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Speed Enforcement in Work Zones and Synthesis on Cost-Benefit Assessment of Installing Speed Enforcement Cameras on INDOT Road Network

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JOINT TRANSPORTATION RESEARCH PROGRAM

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NOTICE

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16. Abstract

Work zone safety is a high priority for transportation agencies across the United States. High speeds in construction zones are a well-documented risk factor that increases the frequency and severity of crashes. It is therefore important to understand the extent and severity of high-speed vehicles in and around construction work zones. This study uses CV trajectory data to evaluate the impact of several work zone speed compliance measures, such as posted speed limit signs, radar-based speed feedback displays, and automated speed enforcement on controlling speeds inside the work zone. This study also presents several methodologies to characterize both the spatial and temporal effects of these control measures on driver behavior and vehicle speeds across the work zones.

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EXECUTIVE SUMMARY

Motivation

Work zone safety is a high priority for transportation agencies across the United States. High speeds in construction zones are a well-documented risk factor that increases the frequency and severity of crashes. It is therefore important to understand the extent and severity of high-speed vehicles in and around construction work zones.

There are several speed compliance measures adopted by agencies to limit speeds in work zones, including traffic control devices, design alterations, and enforcement. Studies have found law enforcement to have a large impact on speed compliance when present; however, this is very resource intensive. Recently, automated speed enforcement programs have been gaining popularity, but assessing them without biasing the data is quite difficult. Connected vehicle (CV) trajectory data now provides an opportunity to perform a comprehensive analysis of work zone speeds using a variety of enforcement strategies over extended periods without introducing any sampling bias.

Study

This study uses CV trajectory data to evaluate the impact of several work zone speed compliance measures, such as posted speed limit signs, radar-based speed feedback displays, and automated speed enforcement, on controlling speeds inside the work zone. This study also presents several methodologies to characterize both the spatial and temporal effects of these control measures on driver behavior and vehicle speeds across the work zones.

Results

Spatial analysis showed that the posted speed limit signs inside work zones had poor compliance, with nearly 90% of vehicles traveling over the posted speed, and 50% travelling more than 11 mph over the posted speed. A 1-week before/after analysis to study the impact of radar-based speed feedback display showed a significant speed reduction beginning approximately 1,000 ft upstream of the radar speed sign. Analysis also showed that the upper extreme speeds (15 mph above the speed limit) in this region dropped by 10%–15%.

This study looked at several work zones in Pennsylvania that had automated enforcement deployed in 2021. For work zones with automated speed enforcement programs, results showed that overall speed compliance inside the work zones increased during the presence of automated enforcement. In the three Pennsylvania work zones analyzed, the proportions of vehicles travelling within the allowable 11 mph legal threshold above the posted speed limit were 63%, 75%, and 84%. In contrast, in Indiana, a state with no automated enforcement, the proportions of vehicles travelling within the same 11 mph threshold were found to be 25% and 50%. Shorter work zones (less than 3 miles) were associated with better compliance than longer work zones. Spatial analysis also found that speeds rebounded within 1–2 miles after leaving the enforcement location.

This study also examined the impact of a radar-based speed feedback display sign with automated enforcement in reducing speeds inside the work zone. Although speed feedback signs had a mild impact in reducing speeds, the median speeds were still 14 mph above the speed limit and around 3 mph above the 11-mph legal threshold. In comparison, automated enforcement had a strong impact in speed compliance with median speeds within 1–2 mph of the speed limit and 9–10 mph below the 11-mph legal threshold.

In late 2022 and early 2023, several intensive enforcement activities were undertaken on I-70 east of Indianapolis. Results from enforcement activities conducted by public safety agencies showed a 5–19 mph reduction in median speeds during the enforcement period. On a few occasions the lasting impact of this enforcement was also seen during the next day and the next week. Although these details were successful, there is broad consensus that these types of details are too resource-intensive to scale broadly and would probably be most effective when paired with an automated enforcement program in high-risk areas.

Recommendations

The main recommendations from this study include but are not limited to the following.

- It is important to have consistent and properly placed speed limit regulatory signs in and around work zones. This is important to ensure motorists are aware of the regulatory speed limits and ensure public safety colleagues that write tickets will not face challenges from motorists that receive tickets.
- It is important to establish an unbiased method to monitor work zone speeds using connected vehicle data to understand which work zones may be of concern and to understand trends.
- Automated enforcement programs are a viable option that allow law enforcement agencies to free up important resources without compromising speed compliance and safety in and around work zones.
- It is important to understand the impact of randomness while conducting enforcement activities. Temporal attributes, such as duration, time of day, and interval of enforcement operations as well as optimal deployment locations (inside, ahead, or near the entrance of work zone), need to be further explored for achieving better speed compliance.
- Additional consideration while setting the right work zone speed limit may also help achieve better compliance.

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LIST OF ACRONYMS

AWZSE	Automated Work Zone Speed Enforcement
CFD	Cumulative Frequency Diagram
CV	Connected Vehicle
GPS	Global Positioning System
DOT	Department of Transportation
IMPD	Indianapolis Metropolitan Police Department
IQR	Interquartile Range
ISP	Indiana State Police
MM	Mile Marker
MPH	Miles per Hour
NB	Northbound
OEM	Original Equipment Manufacturer
SB	Southbound

1. PROJECT OVERVIEW

1.1 Introduction

Ensuring compliance with work zone speeds is a critical objective for transportation agencies and partners across the United States. Every year there are nearly 800 fatalities and more than 120,000 work zone related crashes (National Work Zone Safety Information Clearinghouse, 2021). Enforcing speed compliance is one of the ways to improve work zone safety and reduce crashes. Although several studies have found law enforcement to have the largest impact on speed compliance (Brewer et al., 2005; Noel et al., 1988; Ravani & Wang, 2018; Zech et al., 2005), it is not scalable especially due to the lack of both staffing and resources. Moreover, enforcement activities in work zones can sometimes be dangerous for both traveling motorists and enforcement officers. In the past decade, automated speed enforcement programs using both radar and camera-based technology have gained popularity. Several studies have shown that automated enforcement programs can significantly reduce work zone speeds (Benekohal et al., 2008; Chitturi et al., 2010; Hajbabaie et al., 2009); however, most of them were limited to assessing the localized impact on speeds. The presence of equipment and/or personnel when speeds are collected can also bias the data. Connected vehicle (CV) trajectory data now provides an opportunity to perform a comprehensive analysis of work zone speeds over extended periods without introducing any sampling bias.

1.2 Scope and Objectives

The objective of this report is to understand the extent and severity of high-speed vehicles in and around construction work zones. This study evaluates the impact of several work zone speed compliance measures such as posted speed limit signs, radar-based speed feedback displays and automated speed enforcement on controlling speeds inside the work zone. Moreover, several methodologies are presented in this study that uses CV trajectory data to characterize both the spatial and temporal effects of these control measures on driver behavior and vehicle speeds across the work zones.

1.3 Dissemination of Research Results

The below research studies were prepared in part during this project to facilitate agile dissemination of results.

- Mathew, J. K., Desai, J., Li, H., & Bullock, D. M. (2021). Using anonymous connected vehicle data to evaluate impact of speed feedback displays, speed limit signs and roadway features on interstate work zones speeds. *Journal of Transportation Technologies*, *11*(4), 545–560. https://doi.org/10.4236/jtts.2021.114034
- Mathew, J. K., Li, H., Landvater, H., & Bullock, D. M. (2022). Using connected vehicle trajectory data to evaluate the impact of automated work zone speed enforcement. *Sensors*, *22*(8), 2885. https://doi.org/10.3390/s22082885

These technical papers were prepared throughout the project and distributed to key stakeholders to facilitate early implementation of the research findings. The following sections of the technical report summarize some of the key findings during this research.

2. LITERATURE REVIEW

Speeding is a major factor that influences the severity and frequency of crashes in work zones (Garber & Gadiraju, 1998; Garber & Zhao, 2002; Meng et al., 2010; Wang et al., 1996). Agencies have adopted several measures to control work zone speeding, including but not limited to, reduced speed limit signs (Banerjee et al., 2019), radar-based speed feedback displays (Banerjee et al., 2019; McCoy et al., 1995; Richards et al., 1985), variable message signs (Fudala & Fontaine, 2010; Richards et al., 1985), and transverse rumble strips (McAvoy et al., 2009). Enforcement measures such as presence of law enforcement (Brewer et al., 2005; Richards et al., 1985) and cameras (Banerjee et al., 2019) have also been instrumental in reducing work zone speeds.

Several studies have also looked at the impact of speed limit signs with speed displays (Ardeshiri & Jeihani, 2014; Chitturi & Benekohal, 2006; McCoy et al., 1995; Pesti & McCoy, 2001; Wang et al., 2003). McCoy et al. (1995) studied the effectiveness of the speed display sign on an interstate highway work zone in South Dakota and found that mean approach speeds reduced by 4–5 mph and the percentage of vehicles exceeding the advisory speed limit of 45 mph reduced by 20%–40% (McCoy et al., 1995). Another study conducted between two work zones on I-80 found that the speed monitoring displays were effective in lowering the speeds and increasing the uniformity and speed limit compliance (Pesti & McCoy, 2001). Few studies reported that changeable message signs with radar speeds significantly reduced the speeds in the immediate vicinity of the sign and did not demonstrate any novelty effects (Ardeshiri & Jeihani, 2014; Wang et al., 2003).

Fontaine et al. (2002) conducted a feasibility study of real-time remote speed enforcement for work zones and found that it may overcome many of the legislative barriers that prevent use of automated enforcement and also provide a safety benefit to law enforcement officers (Fontaine et al., 2002). Illinois was the first state to pass legislation in 2004 that allowed the use of automated speed photo-radar enforcement (SPE) in work zones. Subsequent studies on Illinois work zones found that SPE was effective in reducing speeds of cars and heavy vehicles during both free-flow and general traffic stream conditions (Benekohal et al., 2008, 2010; Chitturi et al., 2010; Hajbabaie et al., 2009). Average reductions in speeds were found to be between 4–8 mph for cars and between 3–7 mph for heavy vehicles. The reduction in speeding at 1.5 miles downstream of the enforcement was found to vary between 0%–44%. Studies in Arizona revealed that automated enforcement using a fixed camera on Arizona State Route 101 reduced speeds by 9 mph and estimated total number of target crashes by 44%–54% (Washington et al., 2007). Studies by other agencies including Washington DOT (WSDOT, 2008), Oregon DOT (Joerger, 2010) and Maryland DOT (Maryland SafeZones, n.d.) also found significant speed reductions by using automated enforcement. In Maryland, where the program was deployed at nearly 100 work zones since 2010, the number of vehicles exceeding the legal threshold (12 mph above posted speed limit) has been reduced by nearly 90% since its inception.

