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Evaluating the Effectiveness of Visual and Auditory ADAS Alerts on Rural Roads Using a Driving Simulator

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***Abstract*-- Traffic crashes on rural roads pose a significant safety risk due to a disproportionate number of fatalities. To address this issue, a driving simulation study tested an in-vehicle speed monitoring display (SMD) as an advanced driver assistance system (ADAS), both with and without voice recording. The simulation was based on PR-114, a two-lane rural highway in western Puerto Rico, and included scenarios with and without active ADAS alerts for speeding and roadway hazards. Results indicated that image alerts are associated with speed reductions.**

***Keywords*— Simulation, driver assistance, speed monitoring.**

I. INTRODUCTION

Traffic crashes on rural roads are a critical safety concern due to the disproportionate number of fatalities compared to the rural population. In 2018, 45% of U.S. traffic-related deaths occurred in rural areas, despite only 19% of the population living there. In Puerto Rico, the issue is even more severe, with 58% of fatalities occurring on rural roads and a fatality rate significantly higher than any U.S. state [1]. Speeding is a major contributing factor [2].

Efforts to improve rural road safety have included initiatives such as Focus on Reducing Rural Roadway Departures (FoRRRwD), a Federal Highway Administration (FHWA) program, which promotes countermeasures such as rumble strips and clear zones [3]. While effective, these measures should be complemented by advanced technologies. Advanced Driver Assistance Systems (ADAS) offer a promising solution by providing real-time feedback through features like adaptive cruise control, lane departure warnings, and emergency braking [4].

This study aimed to evaluate the impact of three Advanced Driver Assistance System (ADAS) variants—audio alert, image alert, and a combination of both—on driver behavior in a simulated rural road environment. The ADAS strategy was designed to alert speeding drivers in hazardous locations. To achieve this objective, high-risk roadway features were identified along PR-114, a two-lane rural highway in western Puerto Rico and several simulation scenarios were developed. The study examined driver behavior, particularly speed compliance, with and without ADAS alerts.

II. LITERATURE REVIEW

In 2020, 38,680 fatal crashes occurred in the U.S., marking a 7.2% increase from the previous year, while the fatality rate per 100 million miles traveled surged by 24% [5]. In Puerto Rico, 289 fatalities were reported in 2019, underscoring the need for improved infrastructure and road safety [6]. To reduce crashes, several countermeasures have been implemented, particularly under the FoRRRwD program. Examples of these countermeasures are the implementation of rumble strips, enhanced delineation, and high friction surface treatment, among others.

These strategies keep vehicles in their lanes, provide recovery areas, and reduce crash severity. Their effectiveness is assessed using Crash Modification Factors (CMF). In Puerto Rico, PR-114 has been part of safety improvements, with centerline rumble strips installed to mitigate head-on collisions [7].

While infrastructure improvements are crucial, vehicle-based technologies also play a key role in improving safety on rural roads. Advanced Driver Assistance Systems (ADAS) have shown potential in reducing crashes in various driving conditions, including rural environments. These systems provide features such as adaptive cruise control, lane departure warning, and collision warning, all of which can contribute to reducing crash risks [8]. However, the effectiveness of ADAS depends on the system and driving conditions in which it is applied.

A particularly relevant technology for rural roads is Lane Departure Warning (LDW), which helps prevent run-off-road crashes—one of the most common crash types in rural settings. One study found that LDW systems reduced lane departure incidents by 48% in commercial truck fleets, many of which occurred on rural highways [9].

Intelligent Speed Adaptation (ISA) is another promising safety measure. This system helps drivers maintain appropriate speeds, especially where speed limits change frequently. A particular study found that ISA could reduce speed limit violations by 30% on rural roads [10].

Autonomous Emergency Braking (AEB) has also proven beneficial, particularly in preventing rear-end collisions on high-speed rural roads. It has been indicated that AEB reduces rear-end crashes by 50% in real-world driving conditions, including in rural environments [11].

