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Geometric Constraints and Visual Field Related to Speed Management

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16. Abstract

    This study investigates the challenges inherent in rural arterial roads and highways connecting small towns and cities in Indiana. Despite their pivotal role in transportation and development, these roads often experience a high frequency of traffic accidents attributed to speeding, particularly at transition areas from high-speed to low-speed roads. To address this issue, this study investigated cost-efficient and effective speed management countermeasures. This study emphasized the importance of considering cost-efficient and effective speed management strategies, with a focus on roadside vegetation and lane widths near small-town entrances on arterial roads and highway ramps. Proposing four countermeasures for each scenario—such as large spacing bush, small spacing bush, hedge, and narrow lane width for arterial roads or a delineator for highway exit ramps—the investigation employed driving simulator studies involving sixty human subjects to assess the individual and interactive effects of these interventions. The results on driving speed and deceleration rate show that specific combinations of narrow lanes and roadside vegetation were effective in mitigating speeding on arterial roads and highway ramps, especially during the transition zones. The study also revealed that the speed reduction effects of these countermeasures do not persist in post-countermeasure segments, which reduce the boarder impacts of these interventions. The research underscores the importance of a targeted and context-aware approach in selecting and implementing speed management measures and emphasized the need for tailored interventions based on the specific characteristics of each roadway type and scenario.

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EXECUTIVE SUMMARY

Introduction

Rural arterial roads and highways help connect small towns and cities in Indiana. Despite their significance for transportation and development, these roads can be prone to crashes, as evidenced by the high percentage of fatalities that are occurring at transition areas from high-speed roads to low-speed roads. Speeding emerges as a major contributor to these crashes, with studies indicating that unintentional speeding, influenced by various other factors, is a prevalent issue.

This report addresses safety concerns in two common transition areas: (1) rural arterial roads leading into small towns and (2) highway exit ramps. Two types of countermeasures were studied to reduce speeding-related crashes: lane width and roadside vegetation. The two types of transition areas will be discussed separately in each section. A main area of focus was the unique challenges posed by small-town entrances on rural highways since traditional countermeasures may face limitations due to private lands and resource constraints.

Findings

This study investigated whether roadside vegetation or lane width could be effective speed management countermeasures on rural arterial roads entering small towns and highway exit ramps. For arterial roads, four countermeasures were proposed—large spacing bush, small spacing bush, hedge, and narrow lane width. For highway exit ramps, four similar countermeasures were proposed, including: small spacing bush, large spacing bush, hedge, and delineator. All of these countermeasures were implemented in driving simulator studies using sixty recruited human subjects in two experiments. We used a delineator to simulate reduced lane width in the highway scenario.

Based on these countermeasures, three hypotheses were proposed for arterial roads, and four hypotheses were proposed for highway exit ramps. ANOVA and paired t-tests were conducted against these hypotheses. For arterial roads, it was discovered that the combination of narrow lanes and no vegetation, normal lanes and short vegetation, normal lanes and small spacing tall vegetation, narrow lanes and small spacing tall vegetation, and normal lanes and large spacing tall vegetation can be considered effective countermeasues. Small spacing bush and delineators on highway exit ramps increased the rate at which normal drivers reduced their speed, but drivers tended to deviate from their original lane positions, increasing the risk of colliding with roadside objects.

Implementation

When translating findings into practical implementation, it became evident that the impact of roadside vegetation and lane width on speed management will vary across different scenarios. For both arterial roads and highway exit ramps, the results revealed that neither roadside vegetation nor lane width significantly influenced post-countermeasure speeding range, after-countermeasure speed, or maximum deceleration during the countermeasure. The sole exception to this trend was observed in the highway exit ramps scenario, where a statistically significant difference in after-countermeasure speed was noted between large spacing bush and the baseline condition with no vegetation. This result highlights the nuanced nature of effective countermeasure implementation and emphasizes the importance of tailoring interventions to the specific characteristics of the road.

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1. INTRODUCTION

1.1 Background

The national highway system, which contains interstate, arterial roads, and so on, is vital to the nation's development (FHWA, 2017). Rural roads are especially critical within this massive system as they connect people from small, often relatively isolated towns. However, while providing people with versatile travel options, these rural roads are often some of the most common places for crashes. A study published by the National Highway Traffic Safety Administration (NHTSA, 2015) reveals that although traffic fatalities have been decreasing since the beginning of this century, rural traffic fatalities remain at a significant level. In 2013, 54% of all motor vehicle traffic fatalities occurred in rural areas, whereas only 19% of the U.S. population lived there. Furthermore, the fatality rate per 100 million miles traveled was 2.6 times higher in rural areas than in urban areas. Research has shown that crashes tend to occur near the entrance of small towns or cities (Casado-Sanz et al., 2019; Ehsani Sohi et al., 2019; Harland et al., 2014). These facts highlight the importance of focusing on safety issues on the transition areas in rural roads.

Speeding is one of the leading causes of crashes. According to the NHTSA report (NHTSA, 2015), speeding-related issues caused 30% of fatalities on rural roads. Speed is related to the possibility and severity of crashes (Elvik et al., 2019). One report divided speeding into six types and pointed out that incidental or unintentional speeding was the most frequent (Richard et al., 2016). A survey also revealed that unintentional speeding was one reason for speeding among young drivers (Truelove et al., 2022). They might not be aware of speeding as their perceptions of speed were influenced by the nearby vehicles or failed to check the speedometer regularly (Truelove et al., 2022). In another survey, 60% of participants underestimated their actual driving speed while driving on the road without cameras and signs (Corbett, 2001). The study conducted by Schmidt and Tiffin found that speeding could be explained by speed adaptation (Schmidt & Tiffin, 1969). Compared to subjects who drove at high speed for a short term, those who drove at high speed for a long term were more likely to underestimate their speeds (Schmidt & Tiffin, 1969). Therefore, speed adaptation must be considered when designing roads that require drivers to transit from high-speed areas to low-speed areas to avoid speeding.

This study aims to identify cost-efficient and effective speed management countermeasures that can be applied near small-town entrances on rural highways (arterial roads) as well as exit ramps from highways to local roads. Among different options, roadside vegetation and lane widths were used to create countermeasures and combinations of countermeasures.

1.2 Related Studies

Various countermeasures have been proposed to reduce speeding-related crashes, such as speed cameras, narrowed lane width, rumble strips, and so on (Vadeby et al., 2016). Two studies explored the impact of roadside vegetation density and the distance between roadside vegetation and road on speed (Calvi, 2015; Fitzpatrick et al., 2016). Both studies found that the impact of vegetation density was not significant on speed, and the impact of the distance between roadside vegetation and the road was significant (Calvi, 2015; Fitzpatrick et al., 2016). One study observed that drivers drove slowly as trees were close to the road and fast as trees were far away from the road (Calvi, 2015). Similarly, another study detected that speed in small clear zone width was significantly lower than speed in large clear zone width when driving in tangents and left curves (Fitzpatrick et al., 2016). Another study examined the effects of landscapes with different levels of greenness and complexity on driving performance (Jiang et al., 2021). They found that participants performed best in scenarios with shrubs (Jiang et al., 2021). Apart from introducing roadside vegetation, narrowing the lane width has also been confirmed as an effective countermeasure for speed management. Several studies showed that drivers drove slowly in the narrow lane scenarios and fast in the wide lane scenarios (Lewis-Evans & Charlton, 2006; Liu et al., 2016; Melman et al., 2018). Godley, Triggs, and Fildes (2004) found a significant reduction in the driving speed when the lane width was narrowed from 3.0 m to 2.5 m.