Although the localized impact of automated enforcement is well documented, there are very limited studies that looked at the spatial and temporal compliance of speeds across the work zone. Franz and Chang (2011) conducted a study using tube counters and microwave sensors to understand the spatial (2 miles upstream and downstream) and temporal speeding effects and found that speeds tend to reduce at enforcement location but speed up after going past it (Franz & Chang, 2011). Temporal analysis showed a general reduction in aggressive driving during the enforcement period with more stable spatial speeding distribution. Wasson et al. (2011) used Bluetooth probe data to study the spatial and temporal impact of overall speeding during enforcement activity on a 12-mile work zone in Indiana (Wasson et al., 2011). Results showed that space mean speeds dropped by approximately 5 mph throughout the work zone during enforcement and increased within 30 minutes after the enforcement detail ended.

3. CONNECTED VEHICLE TRAJECTORY DATA

The CV trajectory data, which provides a large sample that extends both spatially and temporally across the work zone, enables researchers to perform a holistic analysis of the speeding patterns inside the work zone.

The CV data used in this study were obtained from a third-party commercial data vendor that partners with original equipment manufacturers (OEM) to provide anonymized vehicle trajectories. Each trajectory consists of a series of waypoints with a reporting frequency of 1–3 seconds and a spatial fidelity of 3 meters (~10 ft). Each waypoint consists of unique trajectory identifiers, geographic coordinates, timestamps, speeds, headings, and ignition statuses for passenger cars. For a typical month in the United States, this amounts to several billion records (Desai et al., 2022). Figure 3.1 shows a split of 503 billion CV records by state ingested for the month of December 2022. Previous studies have indicated that these CV data represent approximately 3%–5% of the total vehicles operating on interstates (Hunter et al., 2021).

The key message from Figure 3.1 is that although CV data was used in both Indiana and Pennsylvania for this study, this data is available nationwide and these techniques scale to all 50 states.

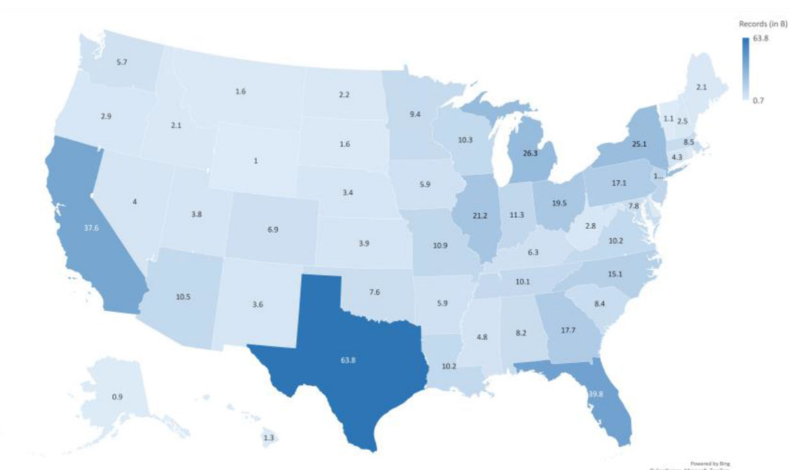


Figure 3.1 CV records (in billions) by state for the month of December 2022.

4. POSTED SPEED LIMIT SIGNS AND SPEED FEEDBACK TRAILERS

This case study used connected vehicle trajectory data to evaluate the speed compliance of different post-mounted speed limit signs and a radar-based speed limit sign with motorist speed feedback display in a work zone (Figure 4.1). Compliance with posted speed limit and a threshold of 11 mph above the posted speed limit (legal threshold for excessive speeding as defined by several states) are evaluated.

4.1 Work Zone Location

The study site was a 15-mile reconstruction project on Interstate I-65 near Lebanon, IN (Figure 4.2). This study focused on the southbound (SB) direction between mile markers (MM) 153 and MM 138. There were five speed limit transitions in the work zone as seen in Figure 4.2—callout i from 70 mph to 55 mph, callout ii from 55 to 45 mph, callout iii from 45 to 55 mph, callout iv from 55 to 45 mph (when flashing) otherwise 70 mph and callout v where speed limit resumes to 70 mph. An additional radar-based speed limit sign with the motorist speed feedback display (Figure 4.1) was placed near MM 148.5 (callout vi on 4.2) during the first week of June 2021 to evaluate its impact on speed compliance.

4.2 Data

Approximately 4 million connected vehicle records were extracted over a 2-week period (May 25–31, 2021, and June 7–13, 2021) that corresponded to approximately 27,000 unique trips passing through the study area. To remove any potential bias, congested conditions were discarded from the data set so that free flow conditions could be used for the statistical analysis.

4.3 Impact of Posted Speed Limit Signs

4.3.1 Work Zone Configuration

Figure 4.3 shows an interquartile range plot or boxplot of the speeds at every 0.1-mile increment along the work zone for a 1-week period (May 25–31, 2021). The x-axis highlights the southbound mile markers in the direction of travel and y-axis highlights the interquartile range of the speeds, with bottom end representing the 25th percentile speeds, midpoint representing median speed and top end representing the 75th percentile speed. This plot is overlaid with dotted lines illustrating the location of warning and posted speed limit signs placed throughout the work zone. Table 4.1 shows a list of all the signs and their corresponding miler marker location.

Figure 4.1 Radar-based speed limit sign with motorist speed feedback placed at I-65 southbound near MM 145.8.

4.3.2 Spatial Analysis

Figure 4.4a shows the same boxplot of speeds from Figure 4.3, with just the location of posted speed limit signs. Callouts i, ii, iii, iv and v denote the location of different speed limit signs posted along the work zone. Callouts i and ii are reduced speed limits from 70 mph to 55 mph and 55 mph to 45 mph, respectively. Callouts iii and v are increased speed limits from 45 mph to 55 mph and 45 mph to 70 mph, respectively. Callout iv shows the sign 45 mph when flashing or 70 mph otherwise. As seen, the speed limit signs have little to no impact near the boundary conditions, except when the speed limit increases. It is interesting also to note that median speeds were mostly above 70 mph except between callouts ii and iv, where geometric constraints such as lane shifts (callout q and x from Figure 4.2) resulted in lower speeds. Additionally, the lowest 25th percentile of speeds for any 0.1-mile section were above 50 mph, even though posted speed limits were below 45 mph for more than 3 miles. On average inside the work zone, nearly 90% of the vehicles were found to be travelling above the speed limit and around 50% above the legal threshold of 11 mph over the posted speed limit.

To evaluate the impact of posted speed limit signs at boundary locations, further spatial analysis within a 0.2-mile (~1,000 ft) upstream and downstream of the sign was conducted. Figure 4.4b shows the boundary condition at callout i from Figure 4.4a, where the posted speed limit reduces from 70 mph to 55 mph. Speed records on a 0.2-mile section upstream (MM 148.8–148.6) and downstream (MM 148.6–148.4) of the speed limit sign (MM 148.6) were compared.

Figure 4.5 illustrates cumulative frequency diagrams (CFDs) comparing the speeds on the 0.2-mile upstream and downstream section of the five speed limit transitions (callout i–v from Figure 4.4a) in the work zone. Overall, none of the reduced speed limit signs (callout i and ii) had any significant impact on reducing speeds. Median speeds remained around 72 mph in the downstream section following the posted speed limit transition from 70 mph to 55 mph (callout i). In the next location, where the speed limit reduced from 55 mph to 45 mph, the observed median speeds also remained around 72 mph. Less than 7% of the speeds were below 45 mph in the downstream section (callout ii)—an increase of 2% from the upstream section. The third location, where the speed limit rose from 45 mph to 55 mph, also had similar distributions in

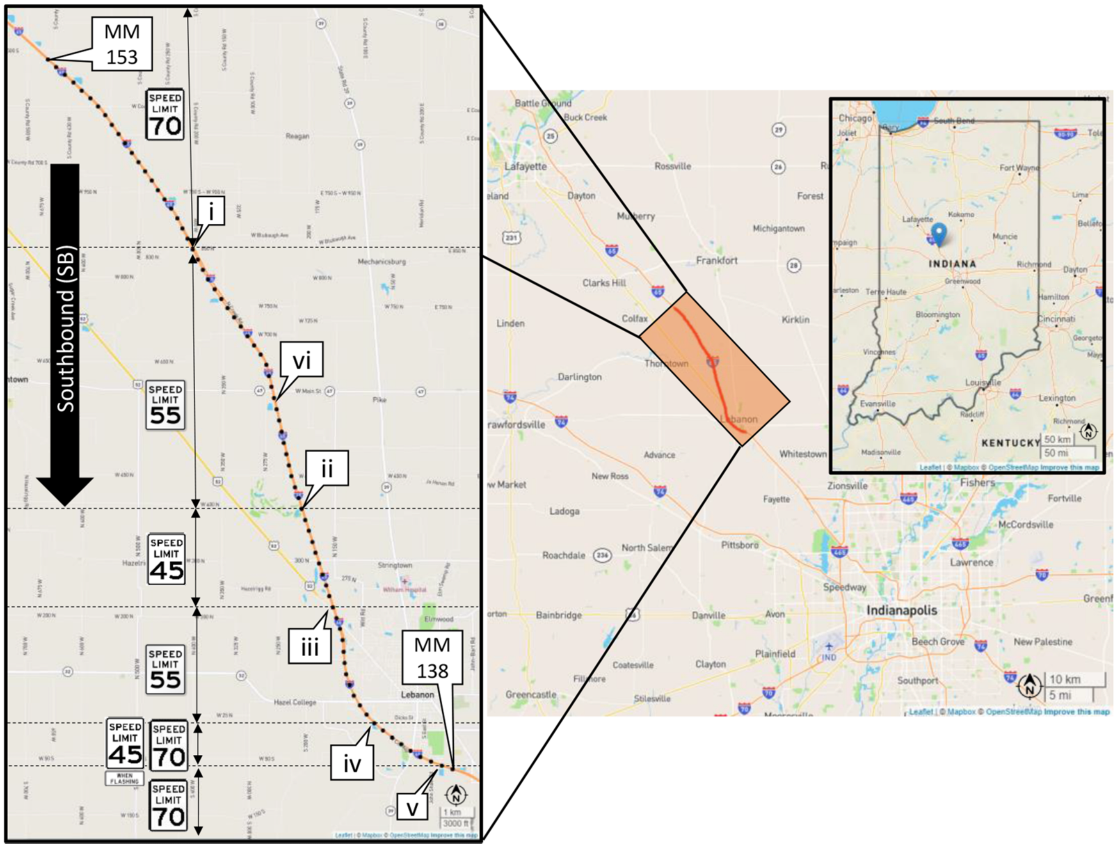


Figure 4.2 Overview map of work zone and location of speed limit signs.

