowed researchers to gather much larger sample sizes.

As with manual matching, a vehicle captured upstream may not be matched because it is obstructed by another vehicle. In the semi-automated process, these occurrences are labeled as VNM, or Verified No Match, if the vehicle is seen but not captured downstream. If a vehicle is captured upstream but cannot be seen anywhere downstream, it is labeled as NM, or No Match. This process, unlike the manual matching, can sometimes

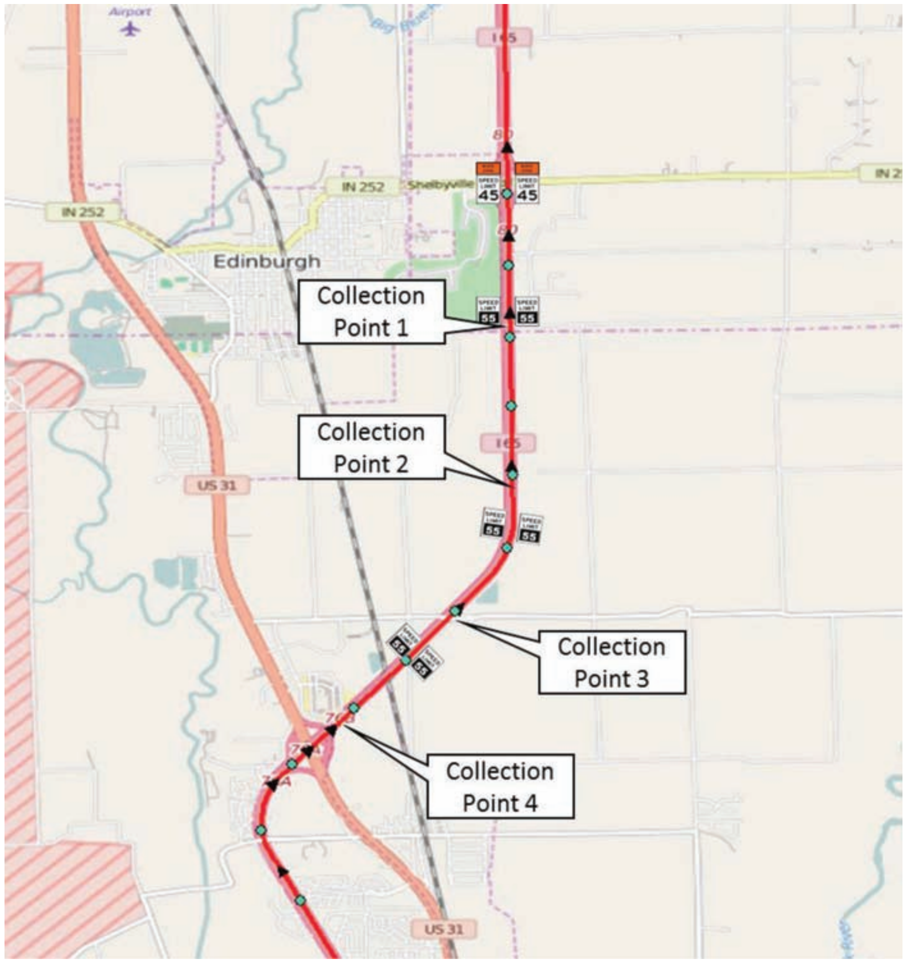


Figure 5.3 Map of variable speed limit sign location and data collection points.

miss extreme outliers, where vehicles have an extreme change in speed. However, it was discovered that these errors can be minimized by reducing the distance between measurement points to approximately one mile or less and ensuring that there are no interchanges between the points.

5.1.2 Classification of Samples by Truck and Cars

On many interstate sections in Indiana, trucks are subject to a different, lower speed limit than passenger vehicles. This is the case for all non-work zone, static interstate speed limits in this study. Commercial vehicles also display different driver behaviors from passenger vehicles. Therefore, matched passenger vehicles and matched commercial trucks are analyzed separately.

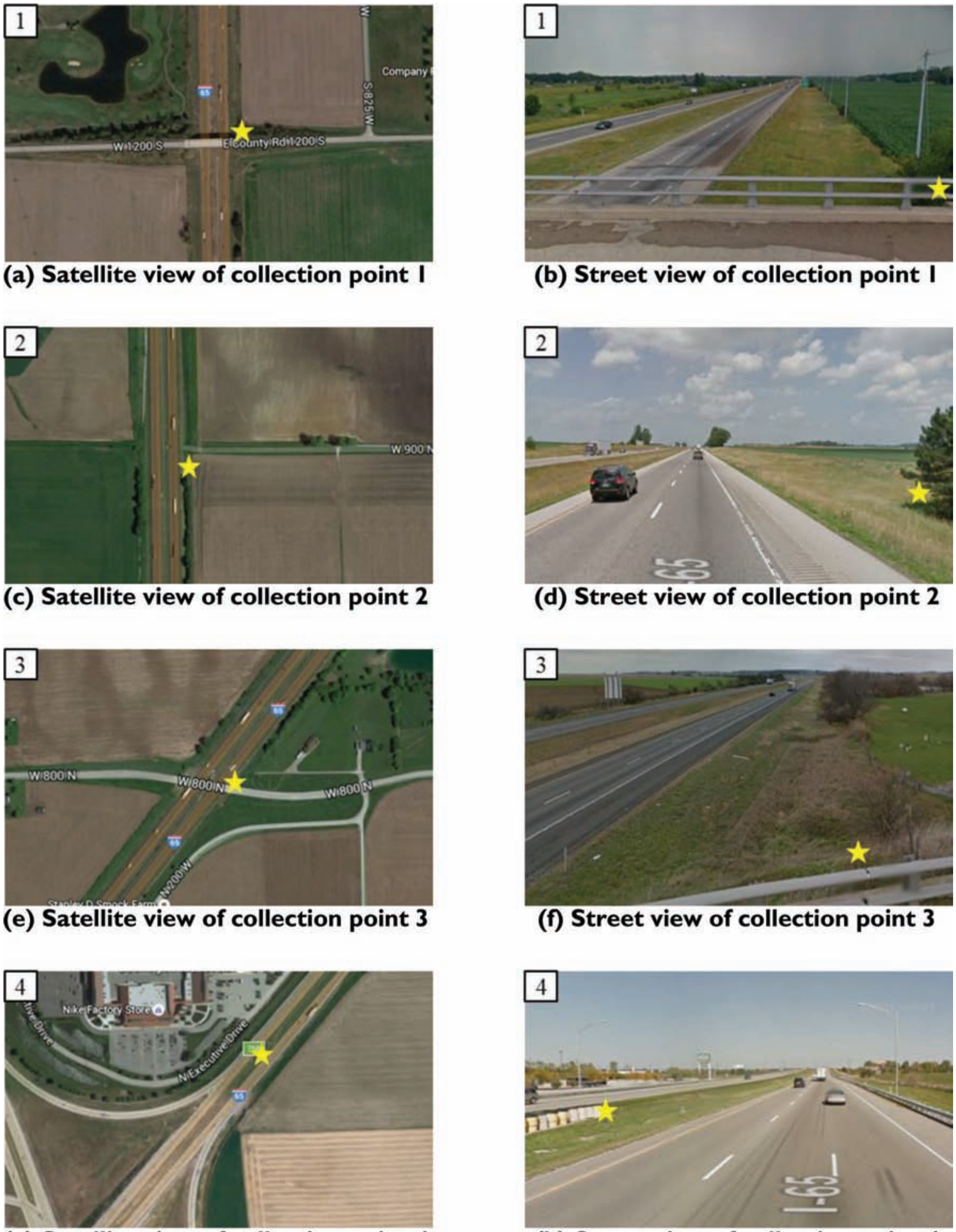
5.1.3 Classification of Samples by Speed Change

For the matched vehicles, changes in driver behavior were also evaluated. Vehicles were separated into four different categories based on the difference between their upstream speed and the upstream speed limit and the difference between their downstream speed and the downstream speed limit, shown below. Speeding is defined as any speed greater than the speed limit.

- Q1: Speeding upstream and also speeding downstream
- Q2: Not speeding upstream but speeding downstream
- Q3: Not speeding upstream and also not speeding downstream
- Q4: Speeding upstream but not speeding downstream

5.1.4 Data Analysis and Visualization Concepts

Figure 5.5 depicts the above concept using example data from a static speed limit sign that changes the speed limit from 70 to 65 MPH for cars and 65 to 60 MPH for trucks. Figure 5.5a shows a plot of upstream vs. downstream speed of cars and trucks. The blue dotted lines represent the passenger vehicle speed limits and the red dotted lines represent the truck speed limits. In this graph, the line $y = x$ separates vehicles that decrease their speed from vehicles that increase their speed. In this sample, 71% of cars and 79% of trucks decrease their speed when they passed the speed limit sign. Ideally, all vehicles would decrease their speed in response to the speed limit drop. Figure 5.5b displays



(a) Satellite view of collection point 1
(b) Street view of collection point 1
(c) Satellite view of collection point 2
(d) Street view of collection point 2
(e) Satellite view of collection point 3
(f) Street view of collection point 3
(g) Satellite view of collection point 4
(h) Street view of collection point 4

Figure 5.4 Satellite view and street view of data collection points.

the same data as Figure 5.5a however the speeds are shown relative to the speed limit and all vehicles are located in one of the four behavioral quadrants discussed above. The difference between upstream speed and upstream speed limit is the initial speeding state and corresponds to the x axis. The difference between downstream speed and downstream speed limit is the final speeding state and correspond to the y axis. If a driver's behavior doesn't change relative to the speed limit, the corresponding point would lie on the line $y = x$. In this chart, 50% of cars lie in Q1, or the speeding/speeding quadrant. Comparatively, only 25% of trucks lie within Q1.

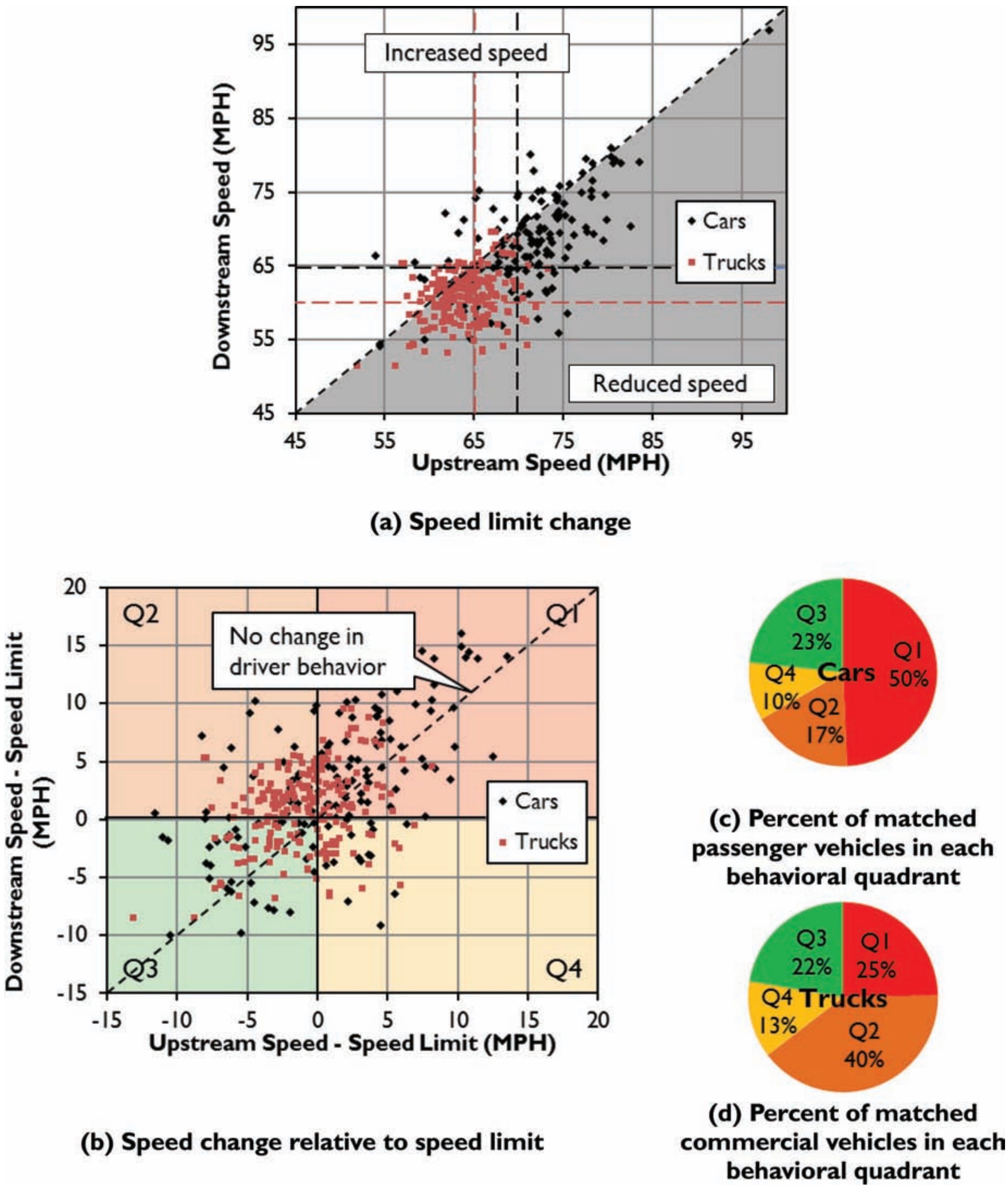


Figure 5.5 Methodology example of evaluating driver response to a static speed limit change at mile marker 178 on I-65 northbound (cars: 70 to 65 MPH; trucks: 65 to 60 MPH).

Speed distributions are commonly analyzed in speed studies. Figure 5.6b is the simplest and most common: upstream and downstream speed distributions of unmatched vehicles. However, this type of chart does not depict differences between vehicle classes and is of limited use. Figure 5.6c shows the upstream and downstream speed distributions by vehicle class. Neither Figure 5.6b nor Figure 5.6c are able to show individual driver responses to the speed limit change. With the vehicle-matching process discussed above, the difference between upstream and downstream speeds of individual vehicles can be calculated. Figure 5.6d shows two distributions of speed changes by vehicle class for individual matched vehicles. This type of figure is

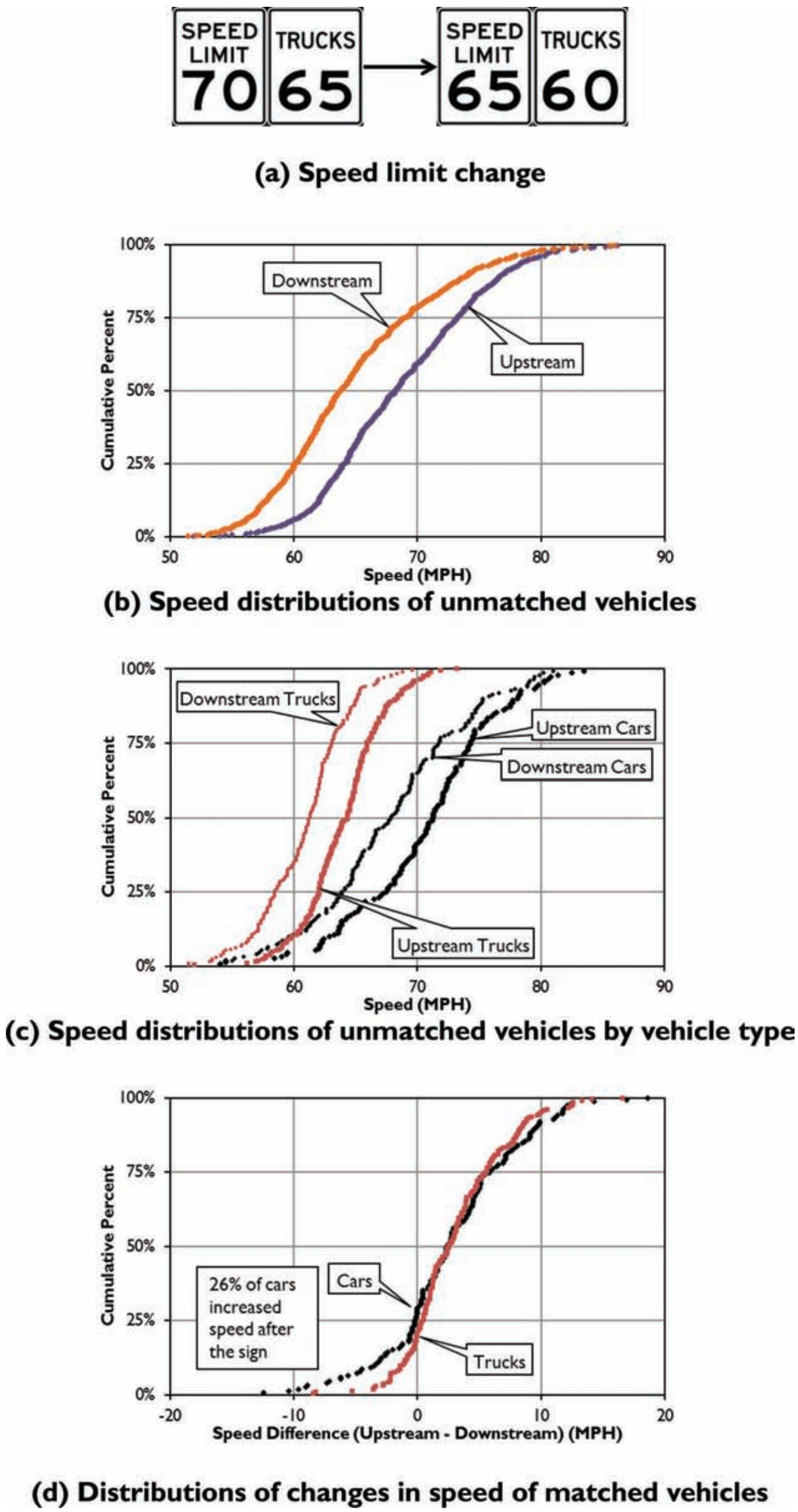


Figure 5.6 Methodology example of speed distributions in response to a static speed limit change at mile marker 178 on I-65 northbound (cars: 70 to 65 MPH; trucks: 65 to 60 MPH).

important later in the paper for evaluating driver behavior during the variable speed studies. For matched cars and trucks, the median change in speed was approximately 2.4 MPH and 2.5 MPH, respectively. Approximately 26% of cars and 20% of trucks sped up after the static sign.