Previous studies have proposed countermeasures from various perspectives. However, there haven't been sufficient studies on driving speed management during the transition from rural roads into small towns with residential areas or exit ramps off highways, which are selected as the main research focus.

1.3 Report Structure

The next sections of this report will discuss experiment design, subject study details, data analysis results, and conclusions. Differences between the experiments conducted on arterial roads and highway exit ramps will be addressed separately when relevant.

2. EXPERIMENT DESIGN

2.1 Arterial Road

To replicate real-life scenarios, we constructed a driving simulator environment based on the state road of US 24, which runs through Goodland, Indiana, as the arterial road in our simulated scenario. The scenario consists of two lanes, one for drivers traveling from west to east (eastbound) and the other for those traveling from east to west (westbound). Figure 2.1 represents the distribution of speed limit signs on the
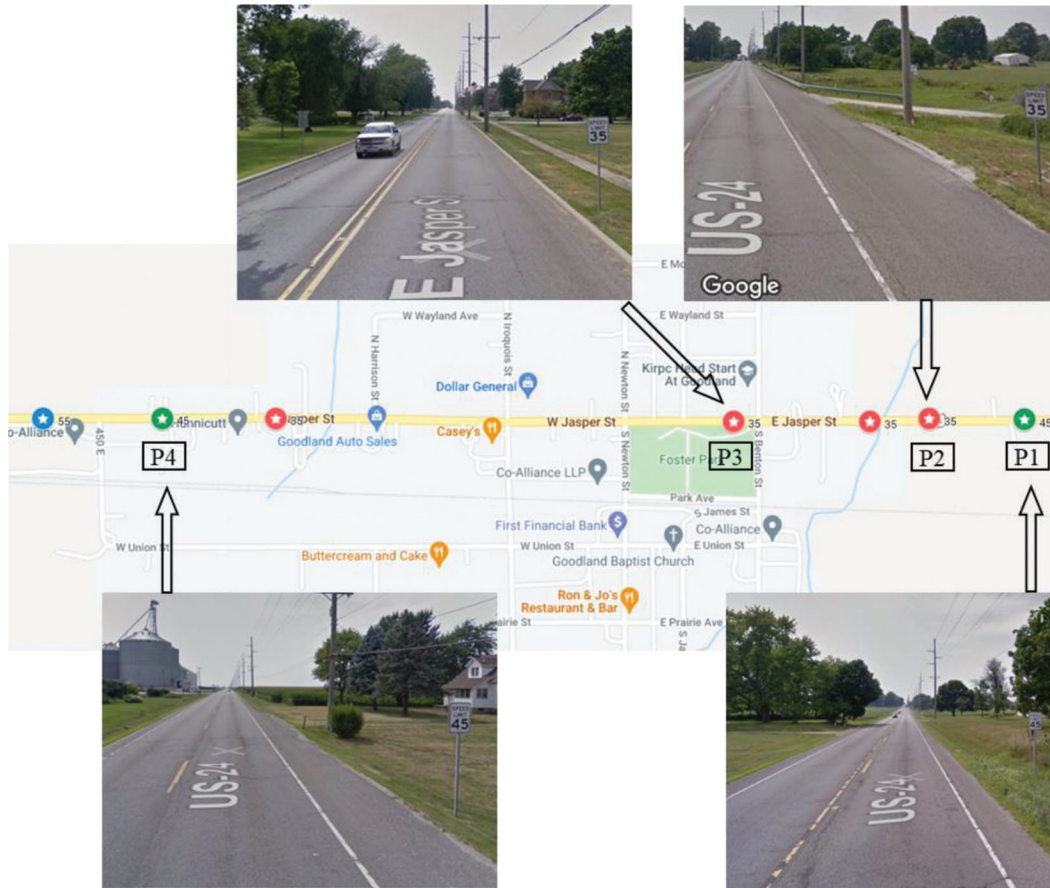
Figure 2.1 Real-world scenario that the arterial road experiment was based on.

Figure 2.2 Simulated scenario for arterial roads.

westbound lane in this area. The markers with different colors indicate the distribution of different speed limit signs. Red markers represent 35 mph speed limit signs. Green markers represent 45 mph speed limit signs. Blue markers represent 55 mph speed limit signs. Drivers drive from P1 to P4. P1 is the point before entering the town with 45 mph speed limit sign. P2 is the point before entering the town with 35 mph speed limit sign. P3 is the point in the town with 35 mph speed limit sign. P4 is the point after leaving the town with 45 mph speed limit sign. Speed limits before P1 and after P4 are 55 mph.

The simulated scenario was divided into different parts based on the speed limit: 55 mph, 45 mph, and

35 mph. Figure 2.2 depicts the simulated scenario, with the black line representing the 55-mph speed limit zone, the red line representing the 45-mph speed limit zone, and the blue line representing the 35-mph speed limit zone. As drivers travel from the 55-mph speed limit zone to the 35-mph speed limit zone, they will pass through a transition zone to decelerate. This transition zone covers the 45-mph speed limit zone and the 150 m stretch of road beyond it, which extends from point 5 to point 3 in Figure 2.2. Vegetation was planted at the roadside in the transition zone.

Three types of vegetation (hedge, small-spacing bush, large-spacing bush) and two types of lane width (narrow lane, normal lane) were applied as countermeasures.

Figure 2.3 Real-world scenario that the highway ramp experiment was based on.

Normal lane width was 12 ft (3.6 m), and narrow lane width was 10 ft (3 m). The height of the bushes was set to 2.5 m. The large-spacing bush was 10 m apart, and the small-spacing bush was 5 m apart. The hedge was 0.7 m tall. To determine whether countermeasures were effective or not, a baseline scenario without vegetation and with normal lane width in the transition zone was included in the experiment. This resulted in a total of eight scenarios, shown in Table 2.1. All scenarios were set in daytime. A within-subject experiment was conducted.

2.2 Highway Exit Ramp

Similarly, we constructed a simulator environment for highway exit ramps. The environment mimics the Exit 29B of I-469 to Maplecrest Road near Fort Wayne. Figure 2.3 shows the sections of the real-life road, and Figure 2.4 shows the simulated environment. In the black section (between point 1 and 100 m after point 2), the drivers would maintain a speed of 70 mph. The green section (between 100 m after point 2 and

point 3) is the exit ramp with a 50-mph advisory speed. The blue section (after point 3) is the section with a lower speed limit, which is 50 mph. As drivers travel from the 70-mph speed limit zone to the 50-mph speed limit zone, they will pass through the exit ramp to decelerate. Plants and delineators were planted alongside the exit ramp.

Four types of roadside features (hedge, small-spacing bush, large-spacing bush, delineator) were applied as countermeasures for highway exit ramps. A baseline scenario with nothing on the side of the ramp was also created. This resulted in a total of five scenarios, shown in Table 2.2. All scenarios were set in daytime. A within-subject experiment was conducted. Note that in scenario S2-DL, the delineators are placed to the right of the yellow line. Note that in scenario S2-DL, the delineators are placed to the right of the yellow line. The purpose is to simulate the driving scenario with the narrow lane width. Although the placement of delineators doesn't follow the MUTCD, it imitates the narrow lane scenario and can help to understand the drivers' behavior when the lane width changes.