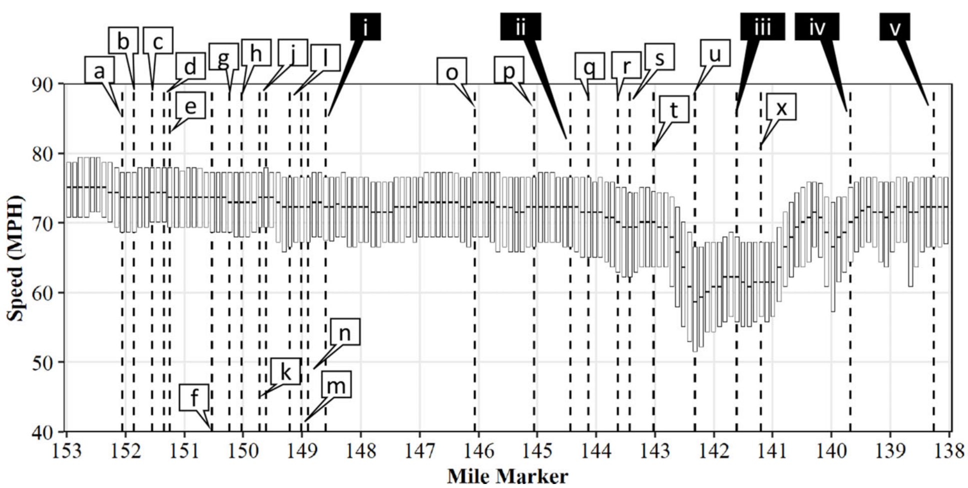


Figure 4.3 Boxplot of speeds every 0.1-mile with the location of road signs.

the upstream and downstream section. In contrast to the previous two locations, median speeds for both the sections in this location dropped to 62 mph (callout iii). As seen earlier, this is due to the geometric constraints within this section of the work zone. In location 4, where the speed limit increased from 55 to 70 mph (or 45 mph when flashing), the observed speeds in the downstream section also increased, as expected. The median speeds in the downstream section increased to 70 mph, an increase of more than 2 mph compared to the upstream section (callout iv). Due to possibly similar speed limits, the speed distributions in the upstream and downstream section of the final location were not substantially different. However, median speeds for both sections rose to 72 mph (callout v).

4.4 Impact of Radar-Based Speed Feedback Display with Speed Limit Sign

A temporal analysis was conducted to study the impact of radar-based speed feedback display sign with

TABLE 4.1
Work zone signs

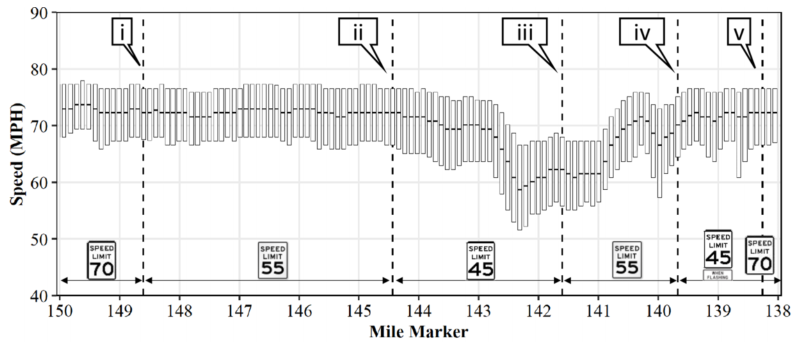
Fig 4 Callout	Mile Marker	Road Sign
i	148.6	Speed Limit 55 mph
ii	144.4	Variable Speed Limit 45 mph
iii	141.6	Speed Limit 55 mph
iv	139.6	Speed Limit When Flashing 45 mph; Speed Limit 70 mph
v	138.2	Speed Limit 70 mph
a	152.0	Road Work Ahead (On a Portable Message Sign)
b	151.8	Added Penalty Sign (XG20-7)
c	151.5	Road Construction 2 Miles
d	151.3	Added Penalty Sign (XG20-7)
e	151.2	Road Work 2 Miles
f	150.5	Road Construction 1 Mile
g	150.2	Road Work 1 Mile
h	150.0	Road Construction 0.5 Miles
j	149.7	Road Work 0.5 Miles
k	149.6	Road Construction Ahead
l	149.2	Road Work Ahead
m	149.0	Road Work Ahead (On a Portable Message Sign)
n	148.9	Speed Limit 55 mph Ahead
o	146.0	Speed Limit 55 mph
p	145.0	Speed Limit 55 mph
q	144.1	Lane Shift Ahead
r	143.6	Added Penalty Sign (XG20-7)
s	143.4	Road Construction Ahead
t	143.0	Lane Shift Ahead
u	142.3	Speed Limit When Flashing 45 mph
x	141.2	Lane Shift Ahead

a 55-mph speed limit advisory (referred to as speed feedback display sign from hereafter). Figure 4.6 shows two boxplots, similar to Figure 4.4a, comparing the speeds before (Figure 4.6a) and after (Figure 4.6b) the placement of the speed feedback display sign (Figure 4.1). The speed feedback display sign was deployed on June 2, 2021, at MM 145.8 (callout vi). Data was compared between the before period extending from May 25–31, 2021, and the after period extending from June 7–13, 2021. Comparing callout vi on Figure 4.6a and b, there is a clear drop in speeds near the sign during the after period, indicating that the speed feedback display sign had some impact on driver behavior. It is also interesting to note that the speed drops begin a few tenths of a mile ahead of the sign.

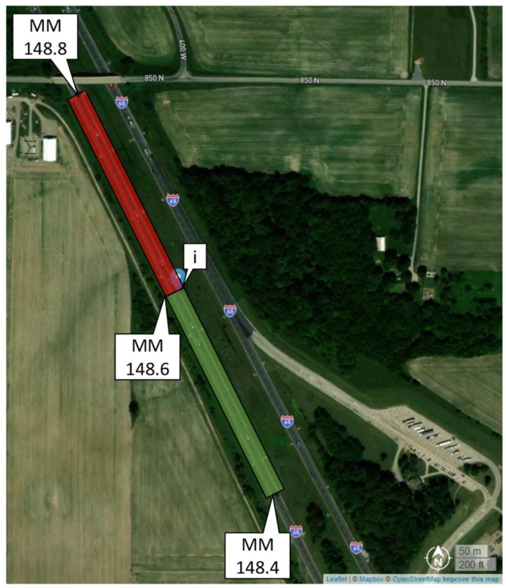
To further evaluate the spatial impact, CFDs of speeds are plotted for sections before and after the speed feedback display sign, as shown in Figure 4.7a. Each panel represents a 0.1-mile section. Callout i shows the CFD for the section between MM 145.8 and MM 145.7, where the speed feedback display sign was deployed. As seen, there is no considerable difference in distributions for the panels between MM 146.3 (0.5 mile before the sign) and MM 146.1 (0.3 mile before). The reduction in speeds begins around MM 146, approximately 0.2-mile (~1,000 ft) upstream of the sign (callout ii), as shown by the "After" curve that begins to shift slightly towards the left indicating the drop in speeds. This is intuitive as motorists possibly react as soon as they see the signs. Speeds continue to decrease downstream of the sign, as shown by the "After" curve shifting further left. Although the speed limit in this region was 55 mph (callout iii), the observed median speeds on both before and after sections were still around 70 mph. The highest reduction in median speed was observed between a 0.1 to 0.2-mile section downstream (callout iv) of the sign, with a 5-mph reduction between the before and after deployment.

A t-test conducted on these segments also confirmed that the mean reduction in speeds near the sign were statistically significant (Table 4.2). The reduction in mean speeds were found to be only statistically significant from 0.2 mile (~1,000 ft) upstream of the sign.

To understand where the shift in speeds occurs, a density plot of speeds for a 0.2-mile before and after section near the sign was plotted. The kernel density plots, which are smooth curves estimating the probability density function of the continuous variable, help compare the distributions in an effective way. The area under each curve always adds up to 1. Figure 4.7b compares the density plot for before and after deployments. The "After Deployment" distribution is slightly flatter and shifted to the left of the "Before Deployment" distribution, indicating a dip in speeds. The shift in the right tail also shows that the upper speeds dropped in the after period (callout v). Analyzing the area under the curve, this translates to a proportion of around 10%–15% reduction in sample speeds greater than 70 mph (callout vi).



(a) Boxplot of speeds with location of posted speed limit signs



(b) Spatial analysis adjacent to MM 148.6 over a 0.2-mile (~1,000 ft) upstream and downstream of the speed limit sign at callout i

Figure 4.4 Spatial analysis of posted speed limit signs.