Despite these benefits, ADAS effectiveness in rural settings can vary due to road conditions, weather, and driver acceptance (Reagan et al., 2018). Additionally, the adoption rate of ADAS in rural areas tends to be lower, as many vehicles tend to be older, which limits the immediate benefits of these technologies (NHTSA, 2021).

Overall, ADAS technologies offer significant safety benefits, but their adoption and effectiveness in rural environments require further study. Improvements in road infrastructure, vehicle safety systems, and driver education will collectively enhance rural road safety.

III. Methodology

The approach for this research involved a structured process to assess driver behavior using a driving simulator and analyze the impact of Advanced Driver Assistance Systems (ADAS) on rural road safety.

A. Crash Data Collection

To establish a foundation for the study, crash data for PR-114 was collected from national and local sources, including the National Highway Traffic Safety Administration (NHTSA) and the Puerto Rico Department of Transportation and Public Works (PRDTPW). From 2014 to 2018, a total of 582 crashes were recorded on PR-114, with varying severity levels (see Table 1). Notably, the number of crashes decreased over time, suggesting improvements in road safety, potentially linked to safety measures such as the installation of centerline rumble strips in 2013 [7].

TABLE 1.
CRASH SEVERITY (20142018)

Type	**2014**	**2015**	**2016**	**2017**	**2018**	**Total**
Fatal	1	0	1	0	0	2
Injury	40	32	32	19	17	140
PDO	96	73	106	90	75	440
Total	**137**	**105**	**139**	**109**	**92**	**582**

The collision types were also collected for the same data; the most common collision types were Entering Intersection at an Angle (EIA), representing 36.8% of all crashes, and Turning in the Same Direction (SDT) with 32.6% of all crashes. These two types of crashes together accounted for almost 70% of all incidents, highlighting the importance of intersections and the potential role of driver behavior (e.g., following too closely) in the high frequency of collisions.

B. Experimental Design

A factorial two-factor experimental design with blocking was employed to evaluate driver behavior in different conditions (see Table 2). The two independent variables were visual presentation (an on-screen image of the posted speed limit) and auditory alarm (a voice alert activated when the driver exceeded the speed limit). A total of 48 participants were recruited for the ADAS simulation experiment, ensuring a balanced representation across different demographics. The sample consisted of 24 males and 24 females, divided into three age groups: 18-25 years, 26-45 years, and 46-80 years. Each age group was further split by gender, with 8 subjects per gender-age combination. All participants had a valid driver's license.

TABLE 2.
SUMMARY OF EXPERIMENTAL DESIGN

Variable	Factor or Block	Numerical or Categorical	Fixed or Random	Levels
Age	Block	Numerical	Fixed	18-25, 26-45, 46-80
Gender	Block	Categorical	Fixed	Female, Male
Visual	Factor	Categorical	Fixed	With, Without
Audio	Factor	Categorical	Fixed	With, Without

Participants were tested in different combinations of these factors, both with and without ADAS. Age and gender were used as blocking variables to control for demographic differences.

C. Development of Simulation Scenarios

To replicate real-world conditions, simulation scenarios were designed based on the roadway characteristics of PR-114, a two-lane rural road. Based on the previously analyzed crash data, three primary scenarios were developed for the driving simulator, each representing a two-lane highway similar to PR-114.

- Scenario 1: Heavy Vehicle Invading the Driver's Lane. This scenario recreates a potential EIA (Entering Intersection at an Angle) collision. A single-unit truck enters the roadway from a side road on the left, making a wide right turn and invading the driver's lane. The truck's intersection point is approximately 1,125 meters (0.7 miles) from the simulation start, after the driver has already covered about 60% of the roadway segment. The truck's encroachment into the driver's lane creates a potential collision risk.
- Scenario 2: Slow Vehicle Traveling in the Same Direction. In this scenario, a slow-moving vehicle (traveling at 25 mph) is encountered by the driver, forcing them to either slow down or attempt to overtake. The slow vehicle appears 425 meters (0.26 miles) from the start of the simulation, causing the driver to potentially engage in a passing maneuver, which is complicated by oncoming traffic. This situation replicates the SDT (Same Direction - Turning) collision risk. It simulates the dilemma drivers face in real-world situations where they must decide between reducing speed or taking risks by overtaking.
- Scenario3: Free Flow Conditions. The Free Flow Conditions scenario was designed to simulate a situation where no potential collision risks exist. The driver is free to drive at any speed, with only occasional vehicles traveling in the opposite direction. This baseline scenario is useful for assessing driver behavior without external factors