TABLE 2.1
Description of arterial road experiment scenarios

Scenario ID	Lane Width	Vegetation	Screenshot
S1-Nor-NV(baseline)	Normal	None	
S2-Nar-NV	Narrow	None	
S3-Nor-SV	Normal	Hedge	
S4-Nar-SV	Narrow	Hedge	
S5-Nor-SSTV	Normal	Small Spacing Bush	
S6-Nar-SSTV	Narrow	Small Spacing Bush	
S7-Nor-LSTV	Normal	Large Spacing Bush	
S8-Nar-LSTV	Narrow	Large Spacing Bush	
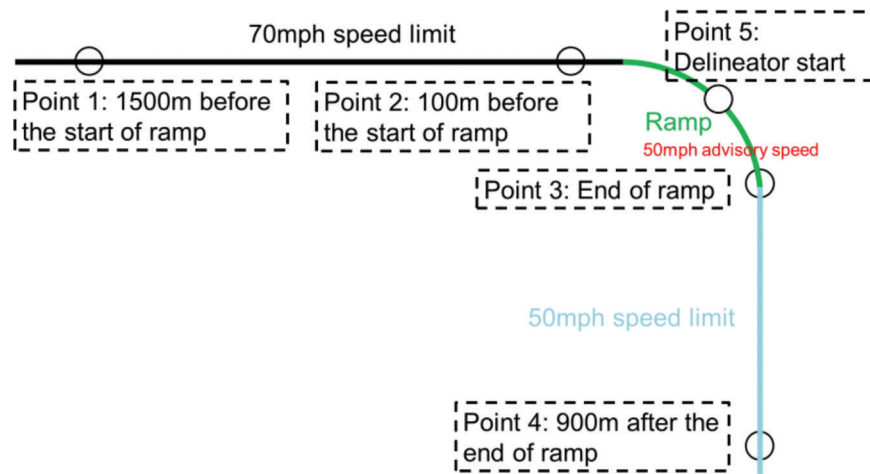
Figure 2.4 Simulated scenario for highway exit ramps.

TABLE 2.2
Description of highway exit ramp experiment scenarios

Scenario ID	Roadside Feature	Screenshot
S1-NV (baseline)	None	
S2 - DL	Delineator	
S3 - SV	Hedge	
S4 - SSTV	Small Spacing Bush	
S5 - LSTV	Large Spacing Bush	

3. SUBJECT STUDY

3.1 Driving Simulator

Subjects were recruited to complete the driving study in a DriveSafety® DS-600c driving simulator, as shown in Figure 3.1. The simulator is a partial Ford Focus cabin with full-width front interior, standard driver controls and active instrumentation. It renders visual imagery at 60 frames per second with horizontal field-of-view of 180 degrees. It also includes three configurable rear view and side mirrors that contribute to a heightened sense of realism. The driving performance data, such as vehicle speed, vehicle location, steering wheel angle, gas and brake pedal data, and lane positions can be recorded automatically during the driving experiments with different scenarios.

3.2 Subject Recruitment

To recruit participants, advertisements were sent out via e-mail, IUPUI billboards, and public libraries. People who were interested in this study, had a valid driving license, and had at least 1-year of driving experience, were selected as potential participants. All potential participants received a screening survey via e-mail and were asked to answer eight survey questions. The appropriate participants were selected based on the survey results and contacted by the group members to schedule their experiment. Different background variables like age, gender, personality, and driving aggressiveness were balanced when selecting the participants.
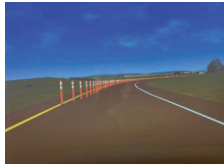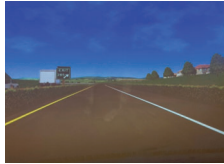
3.2.1 Subject Characteristics in the Arterial Road Experiment

A total of 31 participants were recruited in the arterial road experiment. One participant didn't complete the whole experiment and was dropped from further analysis. Additionally, three participants kept driving recklessly at abnormally fast speeds and were removed as outliers. Therefore, data based on 27 participants were used for further analysis. The demographic information of 27 participants is listed in Table 3.1. Among 27 participants, 13 participants were female, and 14 participants were male. Also, 14 participants were less than or equal to 25 years old, and 13 participants were more than 25 years old. The ages of participants range from 20 to 62 years (mean = 32.0, SD = 12.6). The experiment was carried out during the period from mid-July to late September 2023.

3.2.2 Subject Characteristics in the Highway Exit Ramp Experiment

For the highway ramp experiment, 30 different subjects were recruited. All of them completed the whole experiment, and their driving performance data were used for the data analysis. Table 3.2 shows the demographic information of 30 participants. Among 30 participants, 14 participants were female, and 16 participants were male. Of the 30, 15 participants were less than or equal to 25 years old, and 15 participants were more than 25 years old. The ages of participants range from 19 to 66 years (mean = 36.2, SD = 16.4). The experiment was carried out during the period from early November 2022 to late January 2023.

3.3 Subject Study Process

Before the experiment, each participant first spent 5 minutes practicing driving on the driving simulator to be familiar with the driving simulator and the virtual driving environment. And then, they were asked to drive different scenarios with their normal driving behavior. In the experiment of arterial roads, each participant needs to drive eight different driving scenarios, as listed in Table 2.1. In the experiment of highway exit ramps, five different driving scenarios, which is listed in Table 2.2, need to be completed. Each driving scenario took around 5 minutes. To reduce learning effects, the order of driving scenarios for each participant was randomly assigned. Furthermore, in the experiment of arterial roads, both the westbound and eastbound of the road were built, and the driving direction in each scenario was also randomly assigned. After all the driving sessions, subjects were asked to answer two post-driving survey questions.

Figure 3.1   Driving simulator used in the experiment.

TABLE 3.1
Demographic information for arterial road experiment subjects

Age	Male	Female
≤25	8	6
>25	6	7
Subtotal	14	13

TABLE 3.2
Demographic information for highway ramp experiment subjects

Age	Male	Female
≤25	8	7
≤25	8	7
Subtotal	16	14

Each participant received a $60 gift card after completing the whole experiment. This study received approval from the Indiana University Institutional Review Board (IRB protocol #: 15388).

4. RESULTS DATA ANALYSIS

4.1 Arterial Road

Three metrics were developed as means to evaluate the effectiveness of the countermeasures on arterial roads: Post-Countermeasure Town Average Speed (TAS), Countermeasure Stabilized Speed (CSS), and Countermeasure Minimum Speed (CMS).

Post-Countermeasure Town Average Speed (TAS) refers to the average speed in the area between point 3 and point 4 in Figure 2.2. It is expected to be small for effective countermeasure. This speed is measured after the countermeasure zone, with the intention to apply countermeasures at the entrance while reducing driving speed in the town post the transition zone.

Countermeasure Stabilized Speed (CSS) is defined as the average speed in the last 50 m before point 3 (as shown in Figure 2.2). The effectiveness of the countermeasure is determined by the extent to which drivers decelerate and stabilize their speed during the countermeasure zone. If the stabilized speed is small, the countermeasure is effective.

Countermeasure Minimum Speed (CMS) refers to the minimum speed during the transition zone (from point 2 to point 3 in Figure 2.2), which is expected to be low for effective countermeasures.

Based on these three metrics, the following three hypotheses were proposed.

H1: Town average speed in scenarios with treatment will be lower than in the baseline.

H2: Countermeasure stabilized speed in scenarios with treatment will be lower than in the baseline.

H3: Countermeasure minimum speed in scenarios with treatment will be lower than in the baseline.

4.1.1 H1: Town Average Speed in Scenarios With Treatment Will be Lower Than in Baseline

Figure 4.1 compares the base scenario (S1-Nor-NV) with treatment scenarios. There was no significant change in TAS after implementing treatments, indicating that Hypothesis 1 was not supported.