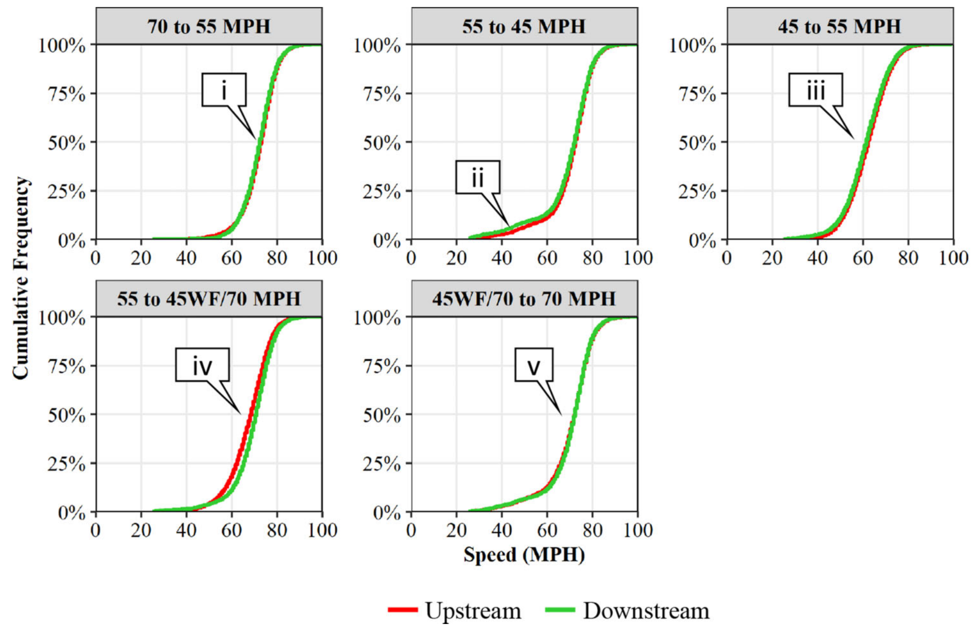
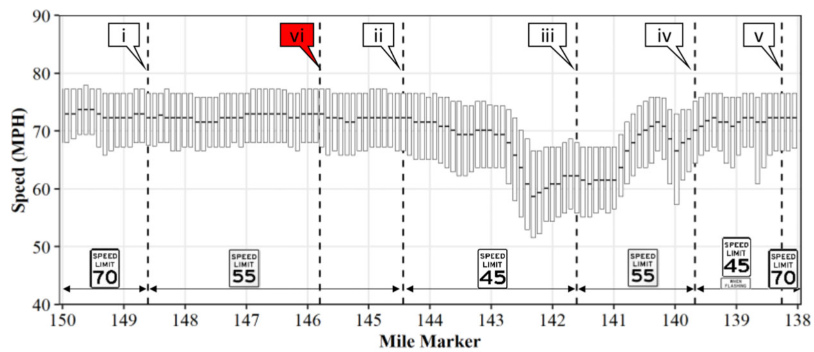
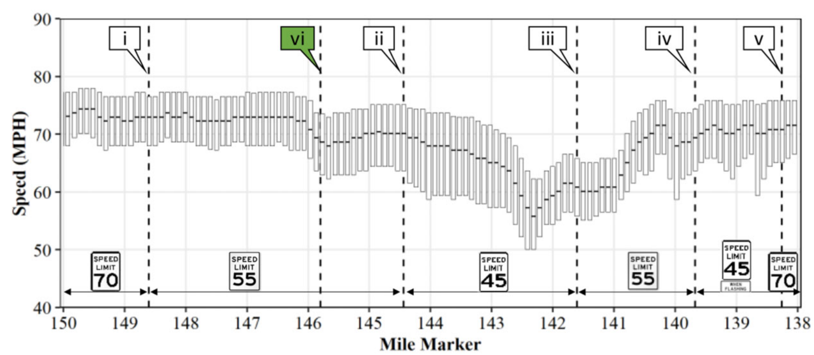


Figure 4.5 CFDs illustrating distribution of speeds on the 0.2-mile section upstream and downstream of the posted speed limit sign transitions.

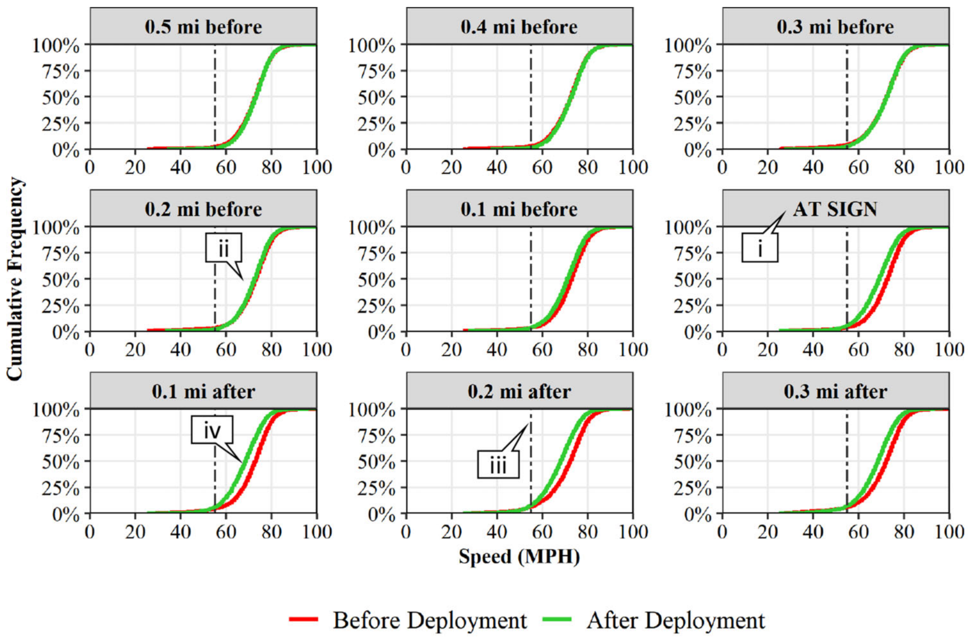


(a) Before (May 25–31, 2021)

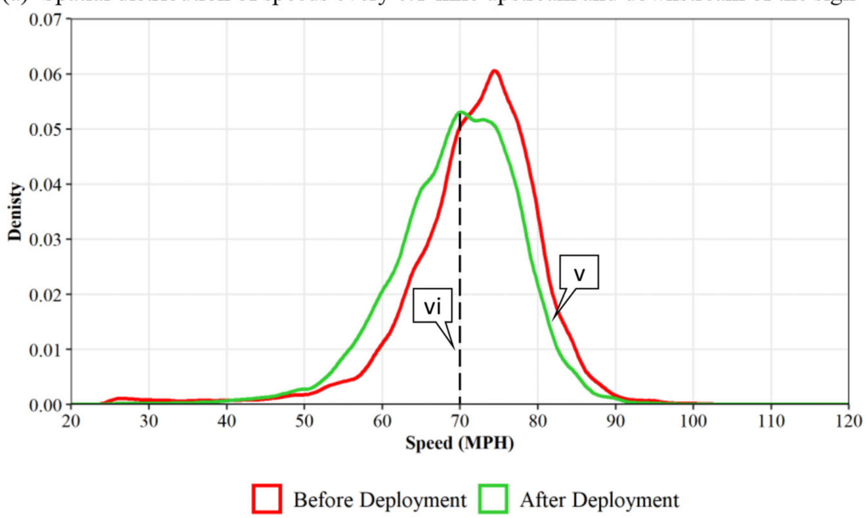


(b) After (June 7–13, 2021)

Figure 4.6 Boxplots comparing speeds before and after the placement of speed feedback display sign (callout vi). Sign was placed at MM 145.8 on June 2, 2021.



(a) Spatial distribution of speeds every 0.1-mile upstream and downstream of the sign



(b) Density plot comparing speeds on a 0.2-mile (~1,000 ft) section before and after the sign

Figure 4.7 Distribution of speeds before and after the deployment of speed feedback display sign.

TABLE 4.2
T-test comparing mean speeds before and after the deployment of the speed feedback display sign

Mile Marker	Sample Size		Mean Speed (mph)		Standard Deviation (mph)		p-value	Significant Reduction in Mean Speeds
	Before	After	Before	After	Before	After		
147.0–146.9	11,946	11,729	71.97	72.46	7.67	6.68	1.000	–
146.9–146.8	12,036	11,764	72.16	72.39	7.43	6.82	0.995	–
146.8–146.7	11,983	11,747	72.35	72.43	7.36	7.03	0.792	–
146.7–146.6	11,944	11,833	72.22	72.09	7.59	7.36	0.09	–
146.6–146.5	11,988	11,770	72.26	72.26	7.37	7.09	0.515	–
146.5–146.4	11,928	11,716	72.38	72.64	7.42	6.70	0.998	–
146.4–146.3	11,986	11,748	72.01	72.41	7.72	6.72	0.999	–
146.3–146.2	12,033	11,814	71.55	72.10	8.33	7.18	1.000	–
146.2–146.1	11,923	11,636	71.20	71.55	9.04	7.79	0.999	–
146.1–146.0	11,029	10,774	71.91	71.77	8.78	7.36	0.093	–
146.0–145.9	11,015	10,956	71.83	70.37	8.59	7.85	<0.001	Yes
145.9–145.8	11,035	11,340	71.66	68.46	8.77	8.16	<0.001	Yes
145.8–145.7[1]	11,122	11,380	71.49	67.70	8.89	8.26	<0.001	Yes
145.7–145.6	11,945	12,147	70.66	67.27	9.57	8.59	<0.001	Yes
145.6–145.5	11,894	12,062	70.65	67.64	9.83	8.76	<0.001	Yes
145.5–145.4	12,038	11,988	69.96	67.32	10.52	9.29	<0.001	Yes
145.4–145.3	12,005	11,925	69.82	67.39	10.21	9.41	<0.001	Yes
145.3–145.2	11,939	11,842	70.17	67.72	9.99	9.51	<0.001	Yes
145.2–145.1	11,855	11,667	70.30	67.92	10.07	9.61	<0.001	Yes
145.1–145.0	11,684	11,546	70.65	68.38	9.79	9.46	<0.001	Yes

[1]Location of speed feedback display sign.

5. AUTOMATED WORK ZONE SPEED ENFORCEMENT IN PENNSYLVANIA

This case study used connected vehicle trajectory data to evaluate the impact of automated work zone speed enforcement. Three work zones in Pennsylvania with active automated speed enforcement were compared with two work zones in Indiana without automated speed enforcement. Analysis was conducted on more than 300 million datapoints from over 71 billion records between April and August 2021.

5.1 Automated Speed Enforcement in Pennsylvania

In 2020, there were nearly 1,300 work zone crashes in Pennsylvania that resulted in over 800 injuries and 15 fatalities (PDOT, 2020). The automated work zone speed enforcement (AWZSE) program in Pennsylvania was enacted into law by Act 86 (2018) that authorizes automated speed enforcement in active work zones (Pennsylvania Turnpike Commission, Pennsylvania Department of Transportation, and Pennsylvania State Police, 2021). This program is jointly supported by the Pennsylvania Department of Transportation, the Pennsylvania Turnpike Commission, and the Pennsylvania State Police with the goal of promoting work zone safety by reducing speeds and improving driver behavior. A field unit is deployed (Figure 5.1a callout i) in the work zone (typically for 8 hours per day) that uses both radar and roof-mounted cameras to capture vehicle speeds. During active enforcement, advance warning signs (Figure 5.1b) are also placed at 500 ft and 1,000 ft ahead of the field unit to alert the incoming motorists. Violations are issued for excessive speeding which is defined by law as 11 mph or more above the posted speed limit. The first offense is treated as a zero-first violation and fines are issued for repeat violators for the second and subsequent offenses. The program is also geared towards complementing the existing speed enforcement operations carried out by the Pennsylvania State Police.

Statewide automated enforcement began in March 2020 but was halted due to the pandemic and resumed at critical and emergency work zones in April 2020. In 2020, there were over 2,000 deployments that resulted in more than 219,000 violations and roughly $1.7 M of fines from nearly 12% repeat offenders. Preliminary results showed that speeds dropped in the work zones, with a 16.6% reduction in percentage of vehicles travelling over the speed limit and a 43.6% reduction in the percentage of vehicles over the 11-mph legal threshold (Pennsylvania Turnpike Commission, Pennsylvania Department of Transportation, and Pennsylvania State Police, 2021).