5.2 Data Collection, Analysis, and Discussion

Spot speed data was collected at the work zone where the VSL signs were deployed at a number times and for a number of configurations. Table 5.1 summarizes the variable speed limit displays and sampling locations for each study, including the distance of each point from the start of the work zone speed limit. Data was collected prior to the VSL sign deployment and was used to determine the existing conditions at the site. The studies conducted between July 15, 2015, and November 6, 2015, were concerned with vehicle speeds in conjunction with single signs at each sign location. Studies conducted after November 6, 2015, used paired signs at each sign location.

Table 5.2 summarizes the quantity of data collected. The number of matched vehicles represents the sample sizes considered by researchers.

Speed data were collected from the northbound interstate section of interest (mile marker 76-80) on April 23, 2015, prior to the VSL signs being deployed. Speeds were found to be consistent along the section and were not affected by existing road conditions and geometry (Figure 5.7, Figure 5.8, and Figure 5.9). The work zone became active on March 16, 2015. The VSL signs were first activated on July 6, 2015, as a test. Otherwise, however, the signs were only active during periods of data collection. Consequently, the data was collected on motorists with little to no experience with the VSL signs on this section of interstate.

5.2.1 Speed Study 0

This study considered the behavior of motorist when the VSL signs were set to the regular posted static speed limit, which is 70 MPH. Figure 5.10b shows that driver behaviors generally did not change when the VSL signs displayed the regular speed limit. Figure 5.10e and Figure 5.10f also support this conclusion.

5.2.2 Speed Study 1

Speed Study 1 evaluated the influence of the first VSL sign set to 65 MPH (Figure 5.11a). In this case, the passenger vehicle speed limit reduced from 70 to 65 MPH, but the truck speed limit remained at 65 MPH. The upstream and downstream median truck speeds were both 65 MPH. Passenger vehicles dropped from an upstream median speed of 73.0 MPH to a downstream median speed of 71.4 MPH (Figure 5.11f). The speed distributions of trucks were more vertical than the speed distributions of cars (Figure 5.11e). Trucks appeared to be more compliant to the speed limit than passenger vehicles (Figure 5.11c and Figure 5.11d).

5.2.3 Speed Study 2

Speed Study 2 analyzed the influence of only the first VSL sign; set to 55 MPH. Figure 5.12b, Figure 5.12c, and Figure 5.12d show that for both cars and trucks, 100% of vehicles were speeding after the VSL sign (no points in Q3 or Q4). Figure 5.12e has very similar speed distributions to Study 1, implying that drivers respond similarly to a 55 MPH speed limit as to a 65 MPH speed limit. Lastly, Figure 5.12f is a plot of the distribution of changes of speed of matched vehicles. The median change in speed is approximately zero for both cars and trucks.

5.2.4 Speed Study 3

Speed Study 3 evaluated the influence of all three variable speed limits, set to 65 MPH, 55 MPH, and 55 MPH consecutively approaching the work zone. Instead of dropping the speed limit directly to 55 MPH, this configuration drops the car speed limit first by 5 MPH and then by 10 MPH. A large majority of vehicles were still speeding downstream of the VSL signs (Figure 5.13b, Figure 5.13c, and Figure 5.13d). However, Figure 5.13e shows that the magnitude of speeding is decreased. There was a median drop in speed of 7.5 MPH for cars and 5.8 MPH trucks (Figure 5.13f).

5.2.5 Speed Study 4

Speed Study 4 also considered the effect of all three VSL signs. In this case, all signs were set to 55 MPH. The percentage of vehicles speeding (Figure 5.14b, Figure 5.14c, and Figure 5.14d) in this study is similar to those in Study 3, as are the speed distributions (Figure 5.14e). There was a median drop in speed of 7.9 MPH for cars and 2.8 MPH for trucks (Figure 5.14f). Some possible explanations for the small drop in speed of trucks are that the sample size is small, traffic flow rates were fluctuating, and inter-truck communication may have alerted truck drivers that there was no enforcement of the speed limit.

5.2.6 Speed Study 2–Continued

Study 2 was repeated in the fall of 2015 order to obtain more data on the set-up. Figure 5.15b has significantly more data points that Figure 5.12b. Very few vehicles travel below the posted 55 MPH speed limit (Figure 5.15b). Figure 5.15f shows that neither cars nor trucks adjust their speeds after only one VSL sign, which is consistent with the conclusion from the original Speed Study 2.

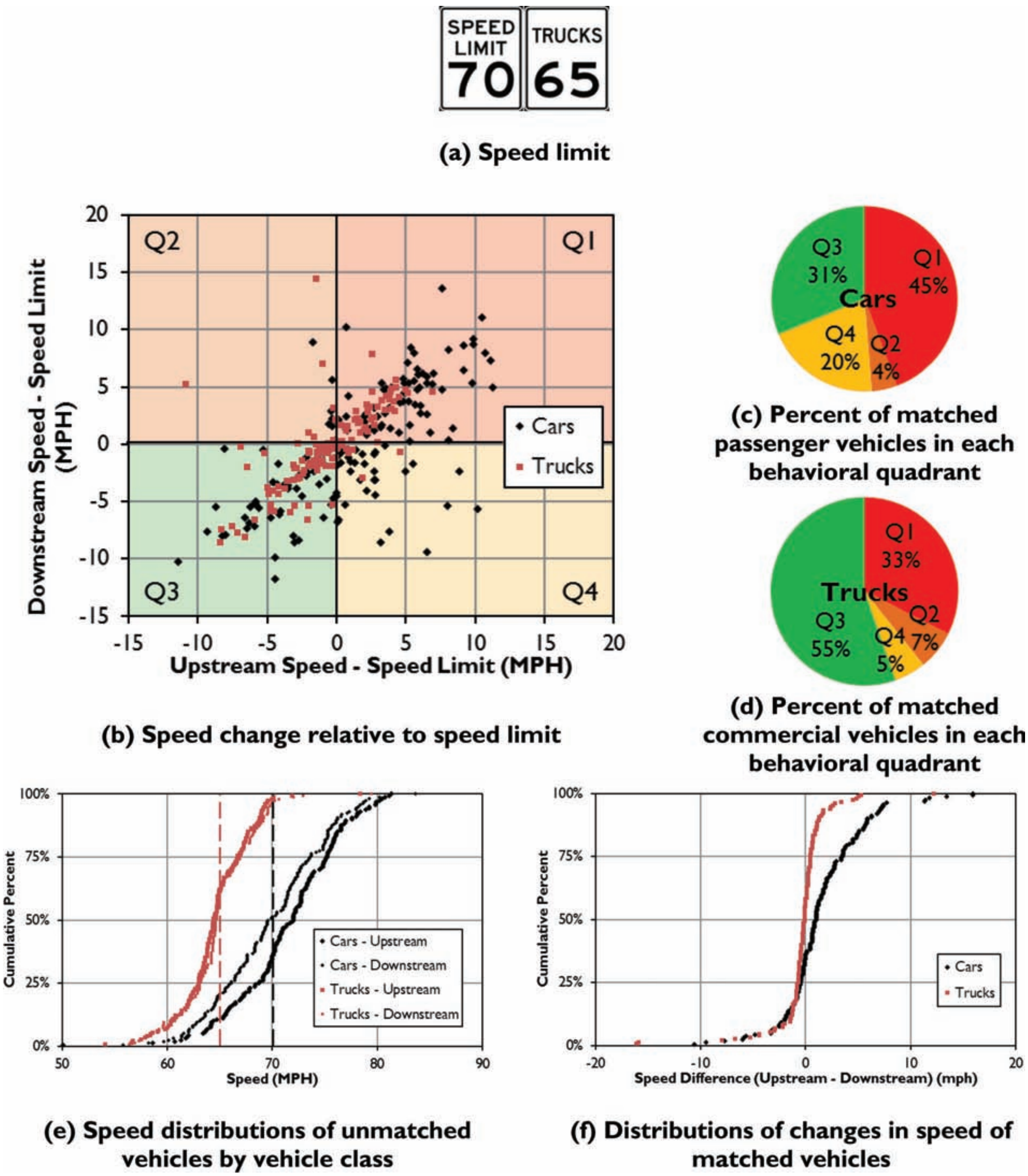
5.2.7 Speed Study 5

This study evaluated vehicle speeds across two sign locations. Both VSL signs were set to 55 MPH. Figure 5.16f shows that while the median change in truck speed is 0.3 MPH (the same as in Speed Study 2, Figure 5.15f), the median speed reduction of cars is 1.6 MPH. Again, very few vehicles travel below 55 MPH (Figure 5.16b).

TABLE 5.1
Speed Study Set-Ups with Sign and Collection Point Locations

			Upstream Static Speed Limit Sign	Collection Point 4	Variable Speed Limit Sign	Collection Point 3	Variable Speed Limit Sign	Collection Point 2	Variable Speed Limit Sign	Collection Point 1	Work Zone Speed Limit Sign
		MM		**75.9**	**76.5**	**77.1**	**77.5**	**78.0**	**79.0**	**79.2**	**79.5**
Date	**Time**	**Dist.***		**3.6**	**3.0**	**2.4**	**2.0**	**1.5**	**0.5**	**0.3**	
4/23	10:00–10:45		SPEED LIMIT 70 TRUCKS 65					X		X	SPEED LIMIT 45
4/23	11:00–11:50		SPEED LIMIT 70 TRUCKS 65			X		X			SPEED LIMIT 45
4/23	13:50–14:50		SPEED LIMIT 70 TRUCKS 65	X		X					SPEED LIMIT 45
7/15	9:40–10:30	Study 0	SPEED LIMIT 70 TRUCKS 65	X	SPEED LIMIT 70	X	SPEED LIMIT 55		SPEED LIMIT 55		SPEED LIMIT 45
7/15	10:30–11:30	Study 1	SPEED LIMIT 70 TRUCKS 65	X	SPEED LIMIT 65	X	SPEED LIMIT 55		SPEED LIMIT 55		SPEED LIMIT 45
7/15	11:30–12:00	Study 2	SPEED LIMIT 70 TRUCKS 65	X	SPEED LIMIT 55	X	SPEED LIMIT 55		SPEED LIMIT 55		SPEED LIMIT 45
7/15	13:40–14:30	Study 3	SPEED LIMIT 70 TRUCKS 65	X	SPEED LIMIT 65		SPEED LIMIT 55		SPEED LIMIT 55	X	SPEED LIMIT 45
7/15	14:30–15:30	Study 4	SPEED LIMIT 70 TRUCKS 65	X	SPEED LIMIT 55		SPEED LIMIT 55		SPEED LIMIT 55	X	SPEED LIMIT 45
10/02	12:20–14:20	Study 2 New	SPEED LIMIT 70 TRUCKS 65	X	SPEED LIMIT 55	X	SPEED LIMIT 55		SPEED LIMIT 55		SPEED LIMIT 45
10/23	10:00–12:00	Study 5	SPEED LIMIT 70 TRUCKS 65	X	SPEED LIMIT 55		SPEED LIMIT 55	X	SPEED LIMIT 55		SPEED LIMIT 45
10/23	13:10–15:10	Study 4 New	SPEED LIMIT 70 TRUCKS 65	X	SPEED LIMIT 55		SPEED LIMIT 55		SPEED LIMIT 55	X	SPEED LIMIT 45
11/06	9:30–11:10	Study 6	SPEED LIMIT 70 TRUCKS 65	X	SPEED LIMIT 55		SPEED LIMIT 45	X	SPEED LIMIT 45		SPEED LIMIT 45
11/06	12:10–14:00	Study 7	SPEED LIMIT 70 TRUCKS 65	X	SPEED LIMIT 55		SPEED LIMIT 45		SPEED LIMIT 45	X	SPEED LIMIT 45
11/20	11:35–12:55	Study 8	SPEED LIMIT 70 TRUCKS 65	X	SPEED LIMIT 55 SPEED LIMIT 55	X	SPEED LIMIT 55 SPEED LIMIT 55		SPEED LIMIT 55 SPEED LIMIT 55		SPEED LIMIT 45
12/04	9:40–11:00	Study 9	SPEED LIMIT 70 TRUCKS 65	X	SPEED LIMIT 55 SPEED LIMIT 55		SPEED LIMIT 55 SPEED LIMIT 55	X	SPEED LIMIT 55 SPEED LIMIT 55		SPEED LIMIT 45
12/11	14:00–13:30	Study 10	SPEED LIMIT 70 TRUCKS 65	X	SPEED LIMIT 55 SPEED LIMIT 55		SPEED LIMIT 55 SPEED LIMIT 55		SPEED LIMIT 55 SPEED LIMIT 55	X	SPEED LIMIT 45

MM = Mile marker.
X = Data collected at sampling station.
Dist.* = Distance from the start of the work zone speed limit in miles.



(a) Speed limit

(b) Speed change relative to speed limit

(c) Percent of matched passenger vehicles in each behavioral quadrant

(d) Percent of matched commercial vehicles in each behavioral quadrant

(e) Speed distributions of unmatched vehicles by vehicle class

(f) Distributions of changes in speed of matched vehicles

Figure 5.7 Existing conditions across Sign A.

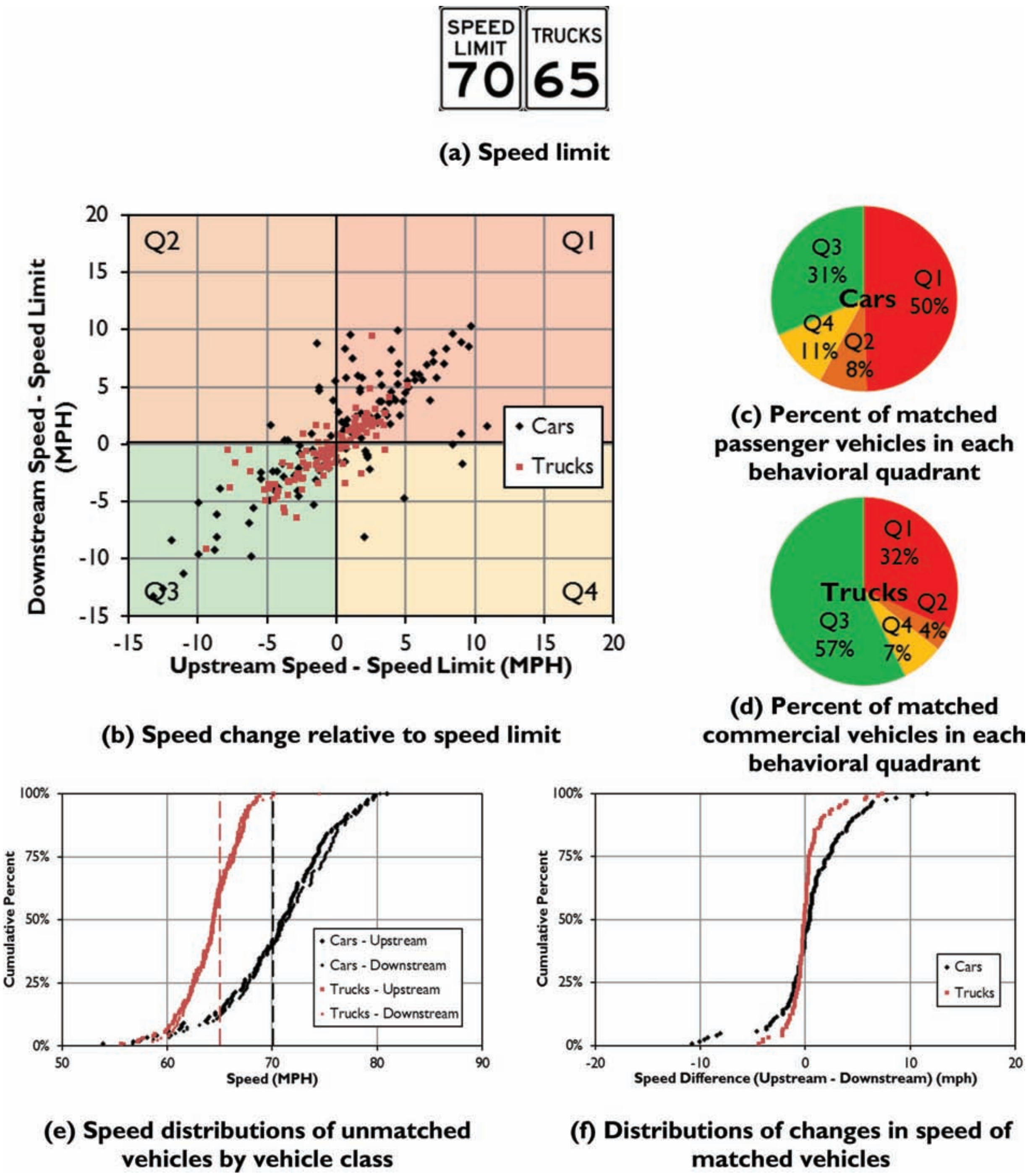


Figure 5.8 Existing conditions across Sign B.