4.1.2 H2: Countermeasure Stabilized Speed in Scenarios With Treatment Will be Lower Than in Baseline

Compared to the baseline scenario (S1-Nor-NV), Figure 4.2 reveals a notable drop in CSS across multiple treatment groups. Notably, S2-Nar-NV (mean difference = -3.097, p-value = 0.049), S3-Nor-SV (mean difference = -4.065, p-value = 0.012), S5-Nor-SSTV (mean difference = -3.086, p-value = 0.011), S6-Nar-SSTV (mean difference = -3.619, p-value = 0.013), and S7-Nar-SSTV (mean difference = -3.041, p-value = 0.042) all showed statistically significant reductions. These findings lend strong support to H2.

4.1.3 H3: Countermeasure Minimum Speed in Scenarios With Treatment Will be Lower Than in Baseline

Examining Figure 4.3, we observe a notable decrease in CMS levels for several treatment scenarios compared to the baseline (S1-Nor-NV). Notably, S2-Nar-NV (mean difference = -3.575, p-value = 0.028), S3-Nor-SV (mean difference = -3.686, p-value = 0.017), S5-Nor-SSTV (mean difference = -2.949, p-value = 0.017), and S6-Nar-LSTV (mean difference = -3.501, p-value = 0.016) all exhibited statistically significant drops. These findings provide support for Hypothesis 3.

4.2 Highway Exit Ramp

Four metrics were developed as means to evaluate the effectiveness of the countermeasures on highway exit ramps: speed difference, speed reduction rate
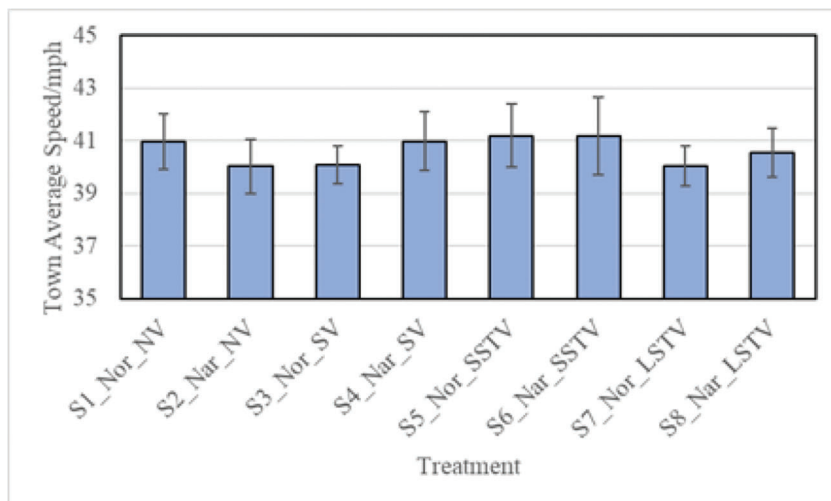

Figure 4.1 TAS in different treatments (error bar represents the standard error).
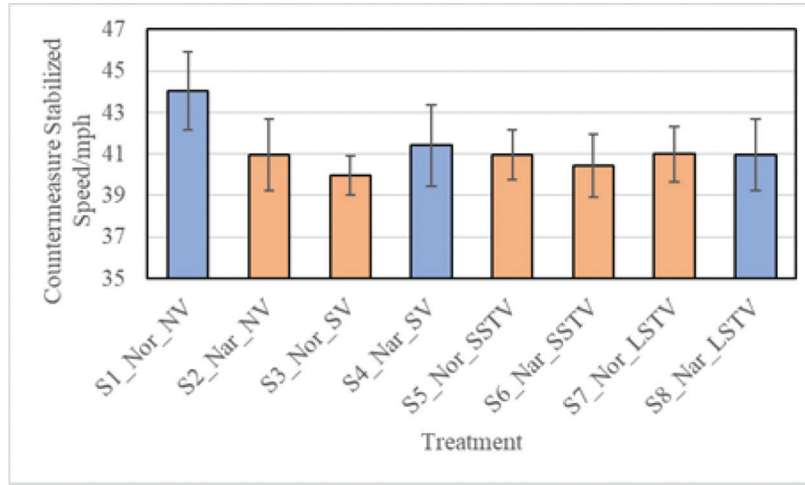
Figure 4.2 CSS in different countermeasure treatments (error bar represents the standard error and orange bar represents significant differences from the baseline).
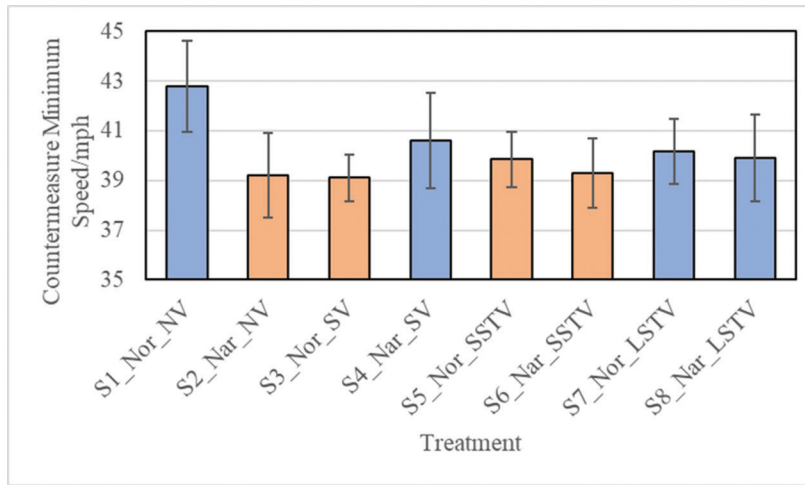
Figure 4.3 CMS in different countermeasure treatments (error bar represents the standard error and orange bar represents significant differences from the baseline).

(SRR), maximum brake pedal press, and maximum lane position.

Speed difference refers to the difference between the after ramp average speed and speed limit, where after ramp average speed is the average speed between point 3 and point 4.

Speed reduction rate (SRR) is defined as the difference between the average speed between point 1 and 2 and the average speed between point 3 and 4 divided by the average speed between point 1 and 2. $SRR = \frac{\bar{v}_{upstream} - \bar{v}_{town}}{\bar{v}_{upstream}}$, where $\bar{v}_{upstream}$ is the average speed between point 1 and 2, and $\bar{v}_{town}$ is the average speed between point 3 and 4.

Maximum brake pedal press is on the scale between 0 and 1, where 0 means no brake pedal press at all, and 1 means full brake pedal press.

Maximum lane position refers to the distance between the center of road and the center of vehicle.

Based on these three metrics, the following four hypotheses were proposed.

H1: The difference between the after ramp average speed and speed limit will be influenced by countermeasures.

H2: Speed reduction rate will be influenced by countermeasures.

H3: Maximum brake pedal from point 5 to point 3 will be influenced by countermeasures.

H4: Maximum lane position from point 5 to point 3 will be influenced by countermeasures.