influencing their decisions. It allows researchers to examine whether drivers adhere to speed limits and respond to ADAS alerts in the absence of other vehicles, and it provides a comparison for the other more complex scenarios.

Figures 1 and 2 show an example of the first two scenarios (heavy-vehicle and slow-moving vehicle, respectively).

Fig. 1 Heavy-vehicle scenario.

Fig. 2 Slow-moving vehicle scenario.

D. *Driving Simulation Experiment*

As mentioned before, the study involved 48 participants, aged 18 to 80, all holding a valid driver's license. Each participant was randomly assigned to one of three distinct driving conditions, ensuring variability in exposure to different safety measures. Each of the three scenarios was tested under four ADAS variants, leading to a total of 12 experimental simulation scenarios. The ADAS variants included:

- Audio-only ADAS (audible warning for speed limit violations).
- Visual-only ADAS (speed limit image displayed).
- Audio + Visual ADAS (combination of audio and visual alerts).
- No ADAS (control scenario with no alerts).

The driving simulation took place at the Transportation Laboratory (CI-102-F) at the Civil Engineering and Surveying Department, University of Puerto Rico at Mayagüez. The simulator setup consists of three primary components: (1) a computer system, which includes a laptop and desktop computer running the SimVista program by Realtime Technologies Inc. (RTI) / SimCreator; (2) a driver's cabin that features a gear lever kit, steering wheel, Logitech pedal, and vehicle seat mounted on an aluminum frame; and (3) three overheads projectors and three folding screens that provide a 120-degree field of vision with 1080p visual quality, as shown in Figure 3. Participants first underwent training on simulator operations and completed a sociodemographic questionnaire. Simulation data were recorded using ISA software, generating detailed files containing position coordinates, speed and acceleration, and time stamps. The collected data were processed using Power BI, which enabled the creation of speed profiles, data tables, and bar graphs to visualize driving performance and behavioral responses.

Fig. 3 Driving simulator used in the study.

E. *Questionnaires*

An initial questionnaire was used to gather participants' perceptions of rural road safety and ADAS use. Pre- and post-simulation questionnaires were administered to assess changes in perception.

IV. Preliminary Analyses

As participants navigated through the scenarios, several dependent variables were recorded to assess their driving behavior. These variables included mean speed, acceleration, speed variance, reaction time, and lateral position. Some of these variables were directly measured by the driving simulator, while others, like reaction time and speed variance, were calculated based on the collected data. The key variable of interest was drivers' compliance with the posted speed limit, as this was a crucial measure in understanding the effectiveness of the ADAS variants.

The three primary scenarios—encounters with heavy vehicles, slow-moving vehicles, and free-flow conditions—were evaluated across different ADAS variants. These variants included audio-only, image-only, and a combination of both audio and image alerts. The "No ADAS" condition was used as the control scenario for comparison purposes.

A. Heavy Vehicle Scenarios

This comparison focuses on the average speeds observed during encounters with heavy vehicles turning into the driver's lane, simulating a potential Entering Intersection at an Angle (EIA) collision. The effectiveness of the different ADAS implementations was analyzed by comparing the speed profiles across the four scenarios. Figures 4 through 7 illustrate the average speeds and 15th and 85th percentiles across these four experimental scenarios.