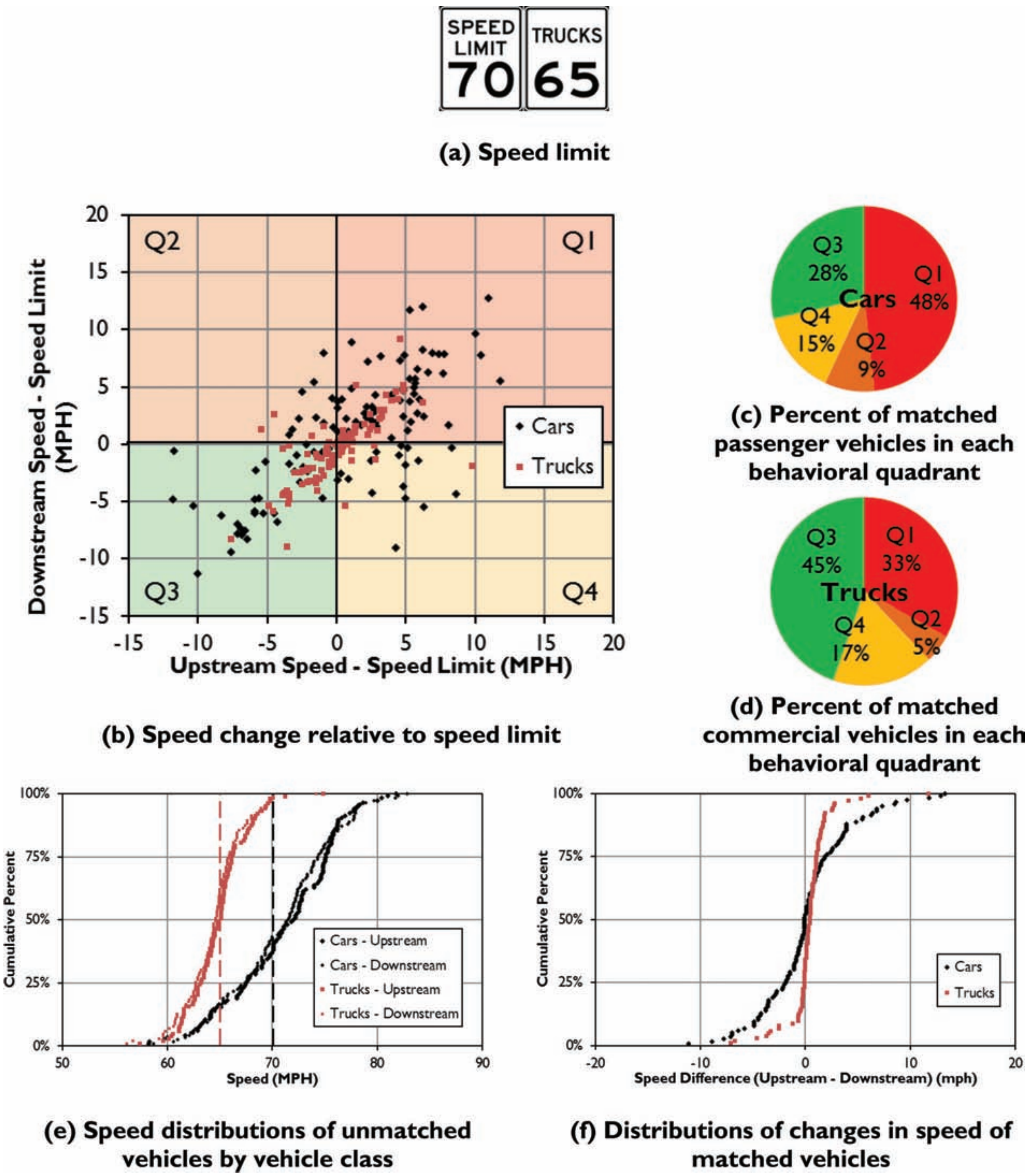


Figure 5.9 Existing conditions across Sign C.

TABLE 5.2
Summary of All Speed Studies Conducted with Speed Radar and Data Collected

Date of Study	Start Time	End Time	Duration (hr)	Type of Speed Limit	Speed Limit	Mile Marker and Direction	Number of Unmatched Vehicles Upstream	Number of Unmatched Vehicles Downstream	Number of Matched Cars	Number of Matched Trucks	Matched Percentage of Vehicles
6/12/2015	9:45	10:45	1.00	Static	70/65 → 65/60	178 SB	638	764	151	207	51%
4/23/2015	10:00	10:45	0.75	N/A	70/65	79 NB	507	616	160	148	55%
4/23/2015	11:00	11:50	0.83	N/A	70/65	77.5 NB	428	425	121	124	57%
4/23/2015	13:50	14:50	1.00	N/A	60/65	76.5 NB	431	689	116	103	39%
7/15/2015	9:40	10:30	0.83	V (1)	70/65 → 70	76.5 NB	416	665	185	101	53%
7/15/2015	10:30	11:30	1.00	V (1)	70/65 → 65	76.5 NB	557	967	266	112	50%
7/15/2015	11:30	12:00	0.50	V (1)	70/65 → 55	76.5NB	279	514	139	53	48%
7/15/2015	13:40	14:30	0.83	V (3)	70/65 → 65-55-55	76.5-79 NB	491	900	199	61	37%
7/15/2015	14:30	15:30	1.00	V (3)	70/65 → 55-55-55	76.5-79 NB	539	1024	198	68	34%
10/2/2015	12:20	14:20	2.00	V (1)	70/65 → 55	76.5 NB	1679	2318	568	584	58%
10/23/2015	10:00	12:00	2.00	V (2)	70/65 → 55-55	76.5-77.5 NB	1956	1787	605	504	59%
10/23/2015	13:10	15:10	2.00	V (3)	70/65 → 55-55-55	76.5-79 NB	1993	1822	566	377	49%
11/6/2015	9:30	11:10	1.67	V (2)	70/65 → 55-45	76.5-77.5 NB	1607	972	369	322	54%
11/6/2015	12:10	14:00	1.83	V (3)	70/65 → 55-45-45	76.5-79 NB	2033	1599	688	409	60%
11/20/2015	11:35	12:55	1.33	V (1) pairs	70/65 → 55	76.5 NB	1384	1305	529	346	65%
12/4/2015	9:40	11:00	1.33	V (2) pairs	70/65 → 55-55	76.5-77.5 NB	1288	1029	447	367	70%
12/11/2015	14:00	15:30	1.50	V (3) pairs	70/65 → 55-55-55	76.5-79 NB	1575	1536	419	304	46%
TOTAL			20.4				17163	18168	5575	3983	54%

N/A = No speed limit sign (study of existing conditions).
V (1) = Variable speed limit sign (1 location).
V (2) = Variable speed limit sign (2 locations).
V (3) = Variable speed limit sign (3 locations).

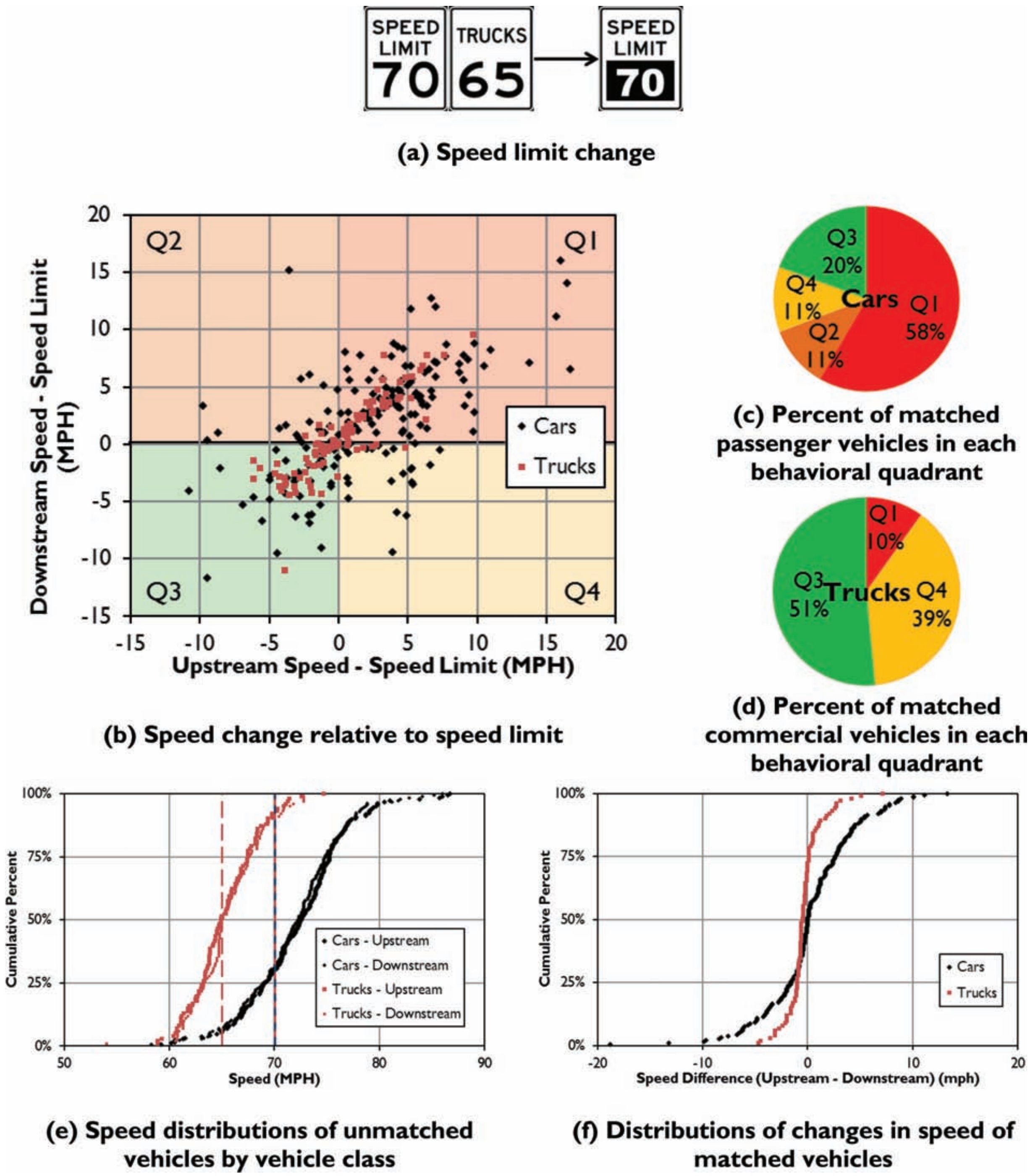


Figure 5.10 Speed Study 0 analysis.

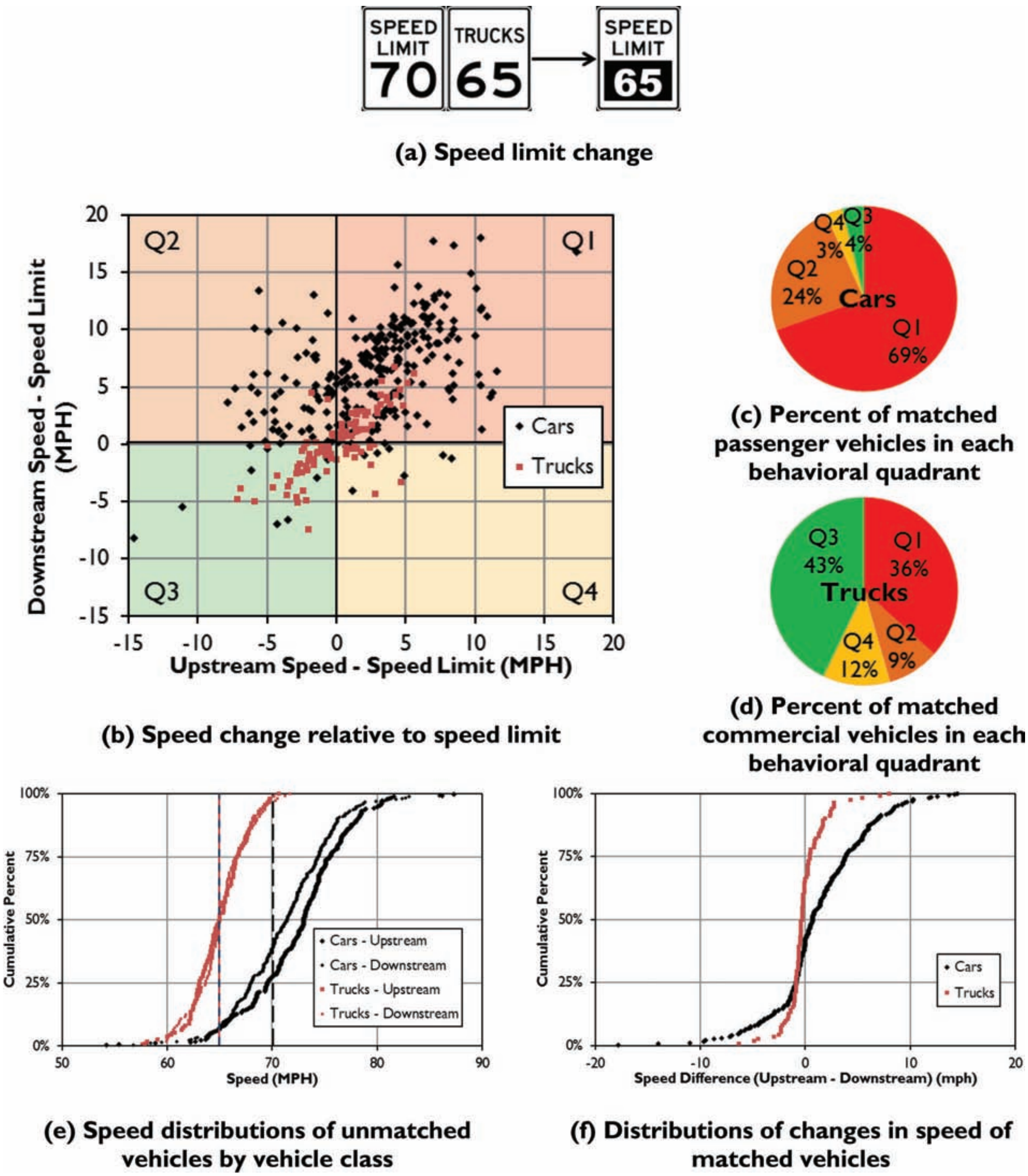


Figure 5.11 Speed Study 1 analysis.

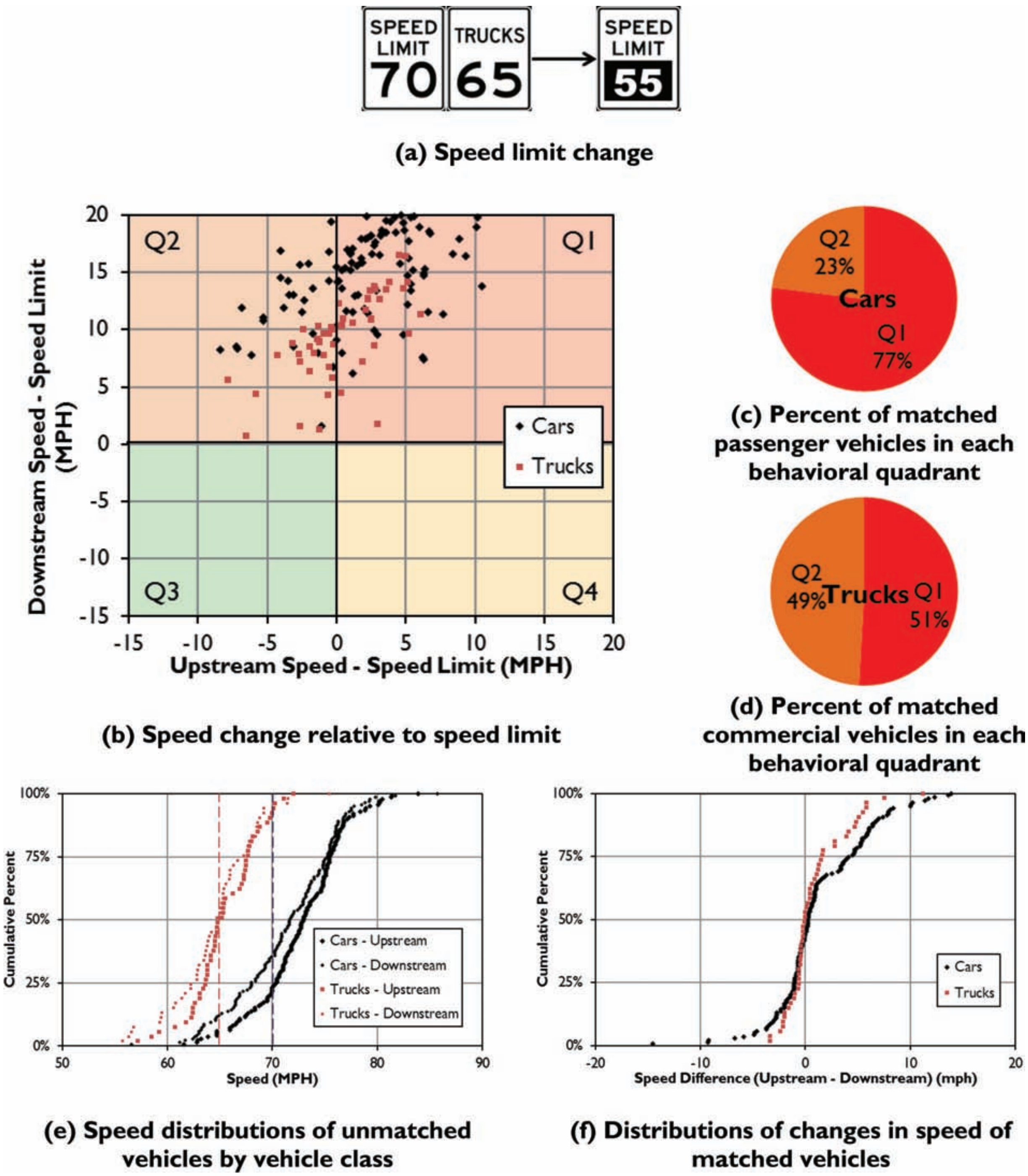


Figure 5.12 Speed Study 2 analysis.