4.2.1 H1: The Difference Between the After Ramp Average Speed and Speed Limit Will be Influenced by Countermeasures

Figure 4.4 compares the speed difference between countermeasure scenarios. Table 4.1 shows the p-value

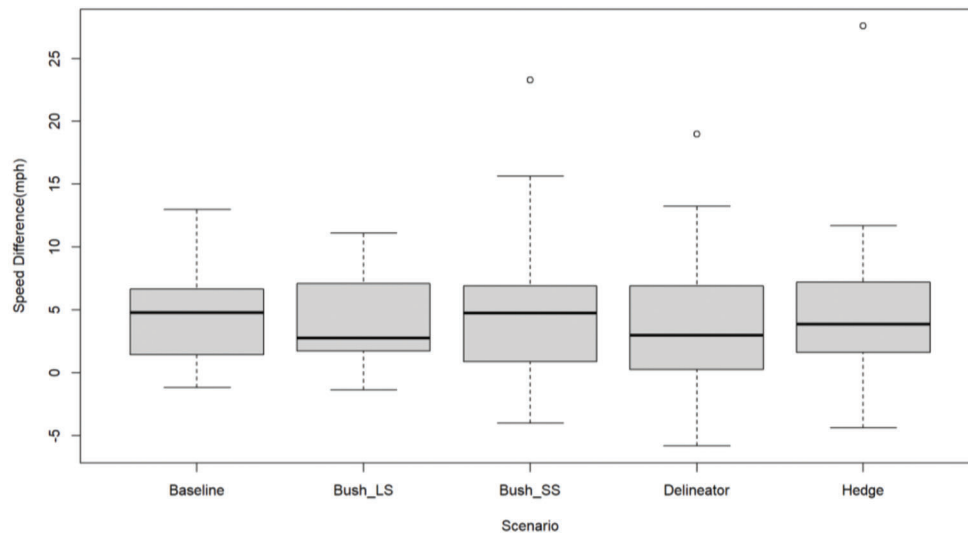**Figure 4.4** Speed difference among different scenarios.

TABLE 4.1
P-value and t-value among different scenarios for speed difference

Group	Mean Difference	T-Values	P-Values
2-1	-0.268	-0.478	0.636
3-1	0.680	0.741	0.465
4-1	-0.250	-0.245	0.808
5-1	0.549	0.497	0.623

and t-value between countermeasure scenarios against the baseline. Groups 1, 2, 3, 4, and 5 represent baseline, large spacing bush, short spacing bush, delineator, and hedge, respectively. Comparing the speed difference in scenarios that have countermeasure with baseline by paired t test, mean difference is not significant in all groups. H1 cannot be rejected based on ANOVA (F-value = 0.257, p-value = 0.905), and countermeasures can't influence speed difference.

4.2.2 H2: Speed Reduction Rate Will Be Influenced by Countermeasures

Figure 4.5 compares the speed reduction rate between countermeasure scenarios. Table 4.2 shows the p-value and t-value between countermeasure scenarios against the baseline. Groups 1, 2, 3, 4, and 5 represent baseline, large spacing bush, short spacing bush, delineator, and hedge, respectively. Comparing the speed reduction rate in scenarios that have countermeasure with baseline by paired t test, mean difference between small spacing bush and baseline, delineator and baseline is significant (see two rows with red text). H2 can be accepted based on ANOVA (F-value = 9.639, p-value < 0.05). Countermeasure can influence speed reduction rate.

4.2.3 H3: Maximum Brake Pedal From Point 5 to Point 3 Will be Influenced by Countermeasures

Figure 4.6 compares the maximum brake pedal press between countermeasure scenarios. The values are very small due to the fact that very few participants actually braked during the experiment. In real life, it is also common to let the vehicle glide when exiting the ramp. Table 4.3 shows the p-value and t-value between countermeasure scenarios against the baseline. Groups 1, 2, 3, 4, and 5 represent baseline, large spacing bush, short spacing bush, delineator, and hedge, respectively. Comparing the maximum brake pedal from point 5 to point 3 in scenarios that have countermeasure with baseline by paired t test, mean difference is not significant in all groups. This hypothesis can be rejected based on ANOVA (F-value = 2.398, p-value = 0.053). Countermeasure can't influence maximum brake pedal from point 5 to point 3.

4.2.4 H4: Maximum Lane Position From Point 5 to Point 3 Will be Influenced by Countermeasures

Figure 4.7 compares the maximum lane position between countermeasure scenarios. Table 4.4 shows the p-value and t-value between countermeasure scenarios against the baseline. Groups 1, 2, 3, 4, and 5 represent baseline, large spacing bush, short spacing bush, delineator, and hedge, respectively. Comparing the maximum lane position in scenarios that have countermeasure with baseline by paired t test, mean difference between small spacing bush and baseline, delineator and baseline is significant (see two rows with red text). This hypothesis can be accepted based on ANOVA (F-value = 6.362, p-value < 0.05). Countermeasure can influence maximum lane position from point 5 to point 3.
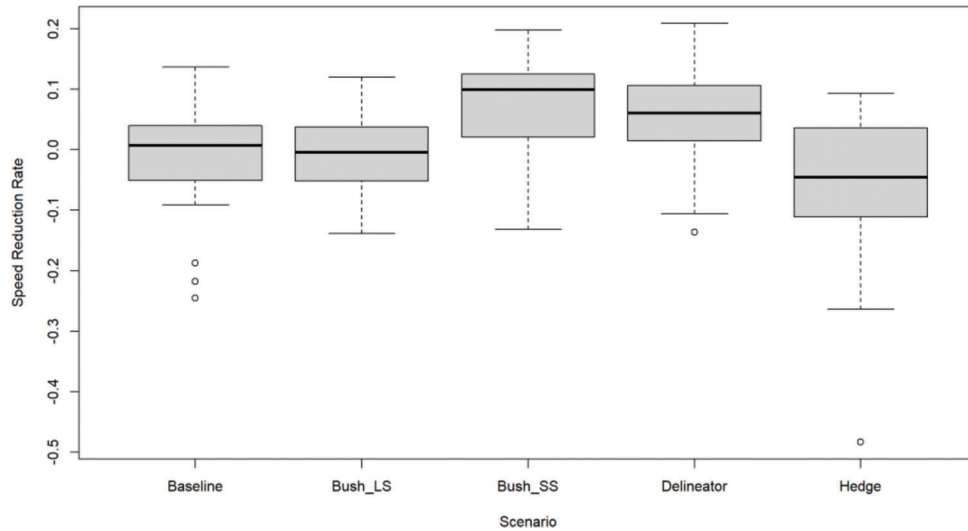
Figure 4.5 Speed reduction rate among different scenarios.
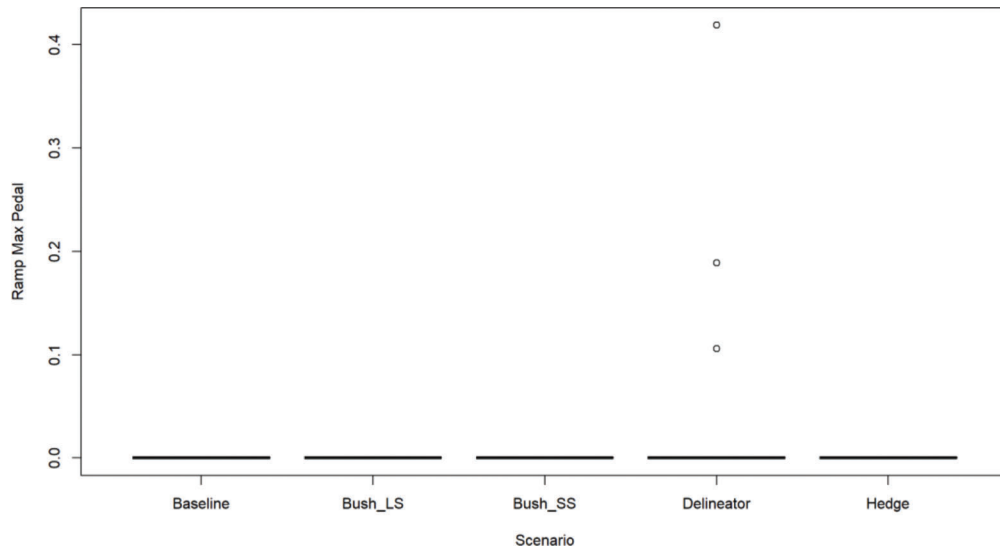
Figure 4.6 Maximum brake pedal press among different scenarios.