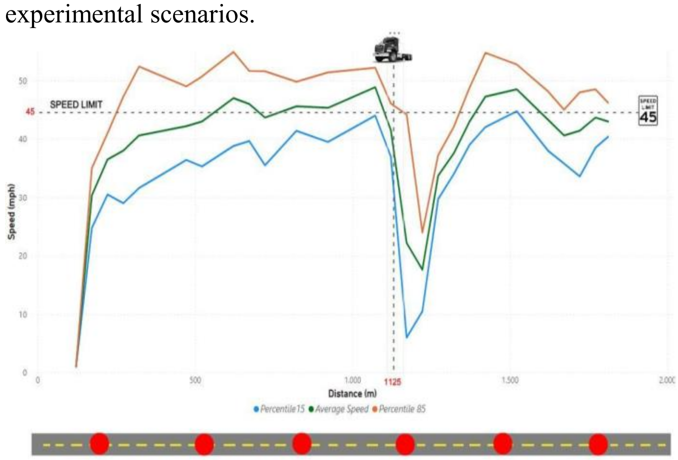

Fig. 4 Heavy vehicle with ADAS audio experimental scenario # 1.

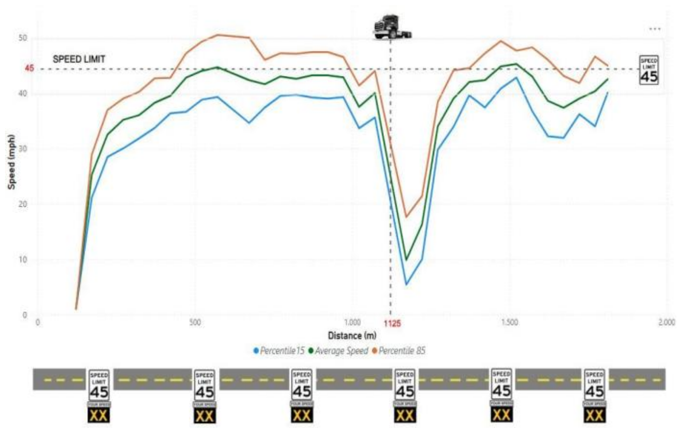

Fig. 5 Heavy vehicle with ADAS image experimental scenario # 2.

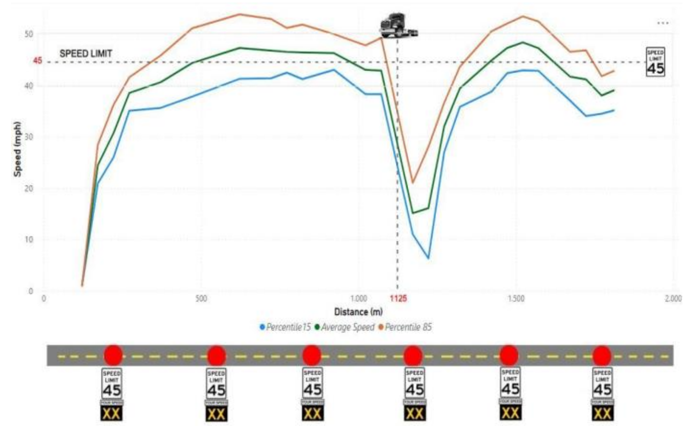

Fig. 6 Heavy vehicle with both ADAS audio and image experimental scenario # 3.

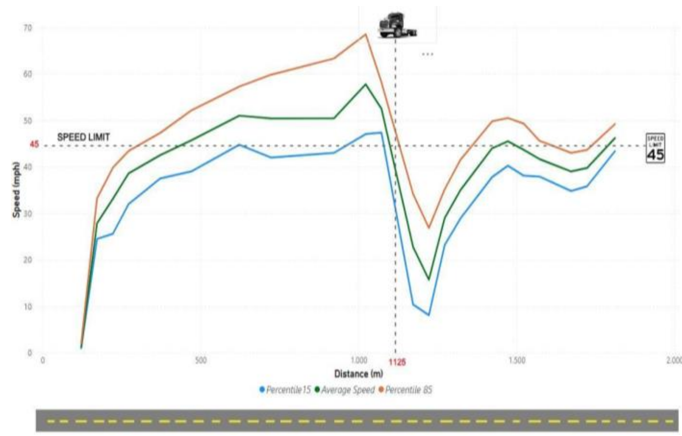

Fig. 7 Heavy vehicle with no ADAS experimental scenario # 4.