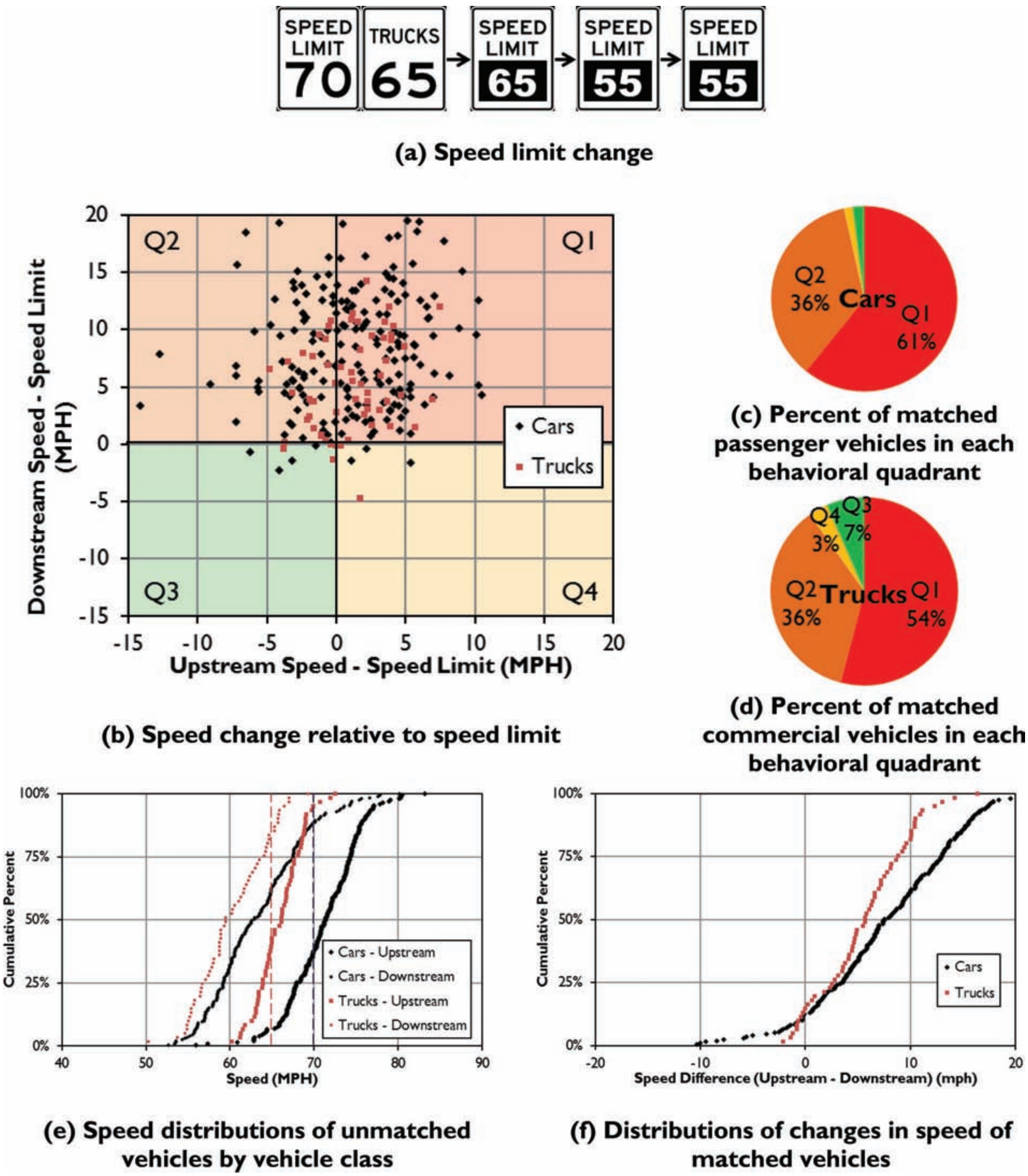


Figure 5.13 Speed Study 3 analysis.

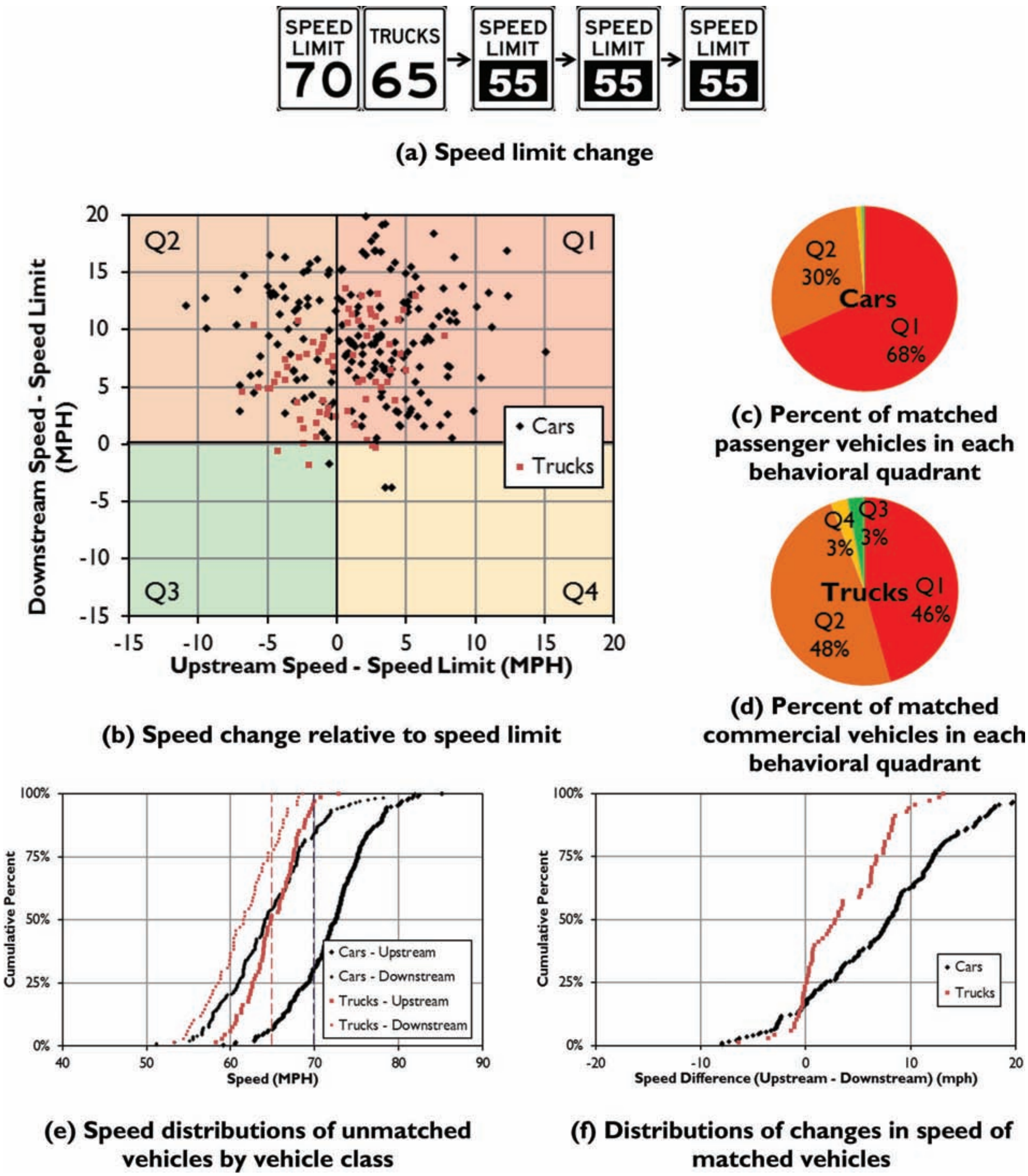


Figure 5.14 Speed Study 4 analysis.

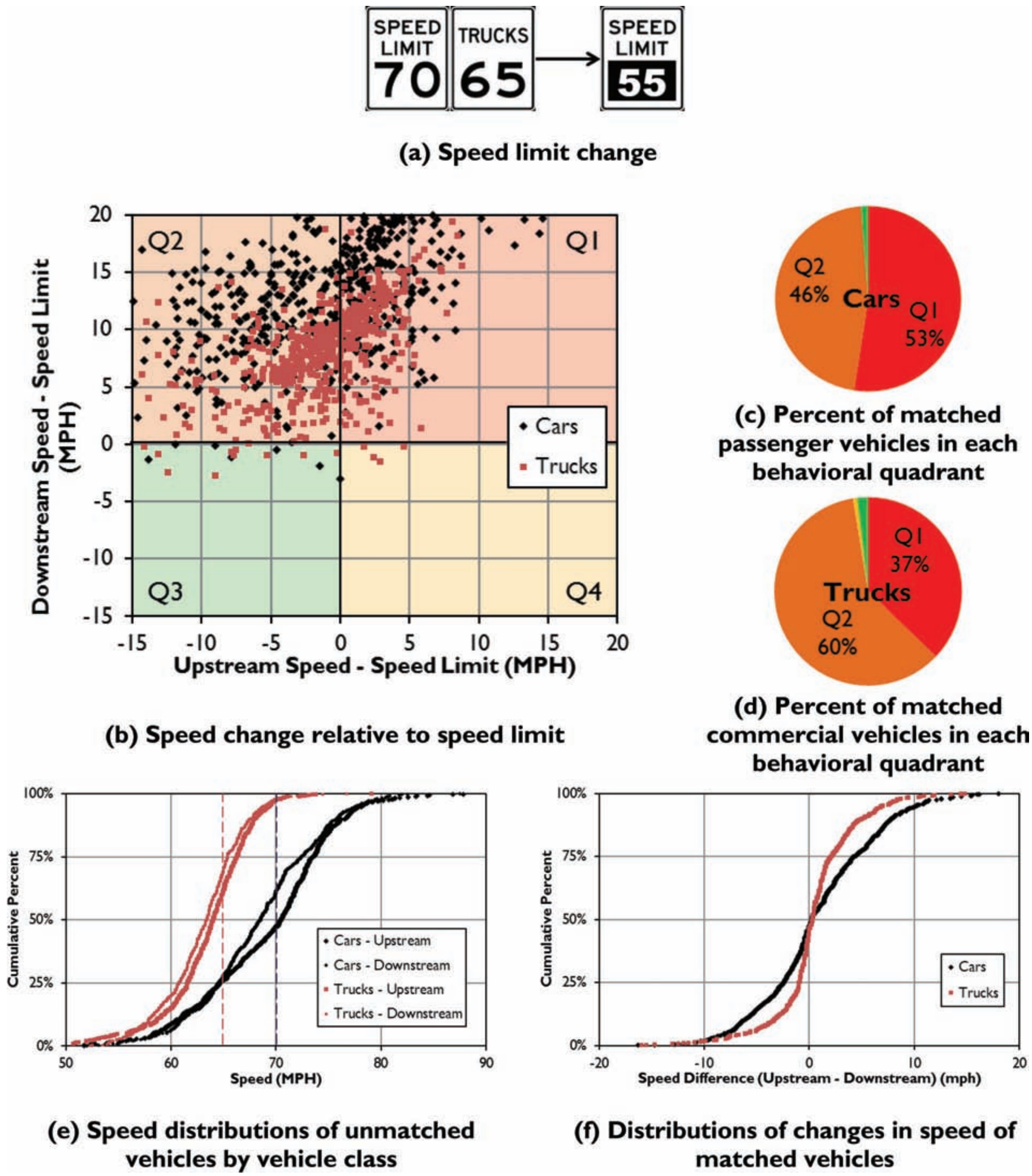


Figure 5.15 Speed Study 2-new analysis.

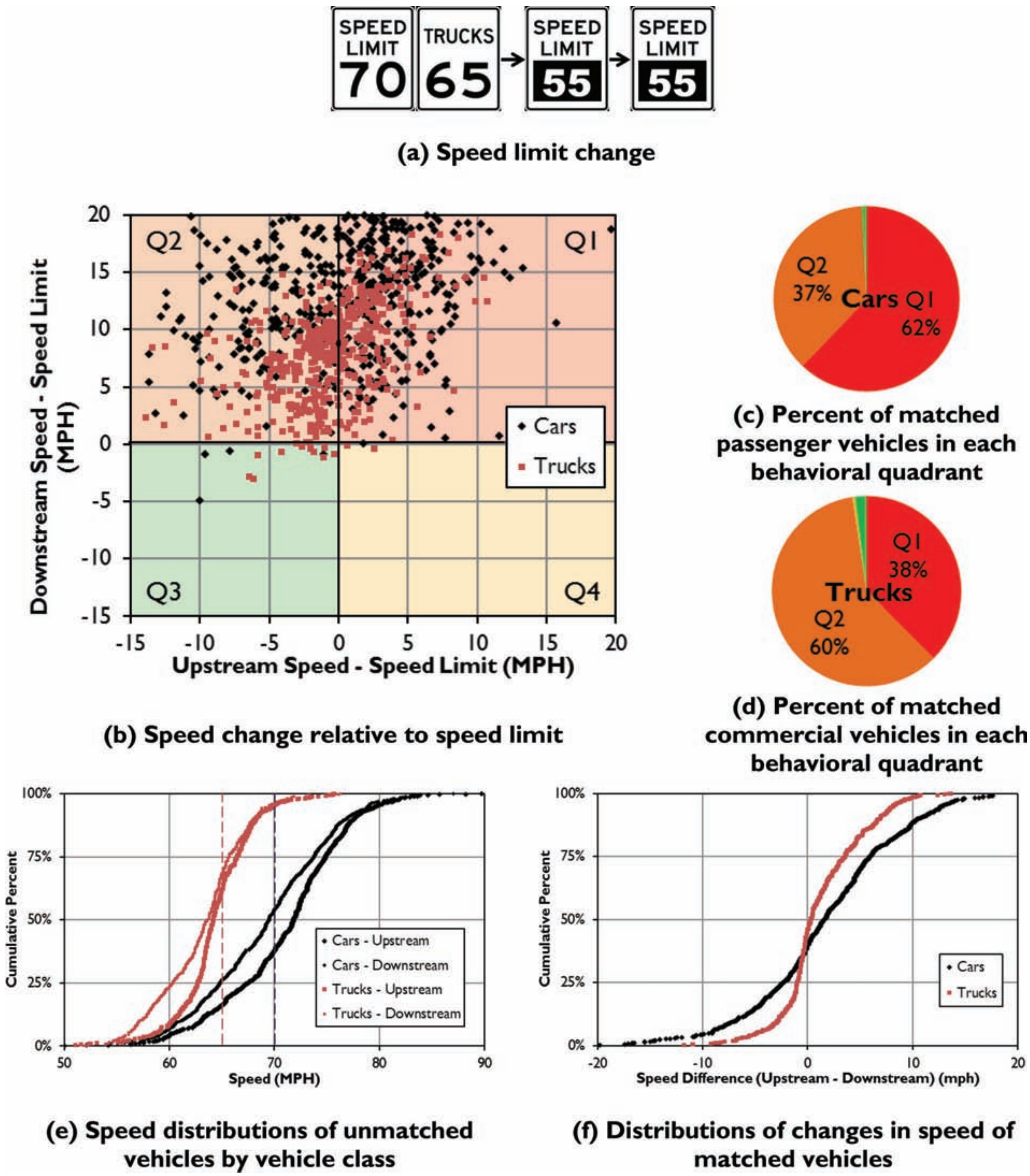


Figure 5.16 Speed Study 5 analysis.

5.2.8 Speed Study 4–Continued

Study 4 was repeated, similar to Study 2, for more data points. Figure 5.17b shows that more vehicles select a speed lower than the 55 MPH speed limit after passing all three VSL signs. The median reduction in speed is 3.3 MPH for cars and 2.1 MPH for trucks (Figure 5.17f).

5.2.9 Speed Study 6

This study was similar to Speed Study 5, in that 2 sign locations were used. However, the first sign was set to 55 MPH and the second sign was set to 45 MPH. Figure 5.18b shows that very few drivers complied with the final 45 MPH speed limit. However, Figure 5.18f shows that the sign set-up had a greater impact on speed

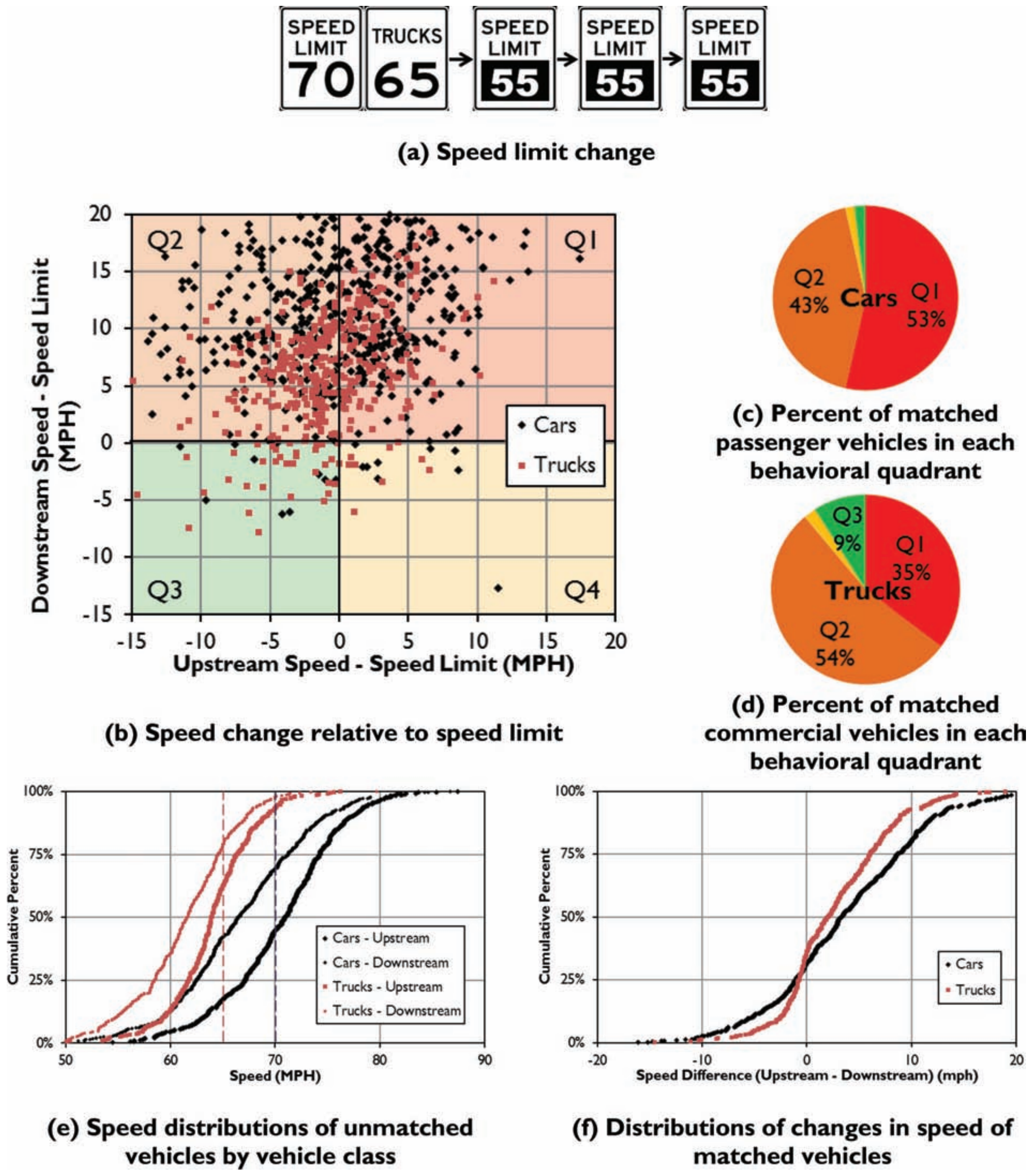


Figure 5.17 Speed Study 4-new analysis.

reductions. Fifty percent of passenger vehicles reduced their speed by more than 3.7 MPH (1.2 MPH for trucks).