5.2 Work Zones in Pennsylvania with Automated Speed Enforcement

Three work zones with active automated speed enforcement between April and August 2021 were selected for this study (Figure 5.2). The first work zone is located south of Pittsburgh on I-79 south (S), between mile markers (MM) 51 and 48, with a work zone speed limit of 45 mph (callout i). The second work

(a) Field unit with radar equipment and roof mounted cameras (b) Warning signs

Figure 5.1 Automated speed enforcement field unit and warning signs.

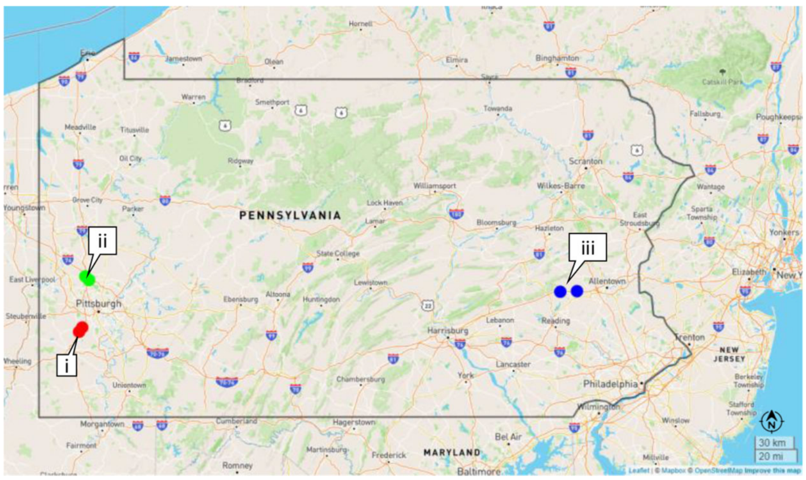


Figure 5.2 Study work zones in PA with active automated speed enforcement.

zone is located north of Pittsburgh on the Pennsylvania Turnpike I-76 W between MM 31 and 28 (callout ii). The speed limit in this work zone is 55 mph. The final work zone is a 10-mile section between MM 45 and 35 on I-78 W. The speed limit in this work zone, located west of Allentown (callout iii) is 50 mph. All three work zones underwent reconstruction activities and generally maintained two travel lanes within barrier protection while enforcement was present. Detailed logs with duration and location of active enforcement on each day were also available. Although previous studies have used probe vehicle data to capture speed variations during rain events (Downing et al., 2018), this paper does not consider the impact of weather.

5.3 Data

For the study period between April and August 2021, there were approximately 71 billion CV records available in Pennsylvania. To portray the extent and coverage of this data, Figure 5.3 shows a map of nearly 35 million CV records generated during the noon hour on 2 day in Pennsylvania. During this study, over 322 million CV records from nearly 538,000 unique trips were ex-extracted across the three work zones of interest. I-79, I-78, and I-76 generated roughly 162, 100, and 60 million records in both directions, respectively. I-79 S, I-78 W, and I-76 W re-turned 87, 50, and 30 million records, respectively.

5.4 Impact of Automated Work Zone Speed Enforcement

Analysis was limited to periods between 6 AM and 6 PM to remove any potential bias outside enforcement hours. Speeds below 25 mph were also discarded to exclude congestion and queuing impacts. In addition, speeds above 120 mph were treated as outliers and excluded from the analysis.

5.4.1 Interquartile Range (IQR) Plots

Figure 5.4 illustrates an IQR plot of speeds every 0.1-miles along the study section between MM 55 and 43 on I-79 S. The x-axis highlights the mile markers along the direction of travel, and the y-axis shows the speeds. The normal speed limit on this section of I-79 is

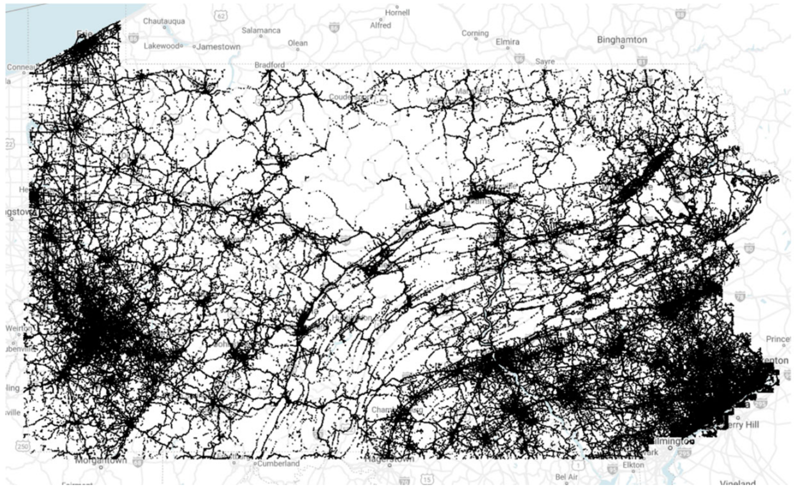


Figure 5.3 One hour of CV trajectory data in PA.

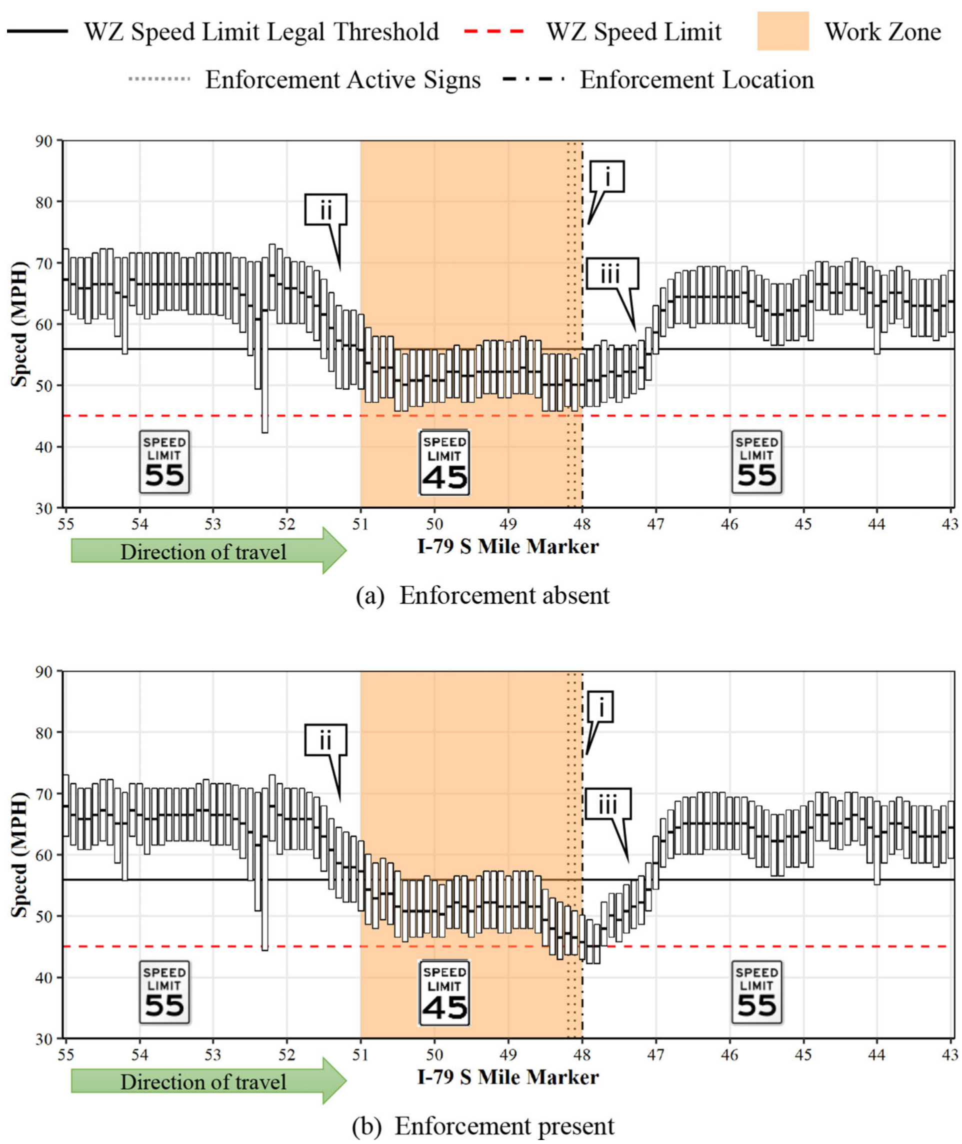


Figure 5.4 IQR plots comparing the impact of enforcement on the I-79 SB work zone.

55 mph. The bottom bar of the interquartile plots shows the 25th percentile, top bar shows the 75th percentile and the middle bar shows the median speed. The tan backfill highlights the work zone extents, the horizontal dotted red line represents the work zone speed limit (45 mph), and the horizontal black solid line represents the 11-mph legal threshold above the posted speed limit (56 mph). The vertical dot-dash line shows the location of automated enforcement (at MM 48) and the two dotted lines before it shows the location of the warning signs (Figure 5.1a).

Figure 4.4a depicts the variation in speeds when automated enforcement was absent (at MM 48), and Figure 4.4b depicts a similar graphic when enforcement was present (at MM 48). When the two figures are compared, there is a noteworthy drop in speeds on Figure 4.4b around the enforcement location (callout i). On closer examination, the drop in speed begins a few tenths of a mile ahead of the warning signs indicating a strong speed limit compliance during the presence of enforcement. It is also interesting to note that irrespective of the enforcement activity, nearly 75% of all the speeds inside the work zone are within the 11-mph legal threshold.

Figure 4.4 also provides an opportunity to understand the speed patterns before entering and after exiting the work zone. The reduction in speeds begins roughly 1 mile before entering the work zone (callout ii). Similarly, the speeds climb back up to 55 mph within a mile after exiting the work zone (callout iii). This is further corroborated in Figure 5.5 which compares the cumulative frequency of the speeds during the presence (green) and absence (red) of enforcement across 1-mile sections before and after the location of enforcement. For the 1-mile stretch just before and after the enforcement location, there is a shift in the green curve (enforcement present) towards the left signaling a reduction in speeds. For all the other sections, the two curves overlay each other indicating similar vehicle speeds.