TABLE 4.2
P-value and t-value among different scenarios for speed reduction rate

Group	Mean Difference	T-Values	P-Values
2-1	0.001	0.081	0.936
3-1	0.082	4.540	<0.05
4-1	0.071	3.850	<0.05
5-1	-0.040	-1.625	0.115

Note: Delineator and baseline scenarios in red.

4.3 Normal Drivers and Aggressive Drivers

During the driving simulator study, it is observed that some subjects drive aggressively in the simulator, while others drive defensively. Although the focus of this study was not to separate the aggressive drivers and

defensive/normal drivers, we conducted some data analysis in the highway exit ramp experiment and tried to understand the effects of countermeasures on the two types of drivers.

Subjects are divided into aggressive drivers and normal drivers based on after-ramp average speed in five scenarios in the highway exit ramp experiment. If the after ramp average speed is greater than 55 mph, it is defined as aggressive driving in that scenario. Subjects who have more than two aggressive driving during the experiment are categorized as aggressive drivers, other subjects are normal drivers. There are 13 aggressive drivers and 17 normal drivers.

Based on ANOVA, countermeasures can influence normal drivers' speed reduction rate (F-value = 6.222, p-value < 0.05) and maximum lane position (F-value = 4.31, p-value < 0.05), but can't influence normal drivers' speed difference (F-value = 0.471, p-value = 0.757) and
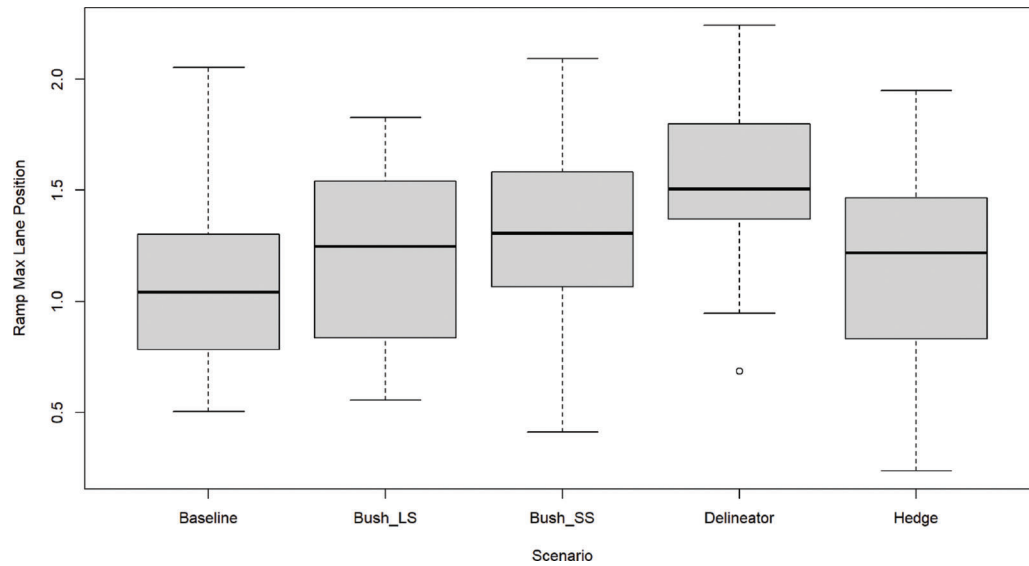
Figure 4.7 Maximum lane position among different scenarios.

TABLE 4.3
P-value and t-value among different scenarios for maximum brake pedal press

Group	Mean Difference	T-Values	P-Value
2-1	0	NA	NA
3-1	0	NA	NA
4-1	0.024	1.549	0.132
5-1	0	NA	NA

TABLE 4.4
P-value and t-value among different scenarios for maximum lane position

Group	Mean Difference	T-Values	P-Value
2-1	0.111	1.606	0.119
3-1	0.218	2.677	<0.05
4-1	0.489	5.889	<0.05
5-1	0.083	0.876	0.388

Note: Delineator and baseline scenarios in red.

maximum pedal (F-value = 1, p-value = 0.413) (see Figure 4.8). Comparing the speed reduction rate in scenarios that have countermeasure with baseline by paired t test, mean difference between small spacing bush and baseline, delineator and baseline is significant. Comparing the maximum lane position in scenarios that have countermeasure with baseline by paired t test, mean difference between large spacing bush and baseline, small spacing bush and baseline, and delineator and baseline is significant.

For aggressive drivers, countermeasures can influence their speed reduction rate (F-value = 5.527, p-value < 0.05), but can't influence aggressive the speed difference (F-value = 0.893, p-value = 0.474), maximum pedal (F-value = 1.536, p-value = 0.203), or maximum lane position (F-value = 2.346, p-value = 0.065) (see

Figure 4.9). Comparing the speed reduction rate in scenarios that have countermeasure with baseline by paired t test, mean difference between delineator and baseline is significant. Comparing the maximum lane position in scenarios that have countermeasure with baseline by paired t test, mean difference between delineator and baseline is significant.

4.4 Comparing With INDOT Speed Study Data

During the project, INDOT carried out a speed study in Goodland, and collected the vehicles' speed at four locations with different speed limits. The ground truth data was compared with the data collected from the driving simulator to ensure the validity of the experiment.

Figure 4.10 shows the locations where the vehicle speed was collected in Goodland. Four stations, S1-S4, were placed near to the 35/45 mph speed limit signs. Both the westbound and eastbound vehicle speed were collected. For the westbound, S1 is in the 45-mph zone before entering the town, S2 is placed near the first 35mph sign, S3 is in the 35-mph zone in the town, and S4 is in the 45-mph zone where vehicles leave the town. While for the eastbound, S4 is located near to the first 35 mph sign entering the town, S3 is in the town with the 35-mph speed limit, S2 is placed where the 35-mph speed zone ends, and S1 is in the 45-mph speed zone. During the data collection period (from August 9 to August 11, 2022), around 3,500 vehicles' speed were recorded. Figure 4.11(a) shows the summary of speed study by INDOT.