5.2.10 Speed Study 7

This study is comparable to Study 4 and Study 4-new, except that the final speed limit is 45 MPH. As seen in Speed Study 6, very few drives complied with the 45 MPH downstream of the VSL signs (Figure 5.19b). But Figure 5.19f shows that the median reduction in speed was 7.9 MPH for cars and 5.4 MPH for trucks. This set-up influences a greater shift in speeds towards 55 MPH than setting all three signs to 55 MPH. However, using the VSL signs in such a manner may cause driver confusion and enforcement difficulties.

5.2.11 Speed Study 8

In this study, only one sign location was considered but two signs were paired at the location. One sign

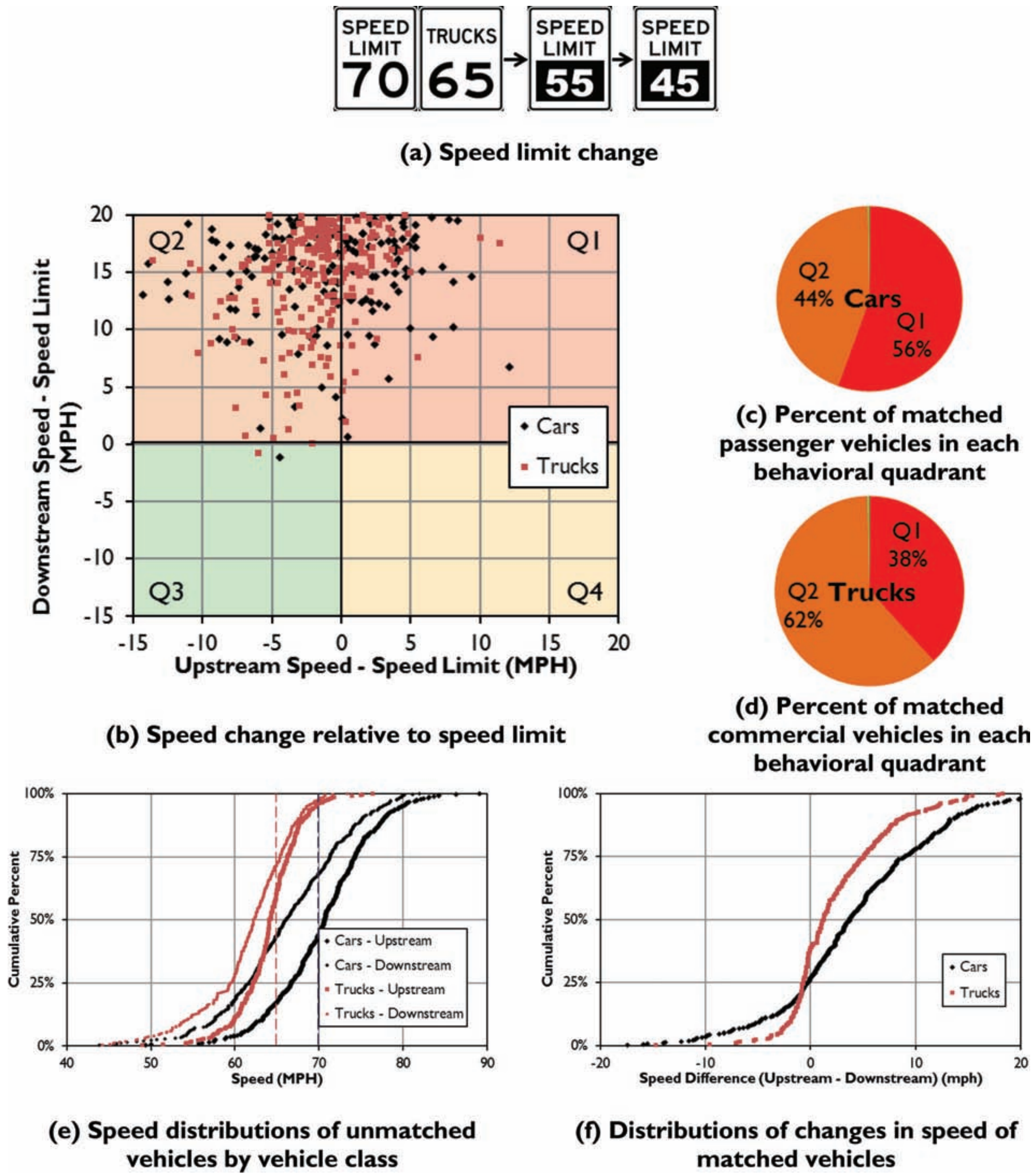


Figure 5.18 Speed Study 6 analysis.

was positioned on each shoulder and both were set to 55 MPH. As with the other studies looking at only one location, there is little to no impact of vehicle speeds. In Figure 5.20b, the data points fall loosely on a straight line, implying no change in individual driver behavior. The median reduction in speed for both vehicle types is nearly zero (Figure 5.20f). In fact, the upstream and downstream speed distributions for trucks are on top of each other (Figure 5.20e).

5.2.12 Speed Study 9

Two locations with paired signs, all set to 55 MPH, have greater impact than a single location. Speed distributions shift for both cars and trucks from upstream to downstream (Figure 5.21e). The median speed reduction is 4.2 MPH for cars and 1.5 MPH for tucks (Figure 5.21f). Compliance with the final speed limit of 55 MPH also increases slightly (see Figure 5.21b, Figure 5.21c, and Figure 5.21d).

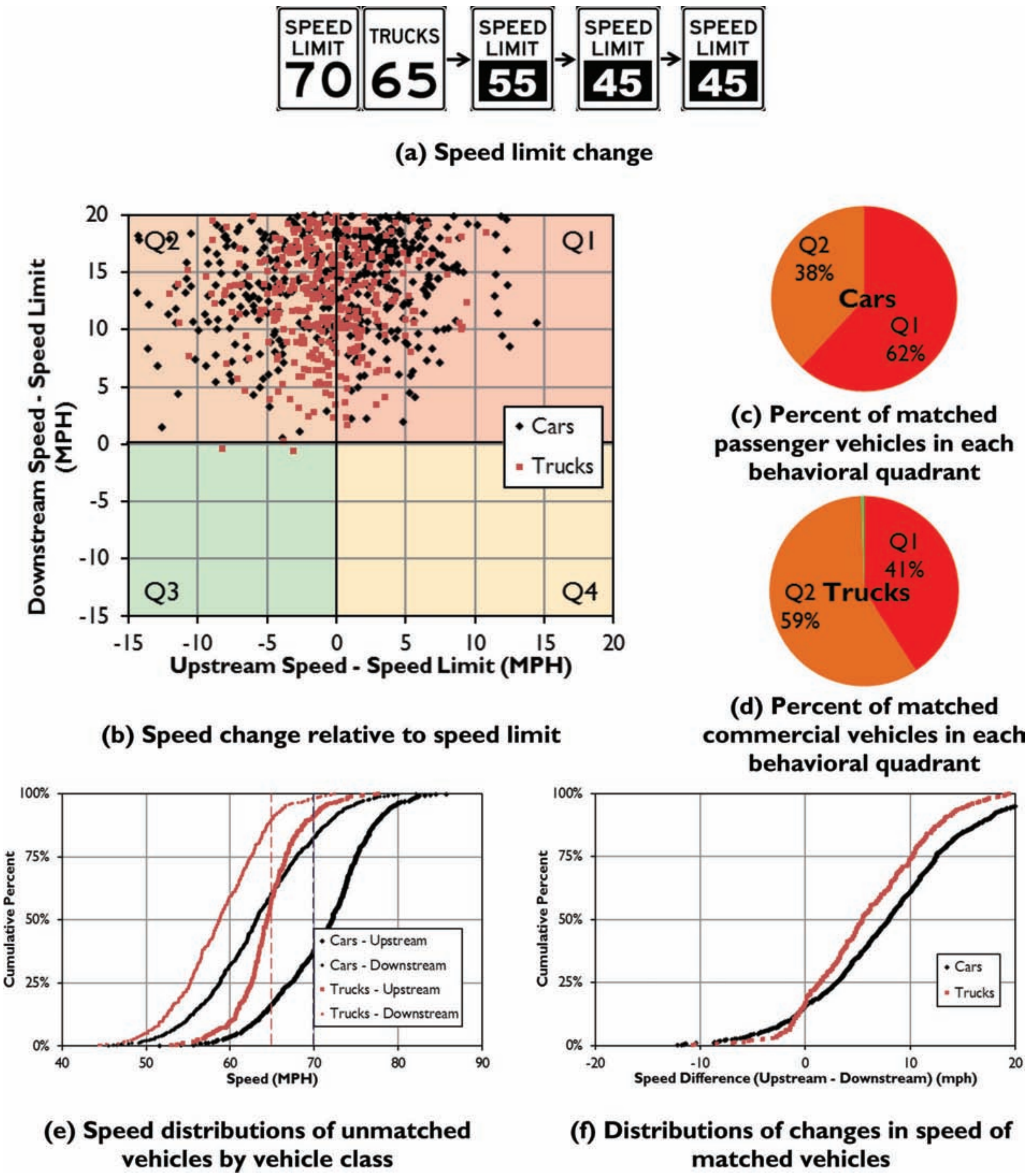


Figure 5.19 Speed Study 7 analysis.

5.2.13 Speed Study 10

Lastly, three locations of paired signs were considered with a final speed limit of 55 MPH (Figure 5.22a). There was increased compliance with the final speed limit for both cars and trucks (Figure 5.22c, Figure 5.22d). The median reduction in speed was 4.7 MPH for cars and 2.8 MPH for trucks (Figure 5.22f).

5.3 Comparison of Consecutive Signs

Figure 5.23 compares the matched-vehicle speed change distributions for Study 2-new, Study 5, and Study 4-new by vehicle class. Study 2-new and Study 4-new were used instead of Study 2 and Study 4 due to the larger sample size. Neither vehicle type appears to be influenced by only a single VSL sign location.

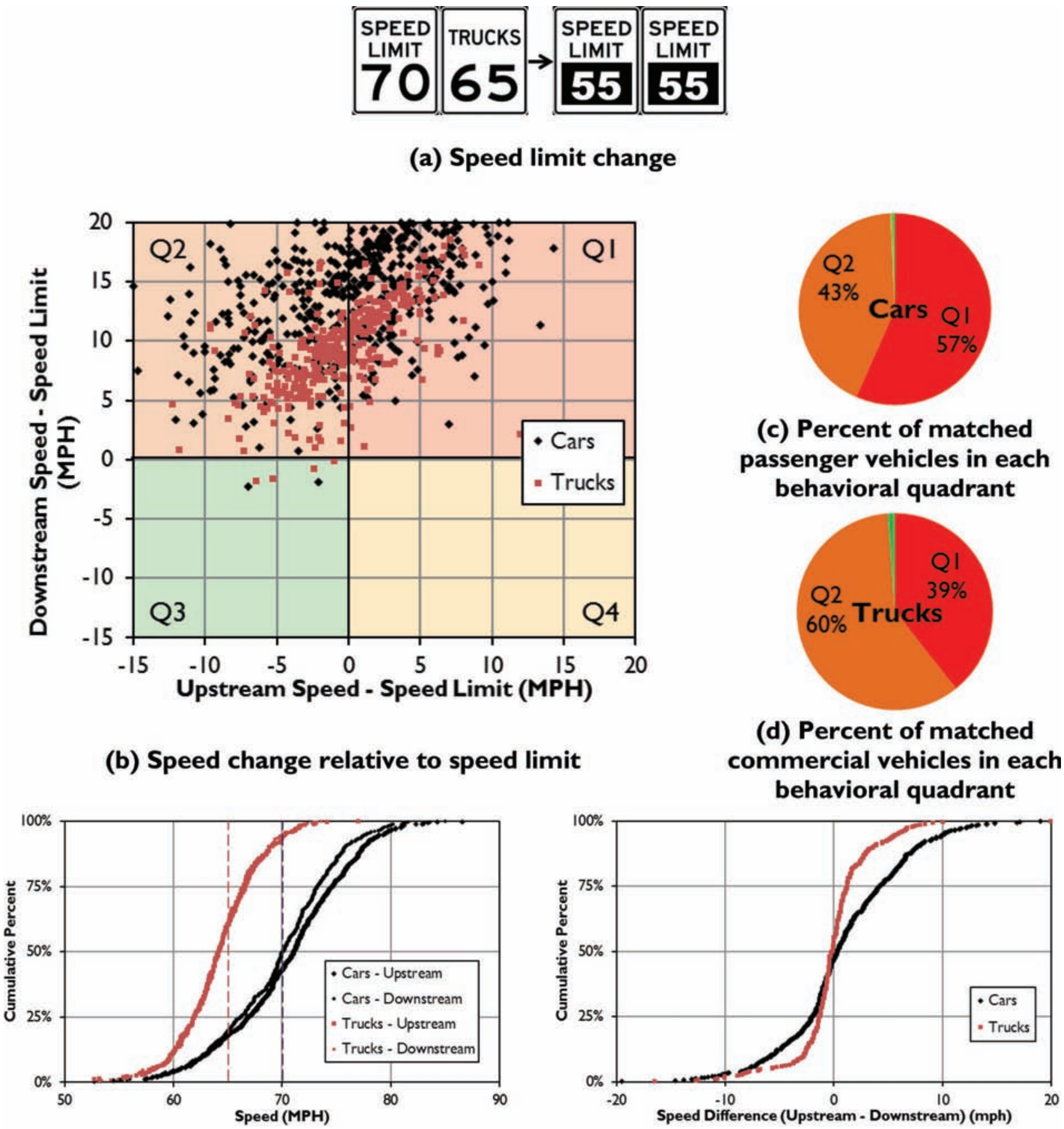


Figure 5.20 Speed Study 8 analysis.

However, the distribution of speed reduction shifts further to the right for both vehicle types as drivers observe more consecutive sign locations. Three consecutive, closely spaced VSL signs influence passenger vehicles to drop in speed by a median of 3.3 MPH (Figure 5.23a). Passenger vehicles drop their speed only by about one-fifth the magnitude required by the change in speed limit. The median speed reduction for trucks across three VSL signs was 2.1 MPH (Figure 5.23b). An important conclusion from Figure 5.23 is that repetition is needed to influence vehicle speeds. Approximately 46% of vehicles sped up across the variable speed signage in Study 2-new but only 31% sped up in Study 4-new. Of all vehicles, 1% of cars and 3% of trucks complied with the 55 MPH speed limit in Study 2-new. In Study 4-new, 4% of cars and 11% of trucks complied with the 55 MPH speed limit.

Figure 5.24 shows similar trends with paired signs. Across only a single sign location, the median speed reduction is negligible for both cars and trucks.

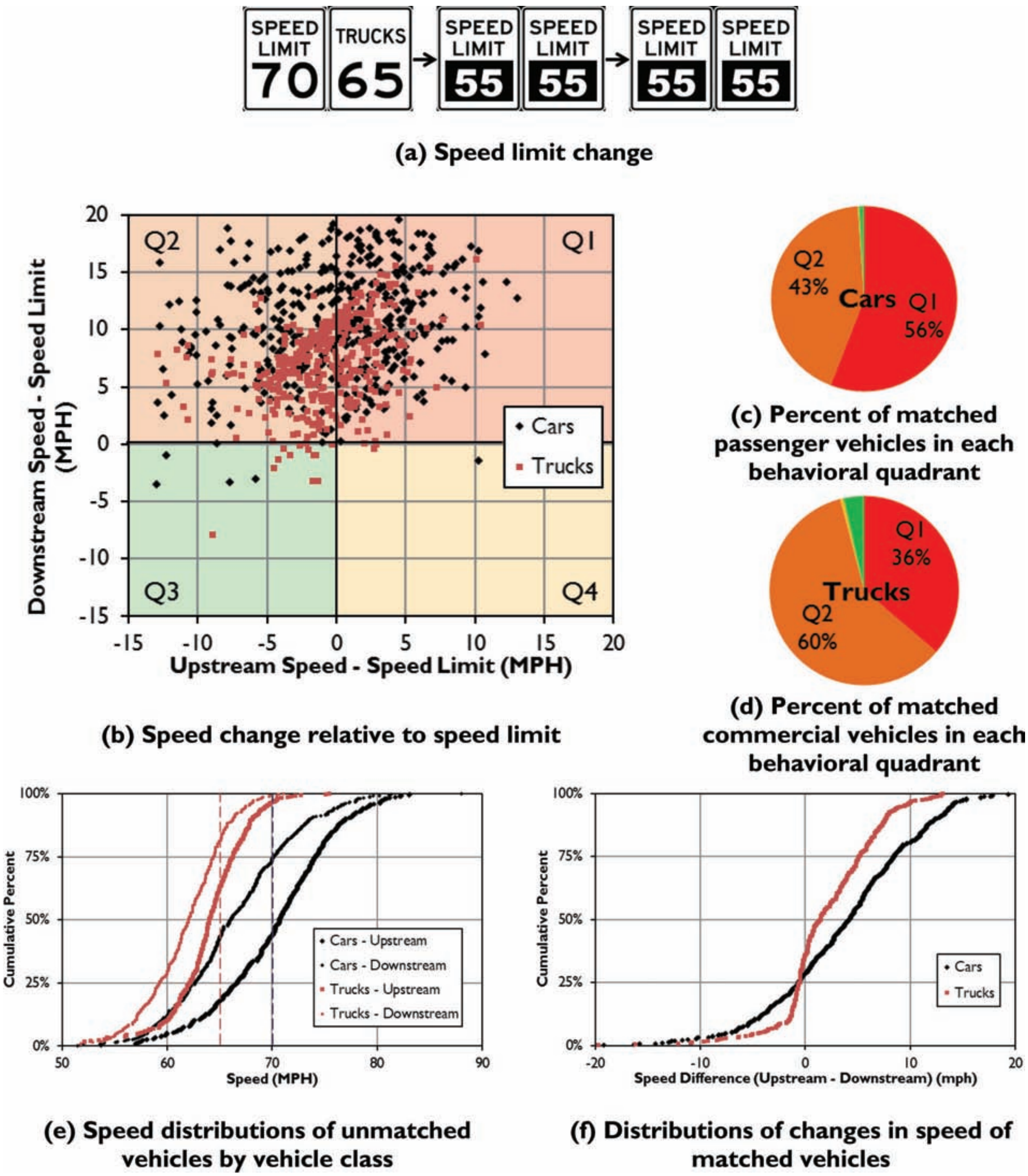


Figure 5.21 Speed Study 9 analysis.