A nonparametric Kolmogorov–Smirnov test (K-S test) is also conducted for detecting the horizontal differences between the two distributions (Siegel, 1956). The D-statistic shows the maximum vertical distance between the two cumulative frequency diagrams on Figure 4.5. Table 5.1 shows the results from the K–S test at every 1-mile section before and after the location of enforcement. Results show that the distributions during the presence and absence of enforcement are statistically significant at all locations (at a 99% confidence level), with the maximum separation observed within 1 mile of the enforcement location.

Although K–S test show statistically significant differences with and without enforcement at multiple locations, the more important takeaway from Figure 5.5 is that the upper tails (high speeds) are quite close and demonstrate the impact of reducing high speeds in work zones, even when the automated enforcement is not present.

TABLE 5.1
Kolmogorov–Smirnov test showing the distributions during the presence and absence of enforcement

Location	D-Statistic[1]	*p*-Value
4–5 mile before	0.033	<0.001
3–4 mile before	0.075	<0.001
2–3 mile before	0.028	<0.001
1–2 mile before	0.024	<0.001
0–1 mile before	0.129	<0.001
0–1 mile after	0.146	<0.001
1–2 mile after	0.03	<0.001
2–3 mile after	0.018	<0.001
3–4 mile after	0.004	0.007
4–5 mile after	0.025	<0.001

[1]Significant at 99% confidence level.

5.4.2 Speed Compliance Proportion

This data also provides an opportunity to conduct a longitudinal analysis of speed compliance over the entire length of the work zone. Figure 5.6 illustrates the speed compliance at both posted speed limit and 11 mph legal threshold across the I-79 S work zone, during the absence (Figure 5.6a) and presence (Figure 5.6b) of enforcement at MM 48.0. In general, irrespective of the enforcement, the average compliance (inside the work zone) under the speed limit was roughly 15%, whereas the compliance under the legal threshold was nearly 75%. During active enforcement, the average compliance under the posted speed limit and legal threshold increased by roughly 3% and more than 1%, respectively, compared to periods without enforcement.

Table 5.2 presents a summary of the average compliance over the three work zones during the presence and absence of automated enforcement. The 3-mile I-76 W work zone recorded the highest compliance with more than 25% under the speed limit and nearly 85% under the legal threshold. However, the presence of enforcement was not found to have a major impact on the speed compliance. I-78 W work zone was found to have the least compliance—a little above 10% under speed limit and close to 60% under the legal threshold. This could be due to the greater length of this work zone stretching over 10 miles.

5.4.3 Impact of Work Zone Length

Among the three study work zones, the two shorter ones (3 miles) were found to have better speed compliance than the longer work zone. As seen before in Figure 5.6, there is less fluctuation in speed compliance within the shorter I-79 S work zone. Figure 5.7 shows the proportion of speed compliance over the longer I-78 W work zone which spans over 10 miles. In contrast, there are a few considerable fluctuations (callout i–iv) in the longer work zone—potentially areas free of work activity and geometric constraints such as lane reductions. The compliance under the legal threshold drops to less than 25% in these zones. It is common for

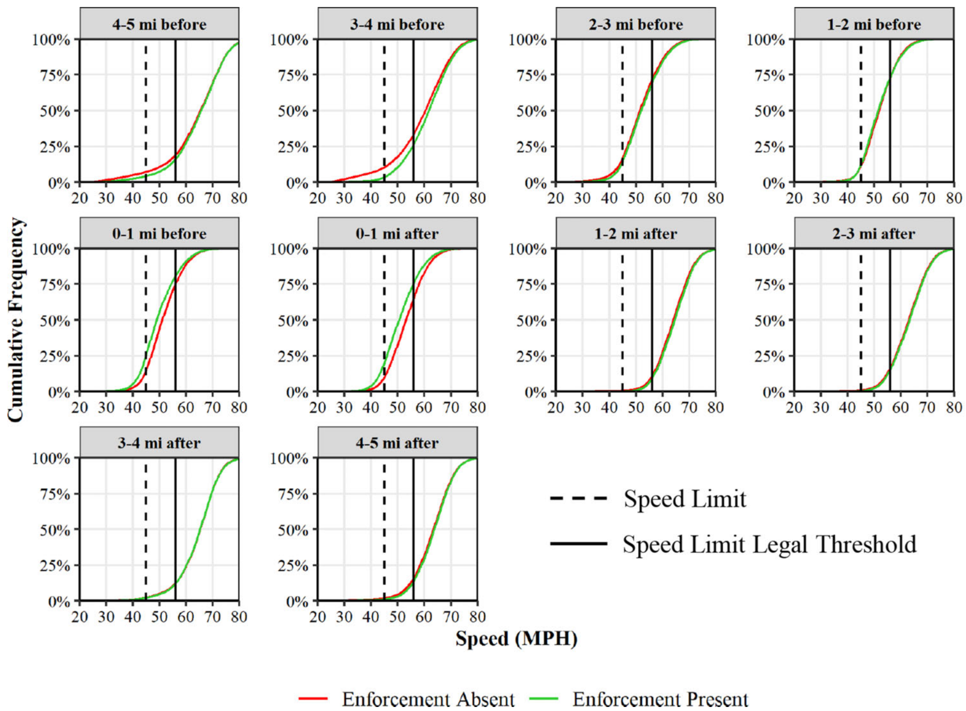


Figure 5.5 Speed compliance with respect to the enforcement location on I-79 S work zone.

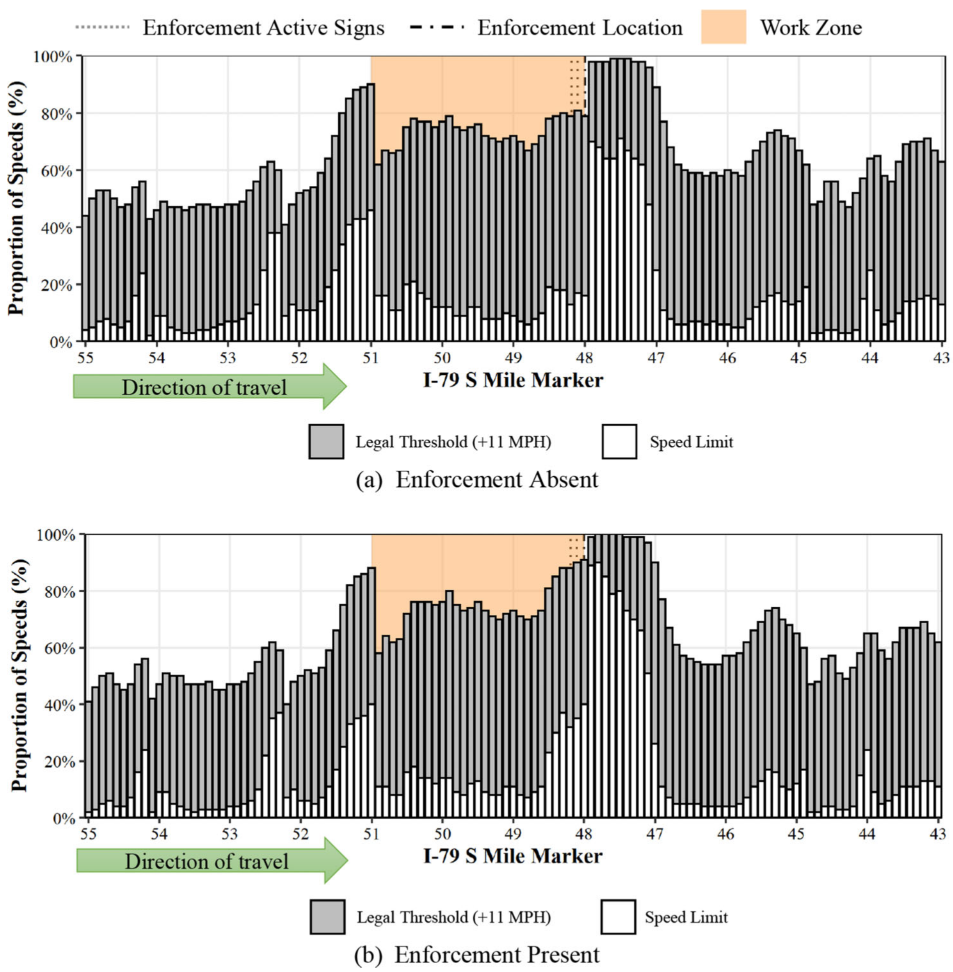


Figure 5.6 Speed compliance below the posted speed limit and legal threshold, with and without enforcement.

TABLE 5.2
Summary of average speed compliance inside the work zone with and without enforcement

WZ	Length (mi)	Posted Speed Limit (mph)	Legal Threshold (mph)	Compliance with Posted Speed Limit		Compliance with Legal Threshold	
				Enf. Absent (%)	Enf. Present	Enf. Absent (%)	Enf. Present
I-79 S	3	45	56	12.7	15.4% (↑)	73.7	74.8% (↑)
I-78 W	10	50	61	10.6	11.5% (↑)	59.3	62.6% (↑)
I-76 W	3	55	66	25.4	26.9% (↑)	84.6	84.3% (↓)

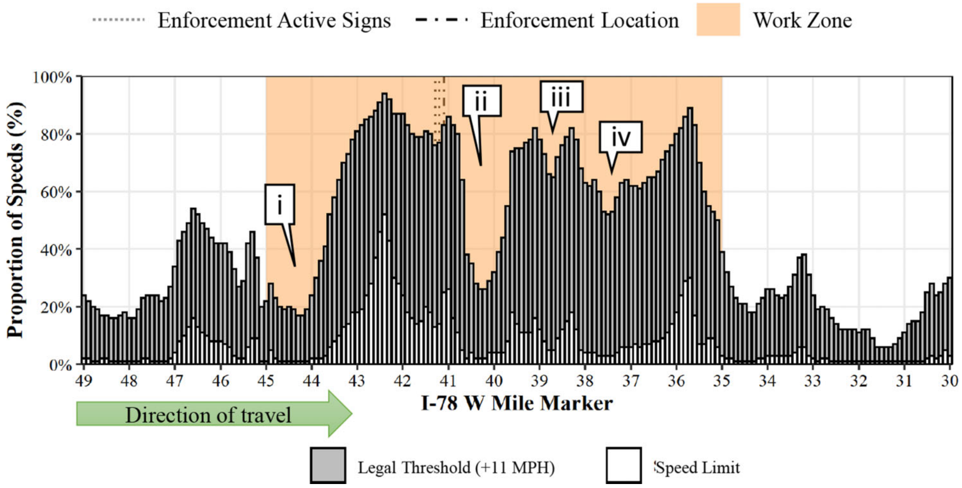


Figure 5.7 Speed compliance below the speed limit and legal threshold on 10-mile I-78 W work zone.

agencies to combine two or more work zones separated by a short distance (less than a mile or two) into a single work zone, however this could lead to a significant reduction in speed compliance.