The data shows that experimental scenario # 2 (image) resulted in speeds closest to or below the posted speed limit of 45 mph, followed by experimental scenario # 3 (both audio and image). Although the mean speeds in experimental scenario # 3 were occasionally above the speed limit, the overall speed profile was smoother compared to the other ADAS variants (experimental scenarios # 1 and # 2). The highest average speeds were observed in the experimental scenario # 4 where participants were not exposed to ADAS.

B. Slow-Moving Vehicle Scenarios

In this section, the average speeds during encounters with slow-moving vehicles, simulating a Same Direction Turning (SDT) collision, were analyzed across the four ADAS variants. The 85th percentile speeds were considered to better assess the effectiveness of the ADAS in maintaining safe speeds in the presence of slower traffic. Figures 8 through 11 compares the four experimental scenarios speed profiles.

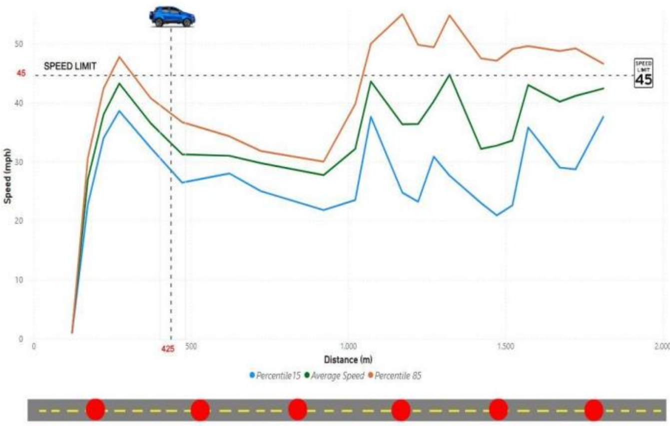

Fig. 8 Slow-moving vehicle with ADAS audio experimental scenario # 5.

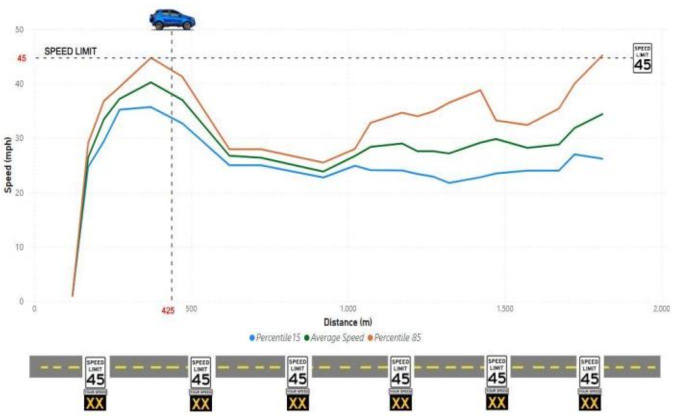

Fig. 9 Slow-moving vehicle with ADAS image experimental scenario # 6.

Fig. 10 Slow-moving vehicle with both ADAS audio and image experimental scenario # 7.

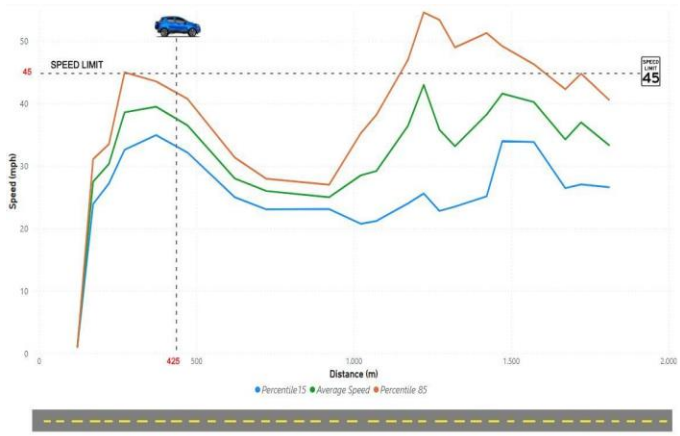

Fig. 11 Slow-moving vehicle with no ADAS experimental scenario # 8.