However, across three sign locations, the median speed reduction is 4.7 MPH for cars and 2.8 MPH for trucks. It is interesting to note that for paired signs, the effects of two and three sign locations on vehicle speeds are similar in magnitude.

5.4 Comparison of Single and Paired Signs

A major change in sign configuration during the study of the variable speed limit signs was the shift from single signs, placed on the right shoulder, to paired signs. Figure 5.25 shows this concept with both a minimalistic diagram and photos of both a single and paired signs at the same location. The motivation for this change was the concern regarding visibility of the single sign to drivers.

Across only a single location, a single sign and a pair of signs are comparable (Figure 5.26). As it was established in the previous section, more than one location is needed in order to have an impact on vehicle speeds.

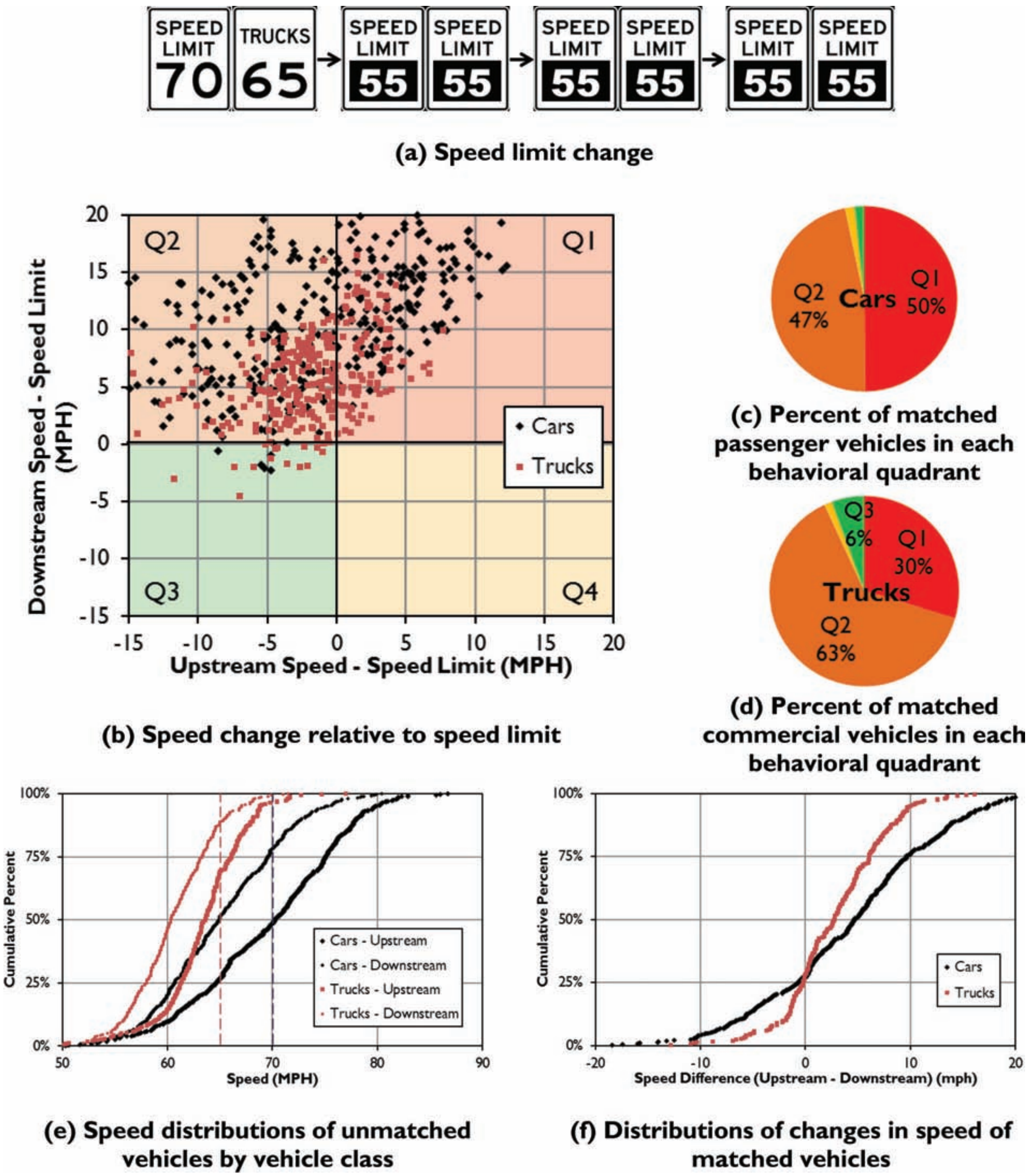


Figure 5.22 Speed Study 10 analysis.

Figure 5.27 shows that paired signs have a greater impact than a single sign across two locations. Lastly, Figure 5.28 shows that the impact of paired signs is not significantly greater than single signs across three locations. However, this may be because the third and final location is within sight of the start of the work zone. The effect of the third location may have been downplayed by the effect of the work zone on vehicle speeds.

Similar conclusions can be made using crowdsourced probe vehicle speed data. Space mean speeds are provided for roadway segments that are based on a proprietary segmentation scheme and are about 1 to 2 miles in length. Different signing conditions can be compared without stationing researchers in the field for data collection, which costs time and money. Traffic conditions and the effect of the variable speed limit signs can be monitored remotely by using real-time

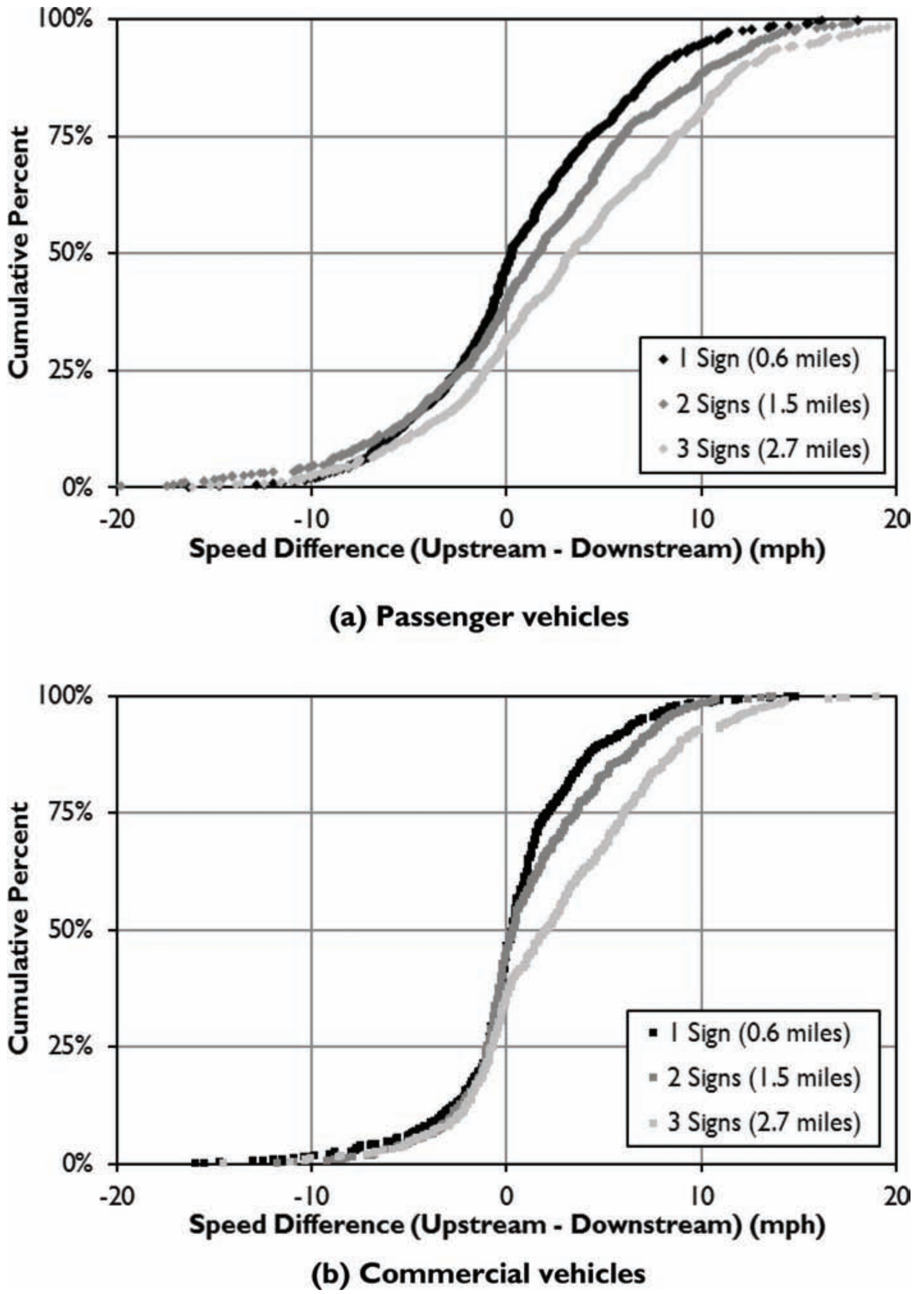


Figure 5.23 Comparison of change of speed of matched vehicles across consecutive single signs from Speed Studies 2-new, 4-new, and 5.

crowdsourced probe vehicle data. In Figure 5.28, each graph depicts the maximum, 75th percentile, median, 25th percentile, and minimum speeds observed in the crowdsourced probe vehicle data for different sign configurations. The data are plotted longitudinally, with the direction of travel being from the left (mile marker 76) to the right (mile marker 80). For each of the three cases, speeds generally decrease as the distance to the work zone decreases.

In Figure 5.29a, the black line represents the median speed during any of the time periods where all of the individual signs were set to 55 MPH. The dashed red line represents the median speed during the time periods when the paired signs are set to 55 MPH. Lastly, the thick grey line represents all the time periods where the VSL signs, either individual or paired, are present but blank. It should be noted that there are significantly more data for this last condition than the first two. However, Figure 5.29a shows that the paired signs slow vehicles more than single signs or signs off upstream of the work zone. The interquartile ranges of the probe vehicle speeds were generally smaller during periods when paired signs were used than when individual signs were used or when the signs were off. This means that variability in the average speed was decreased.

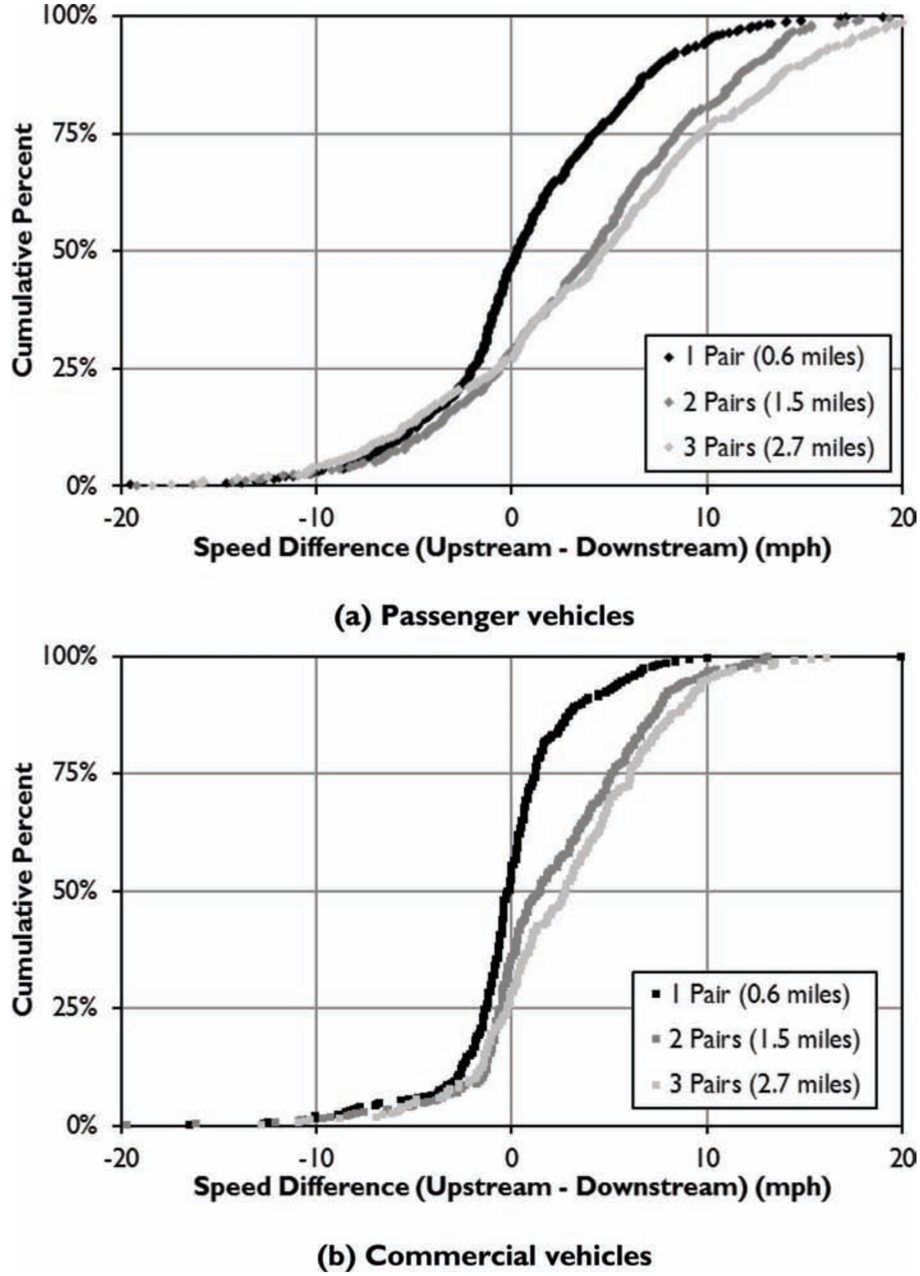
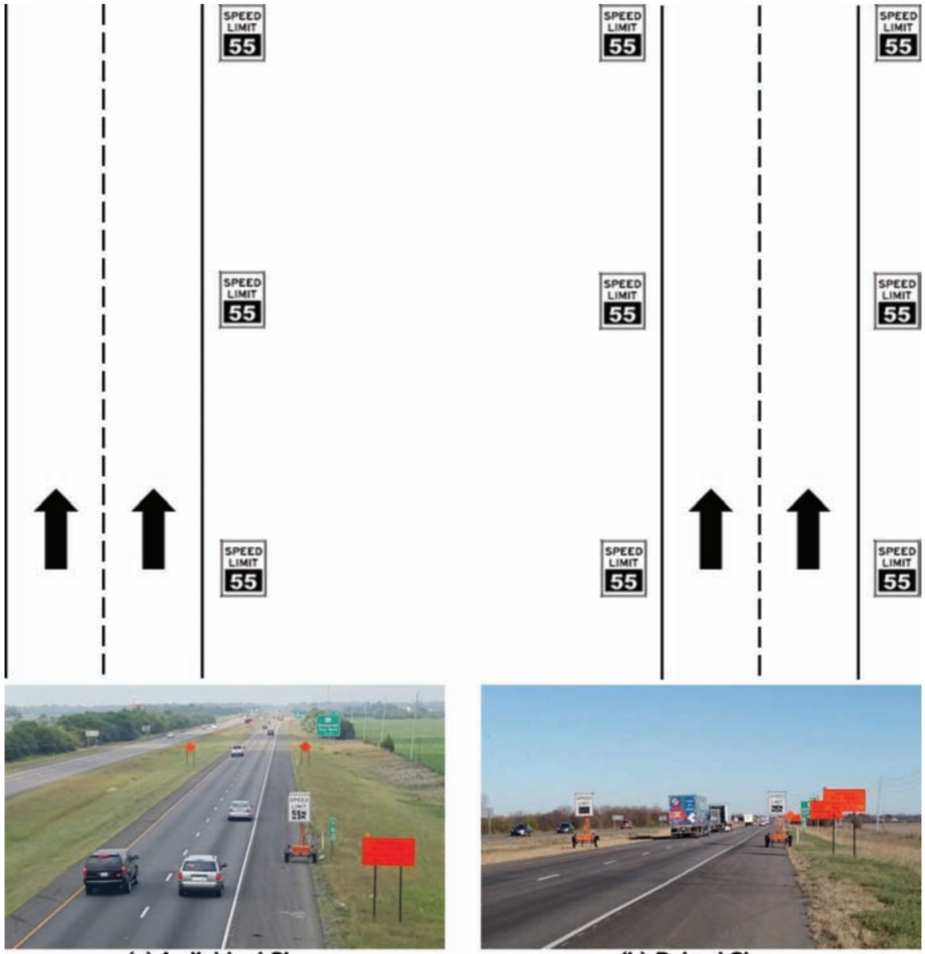


Figure 5.24 Comparison of change of speed of matched vehicles across consecutive paired signs from Speed Studies 8, 9, and 10.