5.5 Comparison with Work Zones Without Automated Speed Enforcement

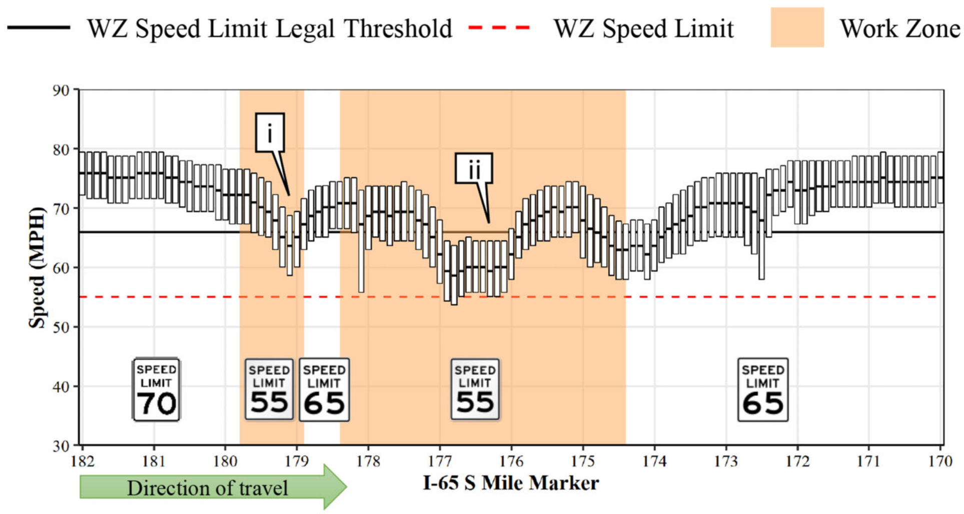
Figure 5.8 illustrates the IQR plots (similar to Figure 5.4) for two work zones on I-65 S in Indiana. Figure 5.8a represents the work zone from MM 182 to MM 170 during the month of July 2021 (to be referred as I-65 Sa) and Figure 5.8b represents the work zone from MM 153 to MM 138 during May 2021 (to be referred as I-65 Sb). The speed limits on both work zones transition from 70 to 55 mph, with I-65 Sb also having a section with 45 mph limit. The legal threshold (solid black horizontal line) is offset by 11 mph from the speed limit. For I-65 Sb, the IQR plots occlude the legal threshold line when the speeds go back to 55 mph at MM 141.6 (Figure 5.8b). Both work zones underwent reconstruction activities with partial lane reductions.

As indicated earlier, neither of these work zones had automated enforcement, and only occasional enforcement by officers in marked cruisers due to narrow shoulders that provided a challenging environment for safely monitoring and/or stopping motorists. In general, there were only a few sections where more than 75% of the speeds were within the legal threshold (callouts i–iii)). Further investigations revealed that geometric constraints such as lane reductions (callouts i and ii)) and narrow lanes without any shoulders (callout iii) resulted in these speed drops (Mathew et al., 2021). On I-65 Sb, almost all of the median speeds were roughly 20 mph over the speed limit, except the zone with narrow shoulder shown by callout iii. The average compliance with the speed limit across the work zone was found to be less than 11% for I-65 Sa and less than 5% for I-65 Sb (Table 5.1). Only half of the analyzed speeds were within the legal threshold on I-65 Sa, whereas for I-65 Sb, less than a quarter of the speeds were within the legal threshold.

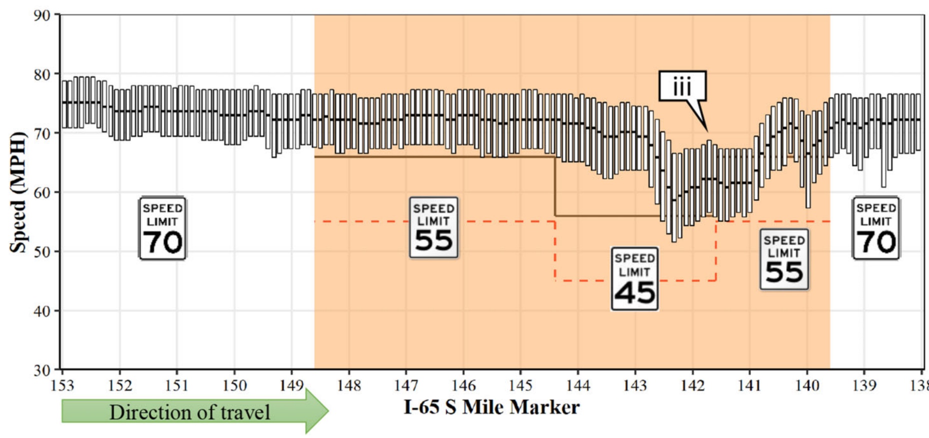
Figure 5.9 provides an overall comparison of the speed compliance across the PA work zones with automated enforcement and IN work zones without automated enforcement. In general, the work zones with automated enforcement performed well with nearly 12%–60% better compliance. I-78 W (PA) and I-65 Sa (IN) work zones have comparable speed compliance, possibly due to their long extents (over 10 miles in length).

5.6 Comparison with Radar-Based Speed Feedback Display Sign

Figure 5.10 compares the impact of radar-based speed feedback display sign with automated enforcement in reducing speeds inside the work zone. Figure 5.10a represents the same data as shown in Figure 4.6



(a) I-65 SB WZ MM 182 to MM 170, IN during July 2021



(b) I-65 SB WZ MM 153 to MM 138, IN during May 2021

Figure 5.8 IQR speed plots for non-enforcement work zones.

TABLE 5.3
Summary of average speed compliance on IN work zones without automated enforcement

WZ	Length (mi)	Posted Speed Limit (mph)	11-mph Legal Threshold (mph)	Compliance with Posted Speed Limit (%)	Compliance with Legal Threshold (%)
I-65 Sa	5	55	66	10.8	50.3
I-65 Sb	9	45/55	56/66	4.3	24.7

on I-65 S. Figure 5.10b represents the same data as shown in Figure 5.4b on I-79 S with automated enforcement. Callout i shows the location of the speed feedback display on Figure 5.10a and automated enforcement on Figure 5.10b. While there was a 4–5 mph drop in median speeds near the vicinity of the speed feedback display sign, the median speeds were still 14 mph above the speed limit (55 mph) and around 3 mph above the 11-mph legal threshold (66 mph). In contrast, near the location of automated enforcement, median speeds were within 1–2 mph of the speed limit and 9 to 10 mph below the 11-mph legal threshold.

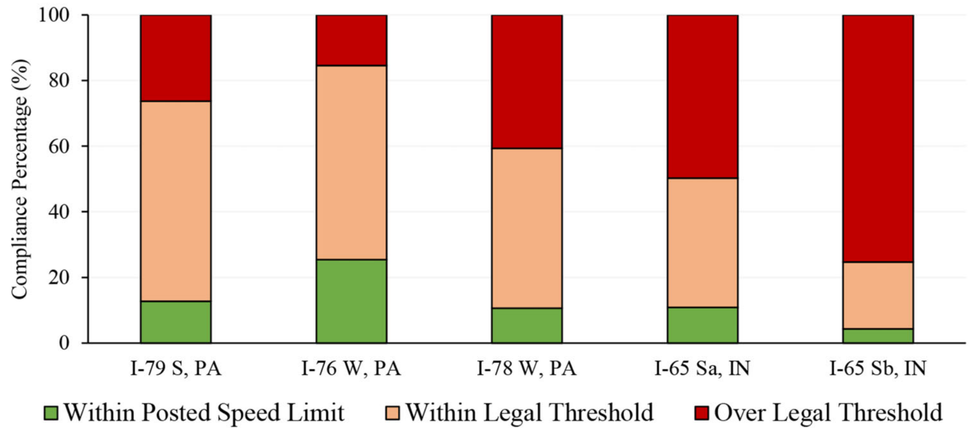
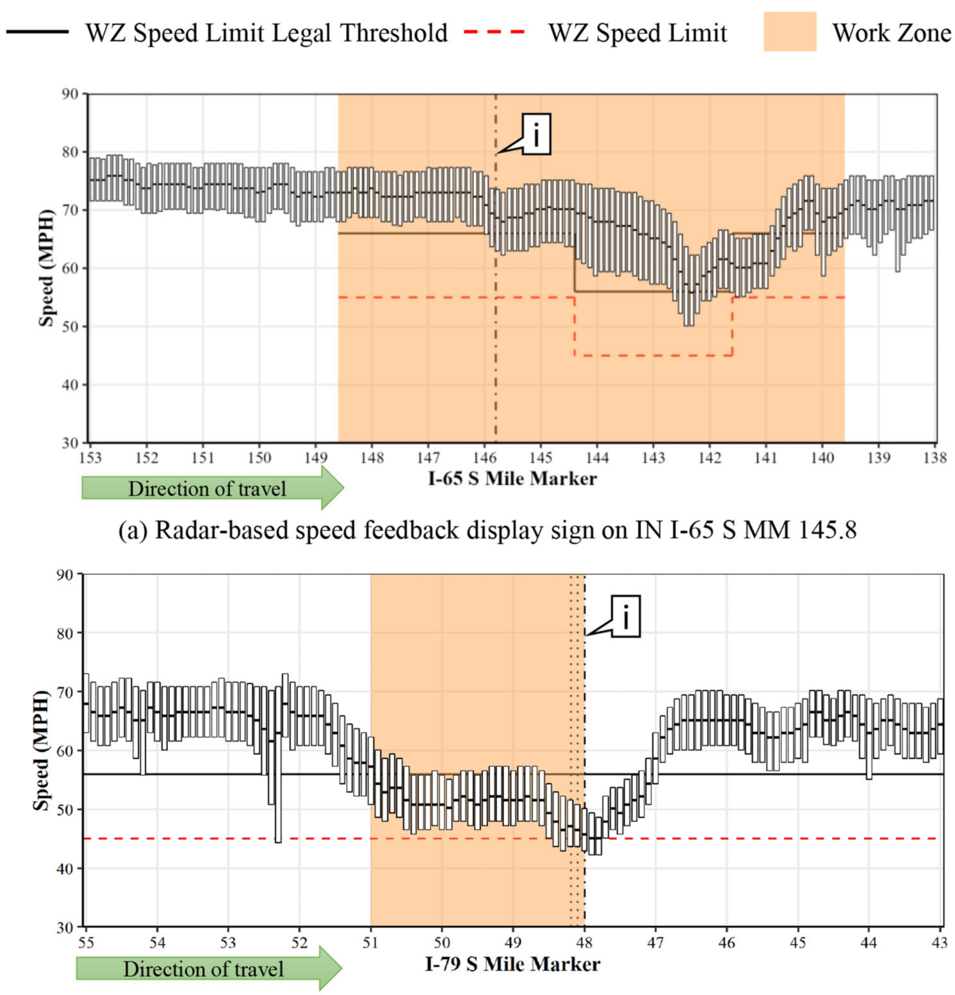


Figure 5.9 Speed compliance comparison across work zones. Callout (i) shows work zones with automated enforcement. Callout (ii) shows work zones without enforcement.