Although the presence of the slow-moving vehicle caused speeds to drop below the posted limit across all four scenarios, experimental scenarios # 6 (image) and # 7 (both audio and image) consistently kept the 85th percentile speeds below the speed limit throughout the simulation. In terms of average speeds, experimental scenario # 6 (image) had the lowest values, with experimental scenarios # 7 (audio and image) following closely behind. Scenarios # 5 (audio) and # 8 (no ADAS) showed higher average speeds, with experimental scenario # 8 displaying the least compliance with the speed limit.

C. *Free-flow Conditions Scenarios*

For the final four experimental scenarios, the speed profiles under free-flow conditions were examined (Figures 12 through 15). These scenarios provided a baseline for evaluating driver behavior without the influence of other vehicles.

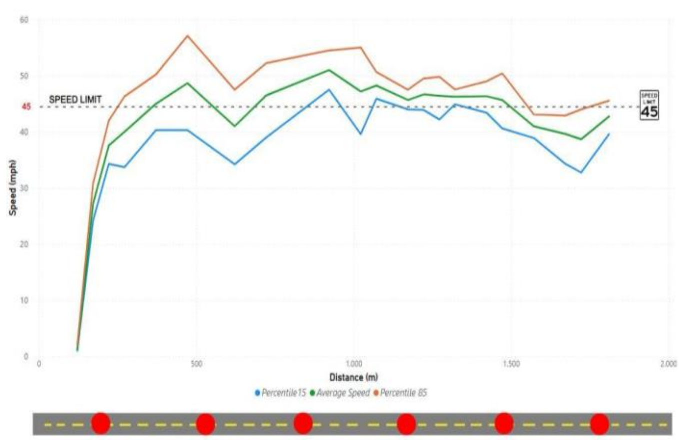

Fig. 12 Free-flow conditions with ADAS audio experimental scenario # 9.

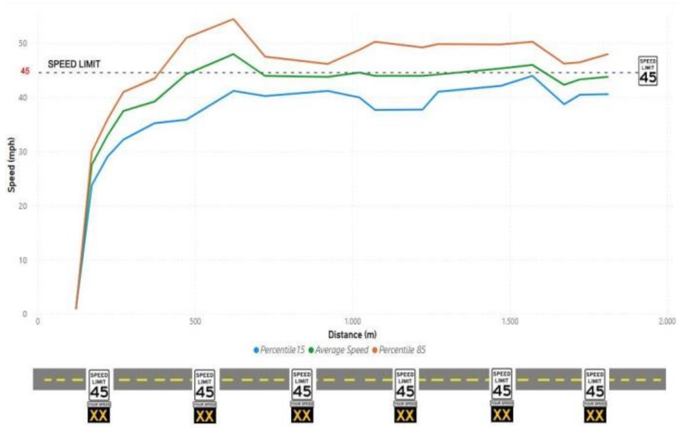

Fig. 13 Free-flow conditions with ADAS image experimental scenario # 10.

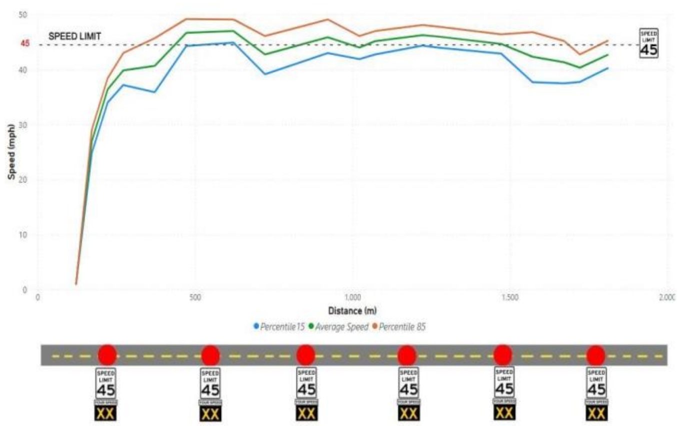

Fig. 14 Free-flow conditions with both ADAS audio and image experimental scenario # 11.