The corresponding vehicle speed obtained during the driving simulator study was also presented in Figure 4.11(b). The baseline scenario without countermeasure is selected to compare with the ground truth data. Both the ground truth data and simulated results confirm that the vehicles slow down when entering the town and speed up when leaving the town, even though the
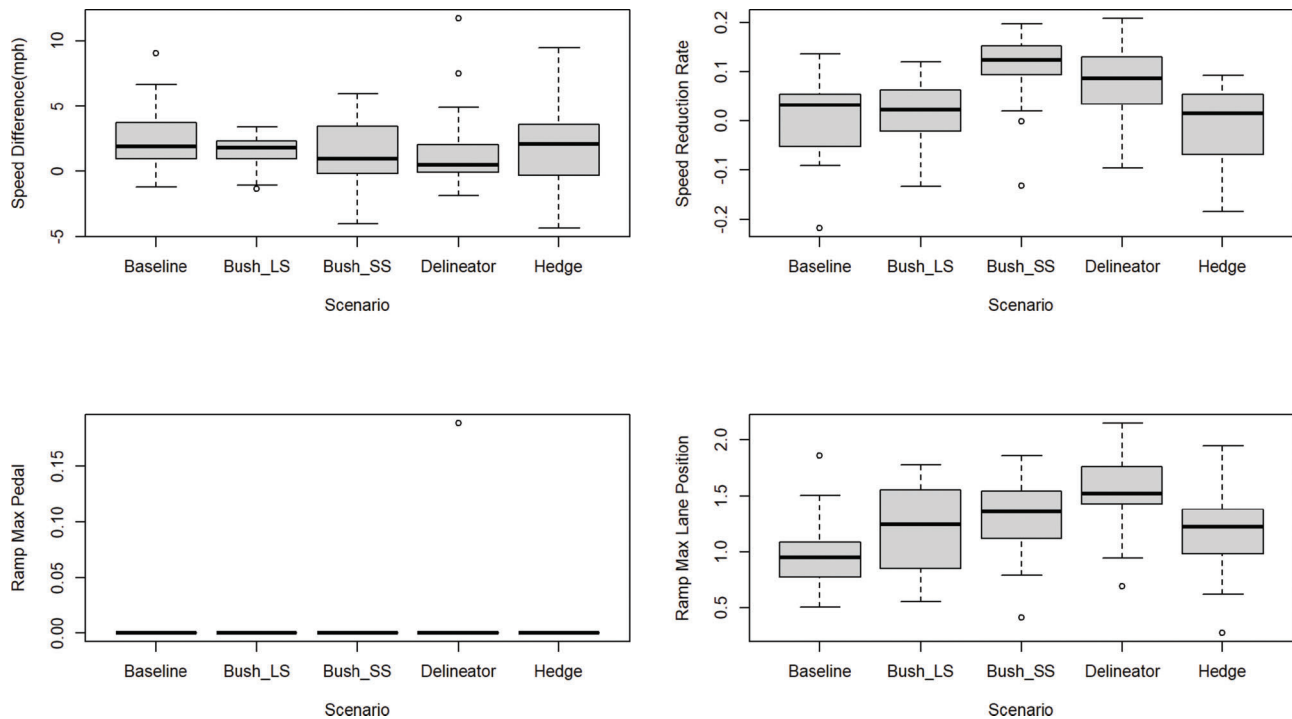
Figure 4.8 Metrics among different countermeasures for normal drivers.
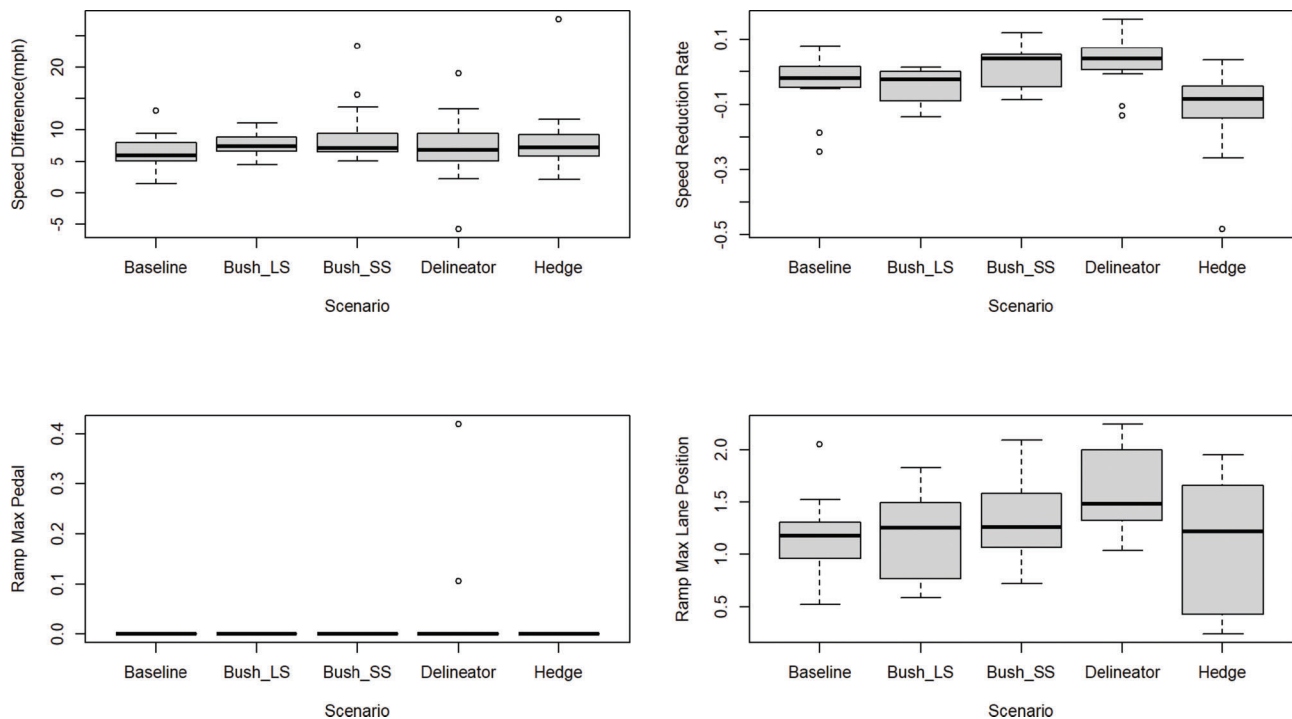
Figure 4.9 Metrics among different countermeasures for aggressive drivers.

vehicles' speed is generally higher than the posted speed limit. This confirms that the driving simulator can provide an insight into the driving behavior.

The comparisons of the average speed and 85th percentile speed indicate that most of the time, subjects drive faster in the driving simulator than in the real vehicle. This implies that subjects' driving behavior may change in the virtual driving environment. It is possible that the subjects in the simulator knew there wouldn't be consequences if going over the speed limit,

Figure 4.10 Goodland ground truth vehicle speed collection locations.