5.5 Variable Speed Study Conclusions and Recommendations

Using vehicle-matched data, an in-depth analysis of driver behavior was possible for the evaluation of the variable speed limit signs upstream of the work zone. From the various speed studies of the variable speed signs, the following conclusions were made:

- Commercial trucks were generally more compliant to speed limits than passenger vehicles.
- Less than 2% of matched vehicles complied with the 55 MPH speed limit after observing one VSL sign, regardless of whether there was a single or pair of signs at that location.
- At least 3 consecutive VSL signs are necessary to significantly impact vehicle speeds.
- Paired signs have a greater impact on vehicle speeds than single signs due to greater visibility.
- It is important to place VSL signs further upstream than expected work zone queueing in order for the signs to be useful for slowing traffic prior to reaching the back of the queue.
- Vehicle-matching is useful for analyzing individual driver behavior in response to speed limit changes.



(a) Individual Signs (b) Paired Signs

Figure 5.25 Conceptual set-up of variable speed limit study.

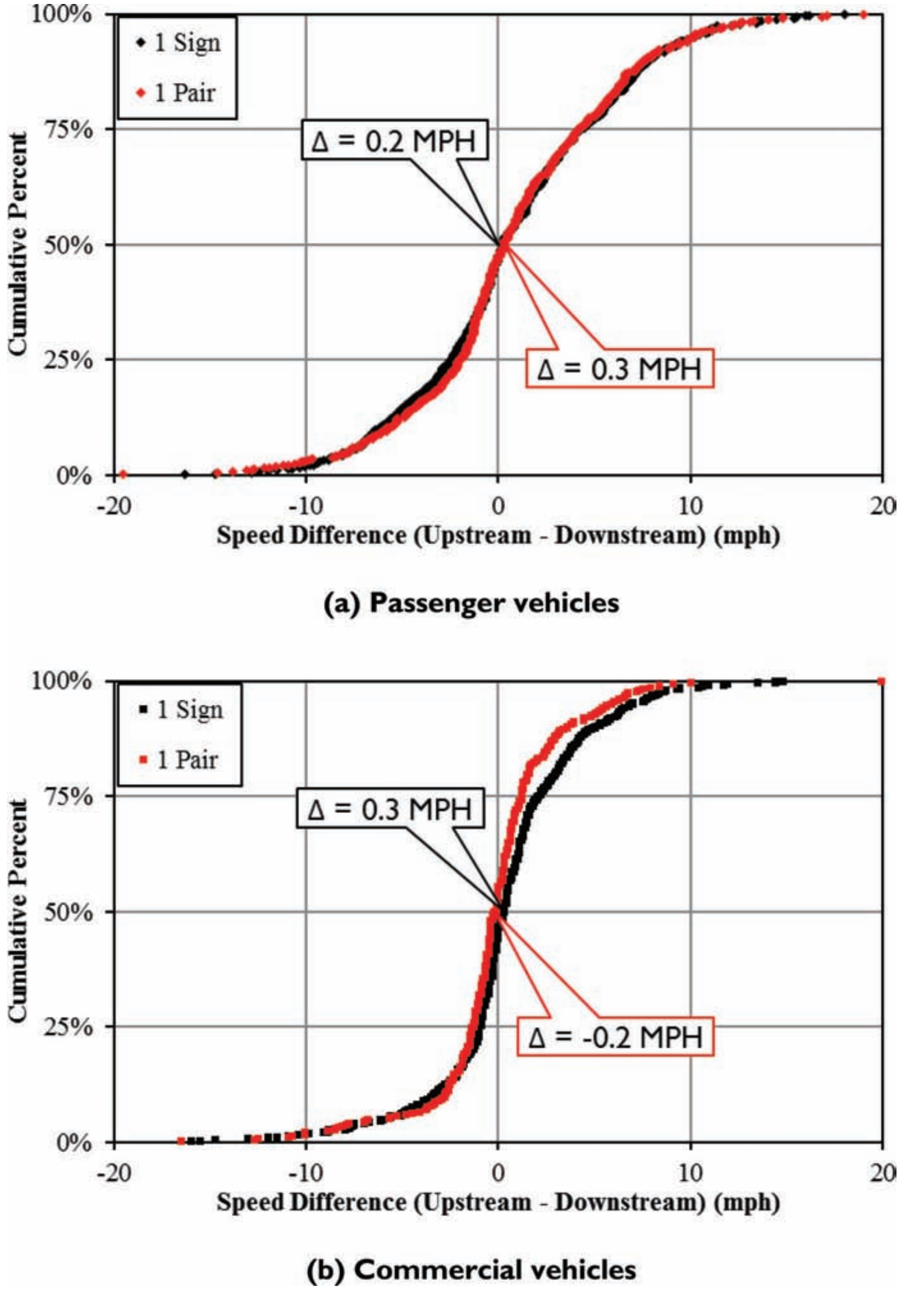


Figure 5.26 Comparison of change of speed of matched vehicles across a single sign and paired signs at one location from Speed Studies 2-new and 8.

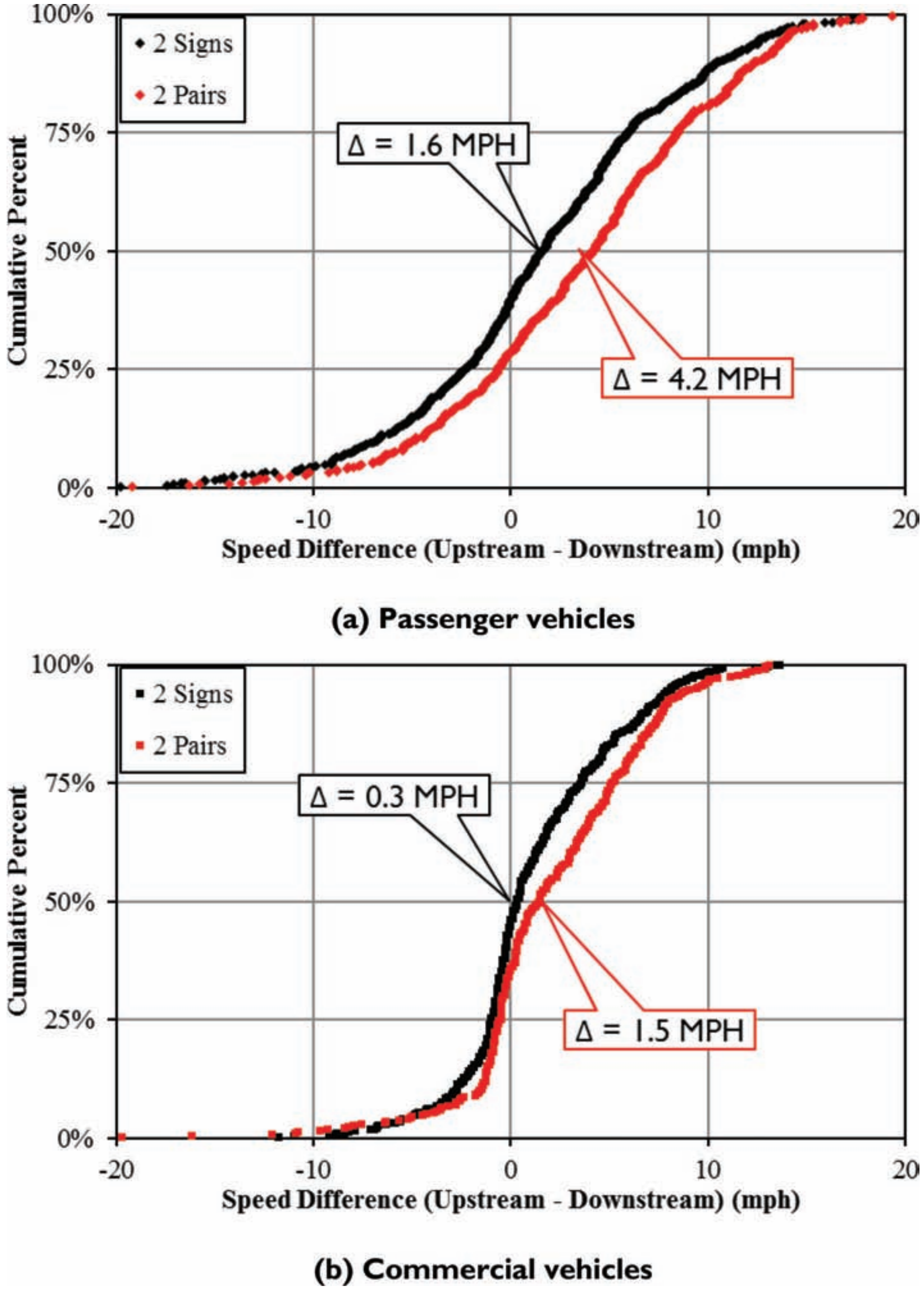
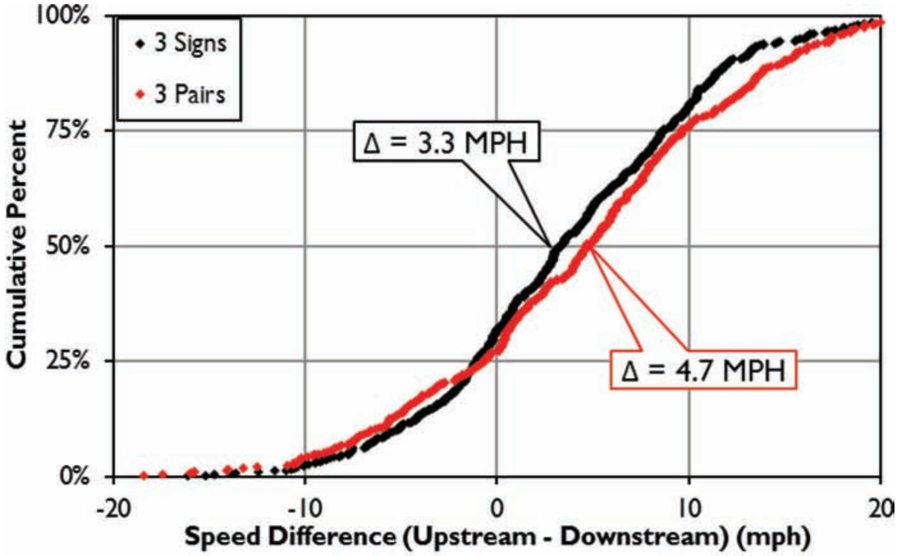
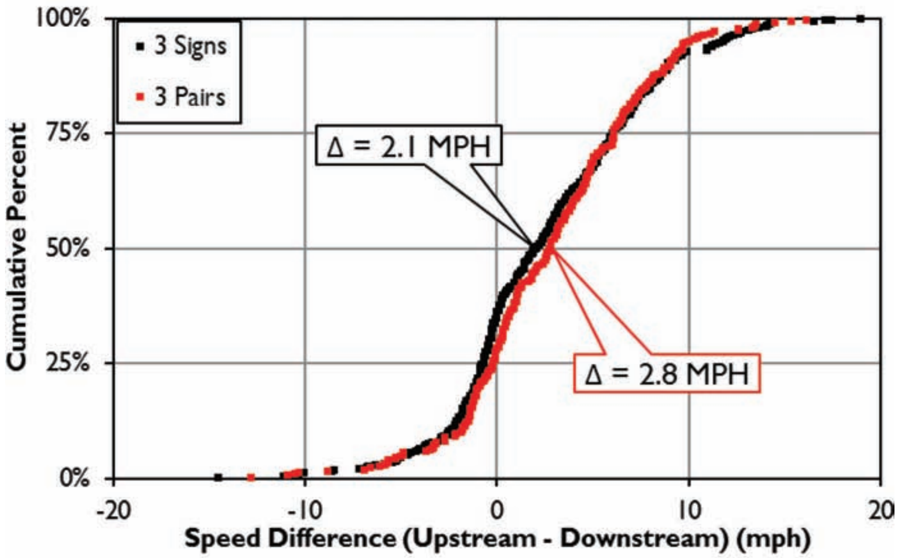


Figure 5.27 Comparison of change of speed of matched vehicles across single signs and paired signs at two locations from Speed Studies 5 and 9.

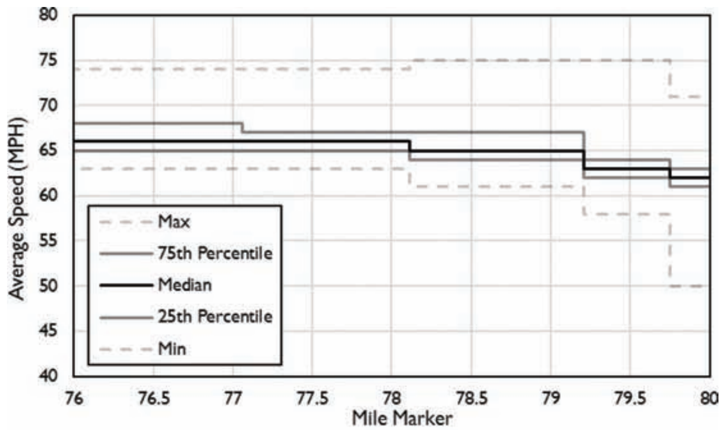


(a) Passenger vehicles

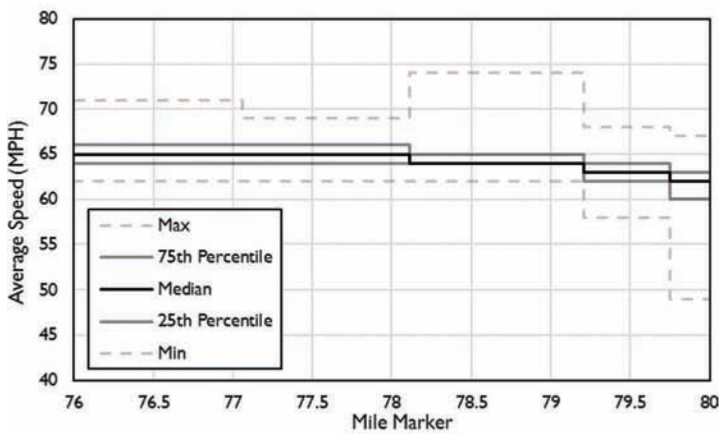


(b) Commercial vehicles

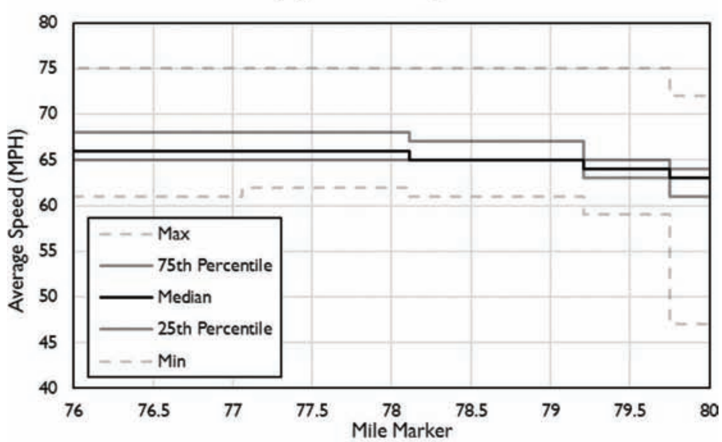
Figure 5.28 Comparison of change of speed of matched vehicles across single signs and paired signs at three locations from Speed Studies 4-new and 10.



(a) Individual signs



(b) Paired signs



(c) Signs off

Figure 5.29 Statistical summary of crowdsourced probe vehicle speed data for single signs, paired signs, and signs-off across study section.

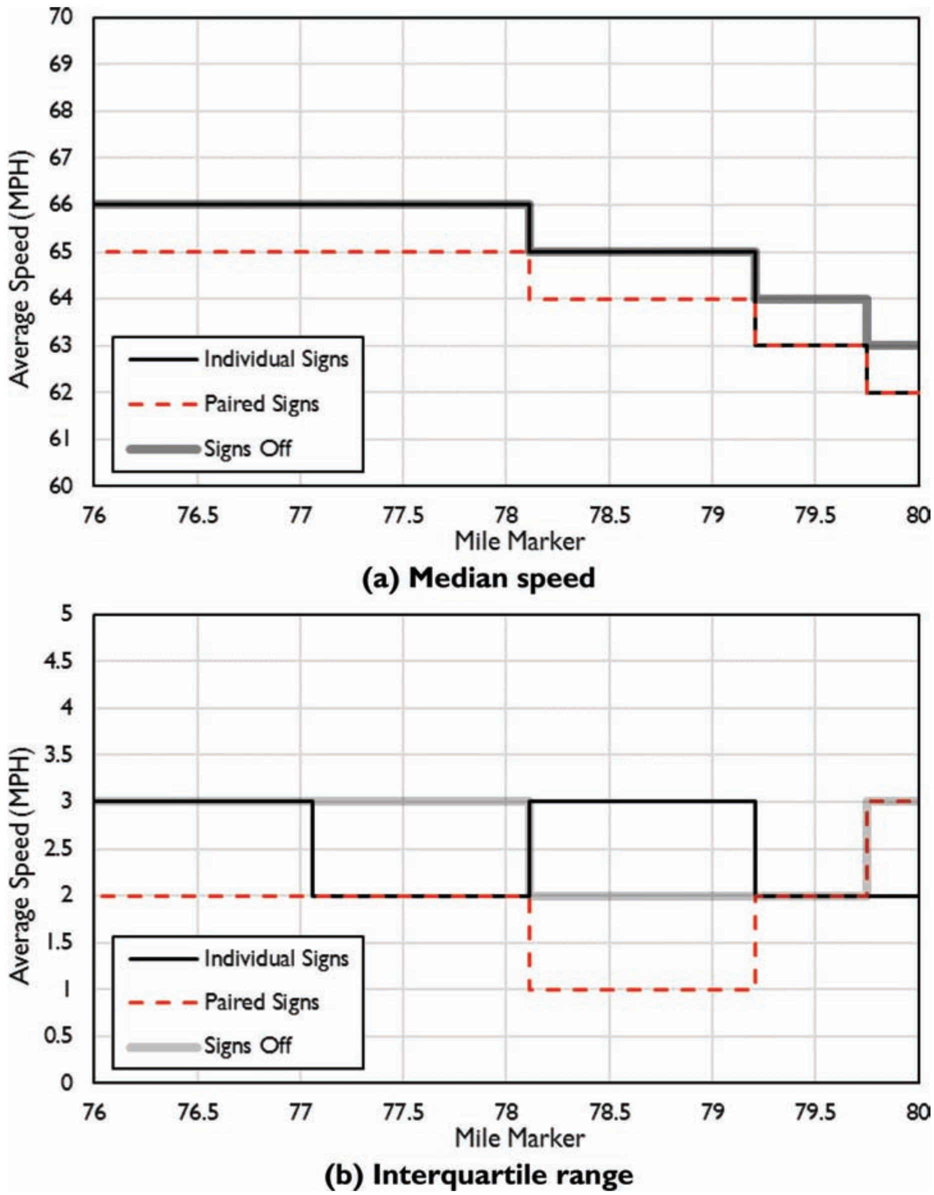


Figure 5.30 Comparison of crowdsourced probe vehicle data for single signs, paired signs, and signs-off across study section.