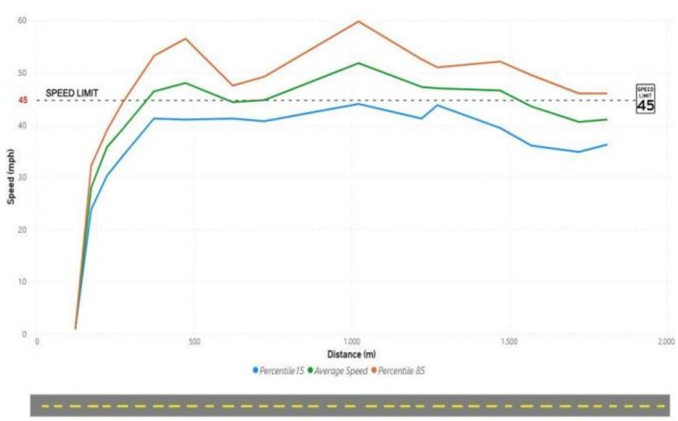

Fig. 15 Free-flow conditions with no ADAS experimental scenario # 12.

In these free-flow conditions, experimental scenarios # 10 (image) and # 11 (audio and image) demonstrated consistent compliance with the speed limit, with average speeds staying close to 45 mph. Experimental scenarios # 9 (audio) and # 12 (no ADAS) showed average speeds that exceeded the posted speed limit. Notably, the speed profile in experimental scenario # 11 (audio and image) had the least variation, as shown by the 15th and 85th percentile speeds, indicating more stable and consistent driving behavior.

The comparison of these experimental scenarios highlights the effectiveness of ADAS alerts in promoting safe driving practices and maintaining speed limits. The image-only variant and the combination of audio and image alerts proved to be the most effective in encouraging drivers to adhere to speed limits across all three types of driving scenarios.

V. Statistical Analyses

To identify the most efficient ADAS variant in terms of speed limit compliance and safety, two tasks were conducted: a rating system and an Analysis of Variance (ANOVA). These methods aimed to evaluate how effectively each ADAS variant influenced driver behavior across different scenarios.

A. Identification of Efficient ADAS Variant

The efficiency of each ADAS variant was assessed based on its performance in the three primary scenarios: heavy vehicle, slow vehicle, and free-flow conditions. Each ADAS variant was ranked on a scale from 1 to 4 for each scenario, where 1 indicated the least effective in achieving speed limit compliance and 4 indicated the most effective in ensuring adherence to speed limits. In the slow-moving vehicle scenario, the rating was determined based on which ADAS variant resulted in the lowest average speed. The results are summarized in Figure 16.

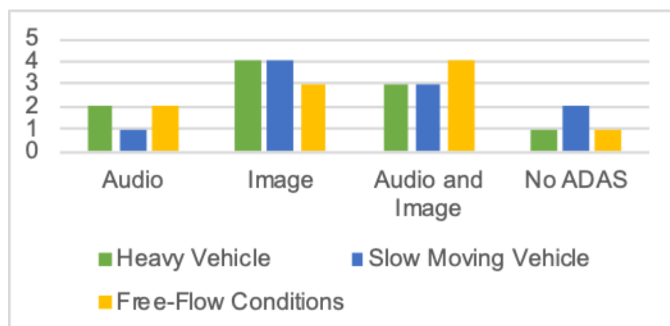

Fig. 16 Ratings for ADAS sensors.