INDOT

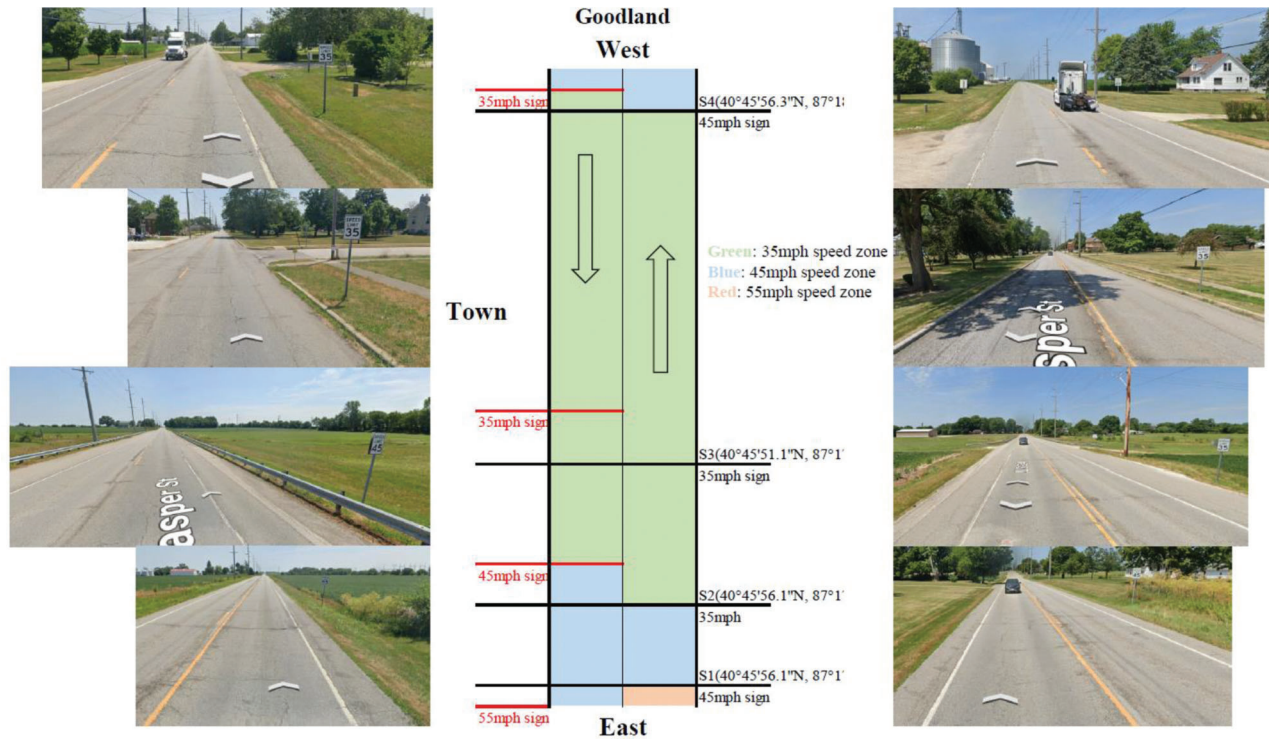| Location	Direction	Speed limit	Description	Average speed	85th percentile	Percent of Traffic Traveling at or below(speed limit			
						0	5mph	10mph	15mph
S1	E	45mph	Close to the 55mph sign leaving the town	51.80	58.00	10.00%	39.00%	73.00%	93.00%
S1	W	45mph	45mph sign entering the town	51.50	57.90	12.00%	41.00%	74.00%	93.00%
S2	E	45mph	Close to the 45mph sign leaving the town	49.80	55.20	18.00%	55.00%	85.00%	96.00%
S2	W	35mph	35mph sign entering the town	48.60	55.10	2.00%	9.00%	29.00%	61.00%
S3	E	35mph	Close to the first 35mph sign entering the town	37.90	43.80	25.00%	67.00%	91.00%	98.00%
S3	W	35mph	Close to the 45mph sign leaving the town	36.30	42.10	38.00%	79.00%	95.00%	99.00%
S4	E	35mph	Close to the first 35mph sign entering the town	44.50	51.40	6.00%	24.00%	55.00%	82.00%
S4	W	35mph	45mph sign leaving the town	45.10	51.40	4.00%	16.00%	48.00%	82.00%

Driving Simulator Scenario(Average Speed in 10m)

Location	Direction	Speed limit	Location in Scenario	Average speed	85th percentile	Percent of Traffic Traveling at or below(speed limit			
						0	5mph	10mph	15mph
S1	E(7 subjects)	45mph	4350	55.20	58.82	0.00%	0.00%	42.86%	100.00%
S1	W(17 subjects)	45mph		57.34	68.26	5.88%	35.29%	47.06%	64.71%
S2	E	45mph	4160	50.22	54.27	14.29%	42.86%	85.71%	100.00%
S2	W	35mph		50.10	68.16	0.00%	35.29%	47.06%	58.82%
S3	E	35mph	3780	40.57	47.80	14.29%	57.14%	85.71%	85.71%
S3	W	35mph		45.05	68.16	5.88%	58.82%	76.47%	76.47%
S4	E	35mph	2400	43.71	54.19	14.29%	57.14%	57.14%	85.71%
S4	W	35mph		52.62	61.91	0.00%	0.00%	5.88%	64.71%

Figure 4.11 (a) Ground truth vehicle speed from INDOT vs. (b) simulator vehicle speed.

whereas the drivers in the real world knew that there could be penalties if caught speeding. It can also be found that in eastbound, the speed difference comparing to the ground truth data is smaller. However, the difference is large in westbound. It is probably due to some aggressive subjects driving westbound. The limited sample size causes the significant discrepancy. It is believed that with a large sample size and by removing the outliers, the discrepancy will be mitigated.

5. CONCLUSIONS AND IMPLEMENTATION

5.1 Arterial Road

The aim of this study was to investigate the impact of roadside vegetation and lane width on speed management performance on rural arterial roads. A total of 30 subjects completed the driving simulator experiment, and 27 subjects were included for analysis. Town average speed (TAS), countermeasure stabilized speed (CSS), and countermeasure minimum speed (CMS) were used to evaluate the speed management performance. Paired t-tests were conducted to verify whether treatments were effective.

The impact of vegetation on improving the speed management performance was confirmed by the significant reduction of CSS and CMS in different treatments. The reduction of TAS was not significant in scenarios with the introduction of vegetation, which indicated that the effect of vegetation no longer existed after the zone with vegetation.

The impact of lane width was also confirmed by the significant reduction of CSS and CMS in some scenarios. TAS was not significantly decreased in scenarios with the change from the normal lane to the narrow lane. The insignificant difference between CSS and TAS indicates that subjects in scenarios with treatments almost completed deceleration before entering the town and the room for deceleration in town was limited. The significant difference between CSS and TAS in the baseline scenario indicates that subjects without treatments kept decelerating after entering the town. Thus, the treatments are effective in reducing driving speed faster in the transition zone.

The results analysis showed that the combination of narrow lane and no vegetation, normal lane and short vegetation, normal lane and small spacing tall vegetation, narrow lane and small spacing tall vegetation, and normal lane and large spacing tall vegetation can be considered effective countermeasures.

5.2 Highway Exit Ramp

This study aimed to assess the influence of roadside vegetation and lane width on speed management performance on highway exit ramps, utilizing data from 30 subjects for analysis. Speed difference, speed reduction rate (SRR), maximum brake pedal press, and maximum lane position served as key metrics to evaluate speed management performance. Paired t-tests were employed to verify the effectiveness of the treatments, revealing that the countermeasure had no impact on speed difference or maximum brake pedal. However, it demonstrated a significant effect on speed reduction rate and maximum lane position. A detailed analysis indicated a substantial increase in speed reduction rate for two scenarios (small spacing bush and delineator), highlighting their efficacy in reducing drivers' speed. Nonetheless, this positive outcome was tempered by a significant increase in maximum lane position, potentially elevating the risk of collisions with roadside objects.

5.3 Limitations

This study is constrained by several limitations that warrant consideration. The assessment of speed management performance primarily relied on metrics such as the average speed at the conclusion of the countermeasure and within the town, as well as the minimum speed during the countermeasure. While informative, there is an opportunity for a more comprehensive evaluation using diverse speed-related perspectives, including mean lateral acceleration and speed standard deviation (Liu et al., 2016). Future research could explore the development of additional speed-related metrics to enhance the thoroughness of speed management performance assessments. Another notable limitation pertains to the disparity between the simulated scenario employed in this study and real-world conditions. Addressing this gap through a comparative analysis between real-road data and simulated environment data would provide valuable insights into the applicability of the study outcomes to real-world driving scenarios. Lastly, the reliance on a limited sample size poses a potential constraint on the generalizability of results. To mitigate this limitation and enhance statistical significance, it is imperative to consider expanding the subject pool through increased recruitment, thereby contributing to a more robust extrapolation of the study's implications to a broader population.

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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.

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