6. CONCLUSIONS

The purpose of this research project was to implement and evaluate a variable speed limit system in Indiana. The project was comprised of three research studies. The first investigated a need for variable speed limit signage, the second developed a methodology to evaluate the effectiveness of static speed limit signage, and the third assessed variable speed limit signage adjacent to an active work zone in Indiana. The research developed analysis techniques to quantify increase in crash rates during congested conditions that can be used to estimate back-of-queue crash rates increases on approach to work zones.

Variable speed limits can potentially increase reduce speeds approaching queues, thus reducing the severity of crashes. A methodology was created to evaluate speed limit signage using probe vehicle data, which will be useful to operations engineers nationwide. In addition, a vehicle matching methodology was developed using laser speed devices which provides individual vehicle speed reductions as a result of speed limit signage.

Using these approaches, the following conclusions were made:

- Paired variable speed limit signs outperform single signs when attempting to slow vehicles.
- Operators and managers should use at least three pairs of variable speed limit signs to obtain any tangible reduction in driver speeds.
- Variable speed limit signage should be placed upstream of the expected back-of-queue location.
- Placement of speed limit signage can be actively monitored using crowdsourced probe vehicle data.

6.1 Future Research

The value of knowing speed limit sign locations and values, paired with the effect of the signs on the travel speed of motorists provides a rich area for further research. The benefit of properly located static and variable speed limit signs with regards to safety should be further investigated. Using the guidelines for placing speed limit signs from the MUTCD, numerous studies can be performed to determine if the placement is having the desired effect in real-time. Using variables such as geometry, volume, number of lanes, occupancy, time of day, and other roadway measurements, a spatially transferable study may be performed to determine the effectiveness of both variable and static speed limit signs. This will be especially valuable to the engineers who are responsible for making the sign placements.

Other future work should be considered including automating the speed limits on the variable speed limit signage. Using the crowdsourced probe vehicle data, an algorithm could be developed to automatically change variable speed limit values based on real-time traffic speeds. This could provide both safety and mobility benefits on a limited access road facility.

7. ACKNOWLEDGMENTS

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REFERENCES

AASHTO. (2010). *Highway safety manual* (Part A, Chapter 3). Washington, DC: Association of American Highway Transportation Officials.

Abdukhai, B., & Tabib, S. M. (2003). Spatio-temporal inductance-pattern recognition for vehicle re-identification. *Transportation Research Part C: Emerging Technologies*, *11*(3), 223–239. http://dx.doi.org/10.1016/S0968-090X(03)00024-X

Agent, K. R., Pigman, J. G., & Weber, J. M. (1998). Evaluation of speed limits in Kentucky. *Transportation Research Record*, *1640*, 57–64. http://dx.doi.org/10.3141/1640-08

Al-Ghamdi, A. S. (2006). Analysis of speeding in Saudi Arabia and effectiveness of enforcement methods. *Transportation Research Record*, *1969*, 1–9. http://dx.doi.org/10.3141/1969-03

Benekohal, R. F., Chitturi, M. V., Hajbabaje, A., Wang, M., & Medina, J. C. (2008). Automated speed photo enforcement effect on speeds in work zones. *Transportation Research Record*, *2055*, 11–20. http://dx.doi.org/10.3141/2055-02

Bennett, C. R., & Dunn, R. C. M. (1995). Driver deceleration behavior on a freeway in New Zealand. *Transportation Research Record*, *1510*, 70–75.

Binkowski, S. E., Maleck, T. L., Taylor, W. C., & Czewski, T. S. (1998). Evaluation of Michigan 70-mph speed limit. *Transportation Research Record*, *1640*, 37–46. http://dx.doi.org/10.3141/1640-06

Brennan, T. M., Remias, S. M., Grimmer, G. M., Horton, D. K., Cox, E. D., & Bullock, D. M. (2013). Probe vehicle based statewide mobility performance measures for decision makers. *Transportation Research Record*, *2338*, 78–90. http://dx.doi.org/10.3141/2338-09

Brewer, M. A., Pesti, G., & Schneider, W., IV. (2006). Improving compliance with work zone speed limits: Effectiveness of selected devices. *Transportation Research Record*, *1948*, 67–76. http://dx.doi.org/10.3141/1948-08

Brodsky, H., & Hakkert, A. S. (1983). Highway accident rates and rural travel densities. *Accident Analysis & Prevention*, *15*(1), 73–84. http://dx.doi.org/10.1016/0001-4575(83)90009-X

Carr, B. R. (1969). A statistical analysis of rural Ontario traffic accidents using induced exposure data. *Accident Analysis & Prevention*, *1*(4), 343–357. http://dx.doi.org/10.1016/0001-4575(69)90080-3

Chapman, R. (1973). The concept of exposure. *Accident Analysis & Prevention*, *5*(2), 95–110. http://dx.doi.org/10.1016/0001-4575(73)90018-3

Coifman, B. (1998). Vehicle re-identification and travel time measurement in real-time on freeways using existing loop detector infrastructure. *Transportation Research Record*, *1643*, 181–191. http://dx.doi.org/10.3141/1643-22

Daktronics. (2007). *Vanguard® VS-5220 variable speed limit sign—Overview*. Brookings, SD: Daktronics. Retrieved from http://www.daktronics.com/Web%20Documents/Transportation-Documents/Vanguard-Products/VS-5220/SL-09868.pdf

Edara, P., Sun, C., & Hou, Y. (2013). *Evaluation of variable advisory speed limits in work zones*. (InTrans Project 06-277). Washington, DC: Federal Highway Administration, U.S. Department of Transportation.

Elvik, R., Erke, A., & Christensen, P. (2009). Elementary units of exposure. *Transportation Research Record*, *2103*, 25–32. http://dx.doi.org/10.3141/2103-04

Ernst, J. M., Krogmeier, J. V., & Bullock, D. M. (2011). Acceleration estimation and signature matching travel time estimation enhancement for standard electromagnetic vehicle detectors. *Transportation Research Record*, *2243*, 27–37. http://dx.doi.org/10.3141/2243-04

Finley, M. D. (2011). Field evaluation of motorist reactions to reduced work zone speed limits and other work zone conditions. *Transportation Research Record*, *2258*, 40–48. http://dx.doi.org/10.3141/2258-05

Garber, N. J., & Ehrhart, A. A. (2000). *The effect of speed, flow, and geometric characteristics on crash rates for different types of Virginia highways* (Publication No. VTRC 00-R15). Charlottesville, VA: Virginia Transportation Research Council.

Garber, S., & Graham, J. (1990). The effects of the new 65 mile-per-hour speed limit on rural highway fatalities: A state-by-state analysis. *Accident Analysis & Prevention*, *22*(2), 137–149. http://dx.doi.org/10.1016/0001-4575(90)90065-S

Habtemichael, F. G., & de Picado Santos, L. (2013). Safety and operational benefits of variable speed limits under different traffic conditions and driver compliance levels. *Transportation Research Record*, *2386*, 7–16. http://dx.doi.org/10.3141/2386-02

Haglund, M., & Aberg, L. (2000). Speed choice in relation to speed limit and influences from other drivers. *Transportation Research Part F*, 3(1). http://dx.doi.org/10.1016/S1369-8478(00)00014-0

Harwood, D. W., Bauer, K. M., & Potts, I. B. (2013). Development of relationships between safety and congestion for urban freeways. *Transportation Research Record*, *2398*, 28–36. http://dx.doi.org/10.3141/2398-04

Hourdos, J. N., Garg, V., Michalopoulos, P. G., & Davis, G. A. (2006). Real-time detection of crash-prone conditions at freeway high-crash locations. *Transportation Research Record*, *1968*, 83–91. http://dx.doi.org/10.3141/1968-10

Jones, J. C., Knopp, M. C., Fitzpatrick, K., Doctor, M. A., Howard, C. E., Laragan, G. M., Young, E. G. (2011). *Freeway geometric design for active traffic management in Europe* (Publication No. FHWA-PL-11-004). Washington, DC: Federal Highway Administration.

Jovanis, P. P., & Chang, H. (1986). Modeling the relationship of accidents to miles traveled. *Transportation Research Record*, *1068*, 42–51.

Kirk, A., & Stamatiadis, N. (2001). Crash rates and traffic maneuvers of younger drivers. In *Transportation Research Record*, *1779*, 68–75. http://dx.doi.org/10.3141/1779-10

Kononov, J., Durso, C., Reeves, D., & Allery, B. K. (2012). Relationship between traffic density, speed and safety and its implication on setting variable speed limits on freeways. *Transportation Research Record*, *2280*, 1–9. http://dx.doi.org/10.3141/2280-01

Kononov, J., Reeves, D., Durso, C., & Allery, B. K. (2012). Relationship between freeway flow parameters and safety and its implications for adding lanes. *Transportation Research Record*, *2279*, 118–123. http://dx.doi.org/10.3141/2279-14

Li, H., Remias, S. M., Day, C. M., Mekker, M. M., Sturdevant, J. R., & Bullock, D. M. (2015). *Shockwave boundary identification using cloud-based probe data*. Paper presented at 94th Annual Meeting of the Transportation Research Board, January 11–15, Washington, DC.

Lin, W., & Tong, D. (2011). Vehicle re-identification with dynamic time windows for vehicle passage time estimation. *IEEE Transaction on Intelligent Transportation Systems*, *12*(4), 1057–1063. http://dx.doi.org/10.1109/TITS.2011.2140318

Lomax, T., Shrank, D., & Eisele, B. (2011). *2011 Urban mobility report powered by INRIX traffic data*. College Station, TX: The Texas A&M University System, Texas A&M Transportation Institute.

Lomax, T., Shrank, D., & Eisele, B. (2012). *2012 annual urban mobility report*. College Station, TX: The Texas A&M University System, Texas A&M Transportation Institute.

Lu, X.-Y., & Shladover, S. E. (2014). Review of variable speed limits and advisories: Theory, algorithm, and practice. *Transportation Research Record*, *2423*, 15–23. http://dx.doi.org/10.3141/2423-03

Lu, X.-Y., Varaiya, P., Horowitz, R., Su, D., & Shladover, S. E. (2011). Novel freeway traffic control with variable speed limit and coordinated ramp metering. *Transportation Research Record*, *2229*, 41–48. http://dx.doi.org/10.3141/2229-07

Martin, J. (2002). Relationship between crash rate and hourly traffic flow on interurban motorways. *Accident Analysis & Prevention*, *34*(5), 619–629. http://dx.doi.org/10.1016/S0001-4575(01)00061-6

Mattox, J. J., Saradua, W. A., Ogle, J. H., Eckenrode, R. T., & Dunning, A. (2007). Development and evaluation of speed-activated sign to reduce speeds in work zone. *Transportation Research Record*, *2015*, 3–11. http://dx.doi.org/10.3141/2015-01

MDOT. (2004). *A field test and evaluation of variable speed limits in work zones*. Washington, DC: Federal Highway Administration, U.S. Department of Transportation. Retrieved from http://safety.fhwa.dot.gov/speedmgt/vslimits/docs/michiganvsl.pdf

Mensah, A., & Hauer, E. (1998). Two problems of averaging arising in the estimation of the relationship between accidents and traffic flow. *Transportation Research Record*, *1635*, 37–43. http://dx.doi.org/10.3141/1635-05

Meyer, E. (2003). Generating vehicle-specific speed profiles from automatic traffic recorders. *Transportation Research Record*, *1855*, 90–96. http://dx.doi.org/10.3141/1855-11

Oei, H.-L. (1996). Automatic speed management in the Netherlands. *Transportation Research Record*, *1560*, 57–64. http://dx.doi.org/10.3141/1560-09

Oh, C., Ritchie, S. G., & Jeng, S.-T. (2007). Anonymous vehicle reidentification using heterogeneous detection systems. *IEEE Transaction on Intelligent Transportation Systems*, *8*(3), 460–469. http://dx.doi.org/10.1109/TITS.2007.899720

Pal, R., & Sinha, K. C. (1996). Analysis of crash rates at interstate work zones in Indiana. *Transportation Research Record*, *1529*, 45–53. http://dx.doi.org/10.3141/1529-06

Papageorgiou, M., Kosmatopolous, E., & Papamichail, I. (2008). Effects of variable speed limits on traffic flow. *Transportation Research Record*, *2047*, 37–48. http://dx.doi.org/10.3141/2047-05

Potts, I. B., Harwood, D. W., Fees, C. A., Bauer, K. M., & Kinzel, C. S. (2015). *Further development of the safety and congestion relationship for urban freeways* (SHRP 2 Report No. S2-L07-RR-3). Washington, DC: Transportation Research Board.

Quddus, M. A., Wang, C., & Ison, S. G. (2010). Road traffic congestion and crash severity: Econometric analysis using ordered response models. *Journal of Transportation Engineering*, *136*(5), 424–435. http://dx.doi.org/10.1061/(ASCE)TE.1943-5436.0000044

Remias, S., Brennan, T., Grimmer, G., Cox, E., Horton, D., & Bullock, D. (2012). *2011 Indiana interstate mobility report—Full version*. West Lafayette, IN: Purdue University. http://dx.doi.org/10.5703/1288284314680

Remias, S., Brennan, T., Grimmer, G., Cox, E., Horton, D., & Bullock, D. (2013). *2012 Indiana mobility report: Full version*. West Lafayette, IN: Purdue University. http://dx.doi.org/10.5703/1288284315190

Remias, S. M., Brennan, T. M., Day, C. M., Summers, H. T., Horton, D. K., Cox, E. D., & Bullock, D M. (2013). Spatially referenced probe data performance measures for infrastructure investment decision makers. *Transportation Research Record*, *2420*, 33–44. http://dx.doi.org/10.3141/2420-04

Remias, S. M., Mekker, M. M., McNamara, M. L., Sturdevant, J. R., & Bullock, D. M. (2015). *Assessment of speed limit locations using crowdsourced probe vehicle data*. Paper presented at 94th Annual Meeting of the Transportation Research Board, January 11–15, Washington, DC.

Riffkin, M., McMurty, T., Heath, S., & Saito, M. (2008). *Variable speed limit signs effects on speed and speed variation in work zones* (Report No. UT-08-01). Salt Lake City, UT: Utah Department of Transportation.

Santiago-Chaparro, K. R., Chitturi, M. V., Bill, A., & Noyce, D. A. (2012). Spatial effectiveness of speed feedback signs. *Transportation Research Record*, *2281*, 8–15. http://dx.doi.org/10.3141/2281-02

Shefer, D., & Rietveld, P. (1997). Congestion and safety on highways: Towards an analytical model. *Urban Studies*, *34*(4), 679–692. http://dx.doi.org/10.1080/0042098975970

Solomon, D. (1964). *Accidents on main rural highways related to speed, driver, and vehicle*. Washington, DC: U.S. Government Printing Office.

Song, S., & Yeo, H. (2012). Method for estimating highway collision rate that considers state of traffic flow. *Transportation Research Record*, *2318*, 52–62. http://dx.doi.org/10.3141/2318-07

Stamatiadis, N., & Deacon, J. A. (1997). Quasi-induced exposure: Methodology and insight. *Accident Analysis & Prevention*, *29*(1), 37–52. http://dx.doi.org/10.1016/S0001-4575(96)00060-7

Thornton, M., & Lyles, R. W. (1996). Freeway speed zones: Safety and compliance issues. *Transportation Research Record*, *1560*, 65–72. http://dx.doi.org/10.3141/1560-10

Thorpe, J. D. (1964). Calculating relative involvement rates in accidents without determining exposure. *Australian Road Research*, *2*(1), 25–36.

USDOT. (2012). *Guidelines for the use of variable speed limit systems in wet weather* (Publication No. FHWA-SA-12-022). Washington, DC: U.S. Department of Transportation.

Wasson, J., Boruff, G., Hainen, A., Remias, S., Hulme, E., Farnsworth, G., & Bullock, D. (2011). Evaluation of spatial and temporal speed limit compliance in highway work zones. *Transportation Research Record*, *2258*, 1–15. http://dx.doi.org/10.3141/2258-01

Weikl, S., Bogenberger, K., & Bertini, R. L. (2013). Traffic management effects of variable speed limit system on a German Autobahn: Empirical assessment before and after system implementation. *Transportation Research Record*, *2380*, 48–60. http://dx.doi.org/10.3141/2380-06

Woo, T. H., Ho, S.-M., & Chen, H.-L. (2007). Monitoring displays coupled with speed cameras: Effectiveness of speed reduction. *Transportation Research Record*, *2009*, 30–36. http://dx.doi.org/10.3141/2009-05

Yeo, H., Jang, K., & Skabardonis, A. (2010). *Impact of traffic states on freeway collision frequency* (Publication No. RR-2010-6). Berkeley, CA: University of California Berkeley Safe Transportation Research and Education Center.

Zhou, M., & Sisiopiku, V. (1997). Relationship between volume-to-capacity ratios and accident rates. *Transportation Research Record*, *1581*, 47–52. http://dx.doi.org/10.3141/1581-06

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

Further information about JTRP and its current research program is available at: http://www.purdue.edu/jtrp

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