(a) Radar-based speed feedback display sign on IN I-65 S MM 145.8

(b) Automated Speed Enforcement on PA I-79 S near MM 48

Figure 5.10 Comparison of automated enforcement with radar-based speed feedback sign.

6. IMPACT OF SPEED ENFORCEMENT BY LOCAL PUBLIC SAFETY AGENCIES

A preliminary analysis of a few speed enforcement deployments in and around metropolitan Indianapolis was conducted to determine the feasibility of using probe data to develop assessment techniques.

A highly visible enforcement blitz involving approximately 8 Indianapolis Metropolitan Police Department (IMPD) officers was conducted near Emerson Ave/I-70 W (MM 86.7) on November 28, 2022 between 1,400 and 1,800 hours (Figure 6.1). Figure 6.2 compares the before/after variation in median speeds using connected vehicle (CV) data during the same hours. Results show a reduction of 19 mph in median speeds during the enforcement (callout i) and a reduction of 6.5 mph in median speeds lasting into the following week (callout ii).

Table 4.1 shows a summary of subsequent details conducted by IMPD and Indiana State Police (ISP). Results indicate a strong impact in reducing vehicle speeds during the enforcement period, with an average reduction of more than 10 mph in median speeds. In several cases, there was a lasting impact on even the next day and next week.

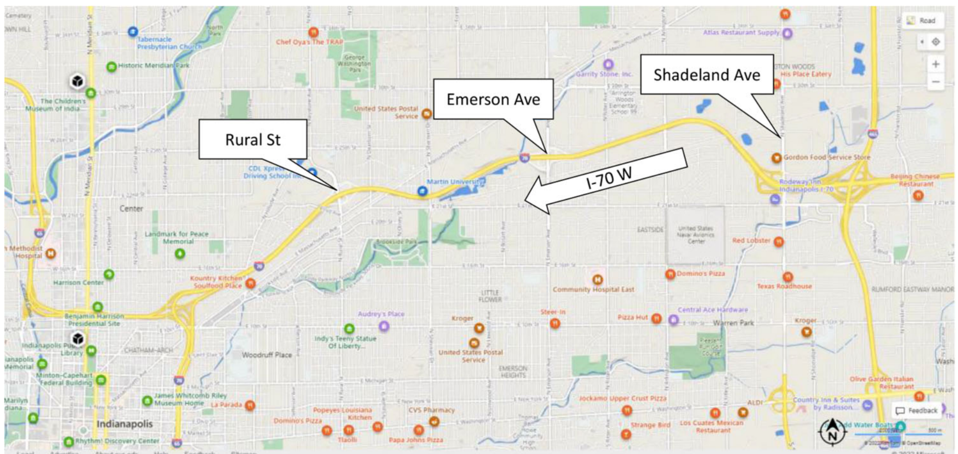


Figure 6.1 Speed enforcement conducted by IMPD on I-70 W near Emerson Ave, Indianapolis.

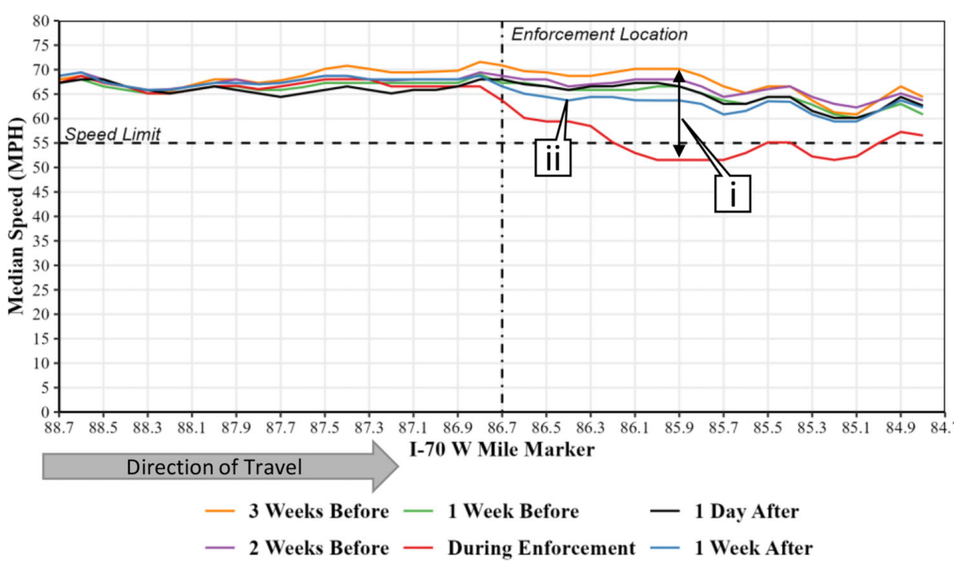


Figure 6.2 Reduction in CV median speeds during enforcement and the next week.

TABLE 6.1
Summary of enforcement details and impact on speeds

Date	Start Time	End Time	Agency	Route	MM	Speed Limit (mph)	Median Speed Drop (mph)		
							During Detail	Next Day	Next Week
11/28/2022	14:00	18:00	IMPD	I-70 W	86.7	55	18.7	4.4	6.5
01/17/2023	08:30	12:30	ISP IMPD	I-70 W	86.7	55	12.2	8.6	2.2
01/27/2023	08:30	12:30	IMPD	I-70 W	86.7	55	13.7	1.4	1.5
01/29/2023	09:30	13:30	IMPD	I-465 OL	35.3	45	7.9	12.9	1.4
02/06/2023	14:30	18:30	IMPD	I-70 W	86.7	55	13.3	4.3	3.4
02/13/2023	08:30	12:30	IMPD	I-70 W	86.7	55	10	12.9	1.4
02/19/2023	10:00	14:00	IMPD	I-65 S	108.3	55	11.9	2.9	1.4
02/21/2023	08:30	12:30	ISP IMPD	I-70 W	86.4	55	10.6	2.2	6.4
02/24/2023	09:00	13:00	IMPD	I-70 W	76.3	55	4.4	2.2	7.2
02/25/2023	09:00	13:00	ISP IMPD	I-465 OL	41.3	55	15.9	0.2	2.1
03/02/2023	08:30	12:30	IMPD	I-70 W	86.6	55	10	58[1]	1.4

[1]Slowdown due to a crash/other incident.

7. SUMMARY AND RECOMMENDATIONS

Speed limit compliance in work zones is a major concern for agencies as higher speeds are correlated with frequency and severity of crashes. It is important for agencies to understand the impact of several speed compliance measures in and around work zones. This study used CV trajectory data to evaluate the spatial and temporal performance of two speed limit compliance measures—posted speed limit signs and radar-based speed feedback display speed limit signs. Additionally, this study reports on both the spatial and temporal effects of automated enforcement on driver behavior and vehicle speeds across the work zones.

Spatial analysis over a 0.2-mile segment before and after the posted speed limit signs over a 1-week period showed that the signs had no impact on reducing speeds (Figure 4.5). A 1-week before/after analysis to study the impact of radar-based speed feedback display showed a significant speed reduction beginning approximately 1,000 ft upstream of the radar speed sign (Figure 4.6). Analysis also showed that the upper extreme speeds (15 mph above the speed limit) in this region dropped by 10%–15% (Figure 4.7b). The maximum drop in speeds occurred at 1,000 ft downstream of the sign (median drop of 5 mph) and overall results were found to be statistically significant (Table 4.2).

Compliance at posted speed limit and a legal threshold of 11 mph over the posted speed limit were evaluated across three work zones in Pennsylvania with automated speed enforcement. Reduction in speeds were found to occur within a mile before entering the work zone. Similarly, speeds went back up within a mile after passing the work zone (Figure 5.5). During the absence of enforcement, the average compliance at work zone speed limit ranged from 10%–25% and at 11 mph legal threshold ranged from 59%–84%. During enforcement, the average compliance at work zone speed limit ranged from roughly 11%–27% and at legal threshold ranged from 6%–84% (Table 5.2). Short work zones (3 miles or less) were found to have better speed limit compliance (Figure 5.7) than longer work zones (10 miles). This study also compared and evaluated the speed limit compliance on two work zones in Indiana without automated enforcement. Compliance at speed limit and at 11 mph legal threshold was estimated to be only around 4%–11% and 25%–50%, respectively (Table 5.3, Figure 5.9).

This study also examined the impact of radar-based speed feedback display sign with automated enforcement in reducing speeds inside the work zone. Although speed feedback signs had a mild impact in reducing speeds, the median speeds were still 14 mph above the speed limit (55 mph) and around 3 mph above the 11-mph legal threshold (66 mph). In comparison, automated enforcement had a strong impact in speed compliance with median speeds within 1–2 mph of the speed limit and 9–10 mph below the 11-mph legal threshold (Figure 5.10).

Results from enforcement activities conducted by local public safety agencies showed a 5–19 mph reduction in median speeds during the enforcement period (Figure 6.2). On few occasions the lasting impact of this enforcement was also seen on the next day and next week (Table 6.1).

The analysis and visualizations presented in this study highlight the reach and scalability of this big data to facilitate a comprehensive analysis of vehicle speeds across the entire length of the work zone. The findings show that posted reduced speed limit signs had no significant impact on reducing speeds whereas the speed feedback display signs had a small impact on reducing speeds in the work zone. Enforcement activities showed the maximum impact on reducing speeds; however, this is not scalable as law enforcement agencies may not have enough staffing and resources to perform persistent enforcement activities. It is also important to make work zones enforcement-friendly for law enforcement officers to conduct their operations in a safe manner. Automated enforcement programs offer a viable option that not only scales well but also allow law enforcement agencies to free up important resources without compromising speed compliance and safety in and around work zones.

As agencies ramp up enforcement efforts, it is important to understand the impact of temporal (duration, interval, and time of day) and spatial (inside, ahead or near the entrance of work zone) randomness on achieving better speed compliance. Additional consideration while setting the right work zone speed limit may also help achieve better compliance.

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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 1,600 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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