The results of the ADAS Ratings were the following:

- Image-only ADAS Sensor: Rated the most effective in two main scenarios (heavy vehicle and slow vehicle), receiving a rating of 4 for these conditions. In the free-flow scenario, it was moderately effective with a rating of 3. This sensor earned a total of 11 points.
- Audio and Image Combined Sensor: Rated moderately effective in the heavy vehicle and slow vehicle scenarios (both with a rating of 3), but was highly effective in the free-flow scenario, where it received a rating of 4. This sensor achieved a total of 10 points.

- Audio-only Sensor: The least effective overall, with lower ratings in all scenarios: a rating of 2 in both the heavy vehicle and free-flow scenarios, and a rating of 1 in the slow vehicle scenario. It scored a total of 5 points.
- No ADAS: Representing the absence of ADAS systems, the No ADAS scenario was least effective in the heavy vehicle and free-flow conditions, and low effective in the slow-moving vehicle scenario. It earned a total of 4 points.

Based on the ratings, the Image-only ADAS sensor was found to be the most efficient variant, followed closely by the Audio and Image combined sensor. These results underscore the critical role of visual cues in improving the performance of ADAS systems, particularly in scenarios that involve higher levels of risk, such as encounters with heavy and slow-moving vehicles.

B. Analysis of Variance (ANOVA)

To identify the most efficient ADAS variant, an Analysis of Variance (ANOVA) was performed. ANOVA is a statistical method used to determine whether there are significant differences in means across different treatments. The null hypothesis for this analysis was that speeds across the scenarios (treatments) were equal.

Since the focus was on isolating the effects of the ADAS variants on drivers' speeds, the four free-flow scenarios (experimental scenarios # 9 through # 12) were selected for this analysis. Moreover, as the driving simulator collected speed data every 0.02 seconds, generating a large number of observations per driver, the dataset was reduced to four observations per driver: at the 680m, 980m, 1280m, and 1580m marks. These locations correspond to the last five sensor positions along the roadway. The first sensor was excluded, as it was too close to the start of the simulation, where initial acceleration occurred.

The descriptive statistics for the reduced dataset are shown in Table 3.

From Table 3 the following is observed:

- At the 680m mark, the average speeds were approximately 2 mph higher in Scenarios 9 and 12 (48 mph) compared to Scenarios 10 and 11 (46 mph). The standard deviation was higher in Scenarios 9 and 12 (around 8 mph) than in the others (around 4-5 mph).
- At the 980m mark, Scenario 11 (Audio + Image) exhibited the lowest average speed (43.8 mph), while Scenario 12 (No ADAS) had the highest (50.4 mph). Standard deviations were lower in Scenarios 10 and 11 (around 3-4 mph), compared to higher variability in Scenarios 9 and 12 (around 6-9 mph).
- At the 1280m mark, Scenario 12 (No ADAS) showed the highest average speed (51.5 mph) and the highest standard deviation (9.6 mph), while the other scenarios had average speeds between 43.7 and 46.3 mph and standard deviations between 4.7 and 6.3 mph.
- At the 1580m mark, the speeds were similar across all scenarios, ranging between 42.3 and 44.1 mph, with minimal variation in standard deviations (3.6–5.7 mph).

TABLE 3.
DESCRIPTIVE STATISTICS AT FOUR LOCATIONS IN FREE-FLOW SCENARIOS

Location	Scenario	Speed Values (mph)			
		Mean	St Dev	Min	Max
1 (680 m)	9	48.04	8.4	28.75	60.95
	10	46.06	4.03	37.35	54.36
	11	46.25	4.94	35.93	58.02
	12	48.07	8.09	37.27	68.66
2 (980 m)	9	47.75	6.48	35.95	61.4
	10	44.856	3.418	40.784	52.42
	11	43.751	2.929	37.169	48.287
	12	50.38	8.77	35.17	73.8
3 (1280 m)	9	46.35	5.08	37.66	56.22
	10	43.72	6.28	29.13	54.57
	11	44.42	4.68	32.21	52.16
	12	51.49	9.6	33.75	73.52
4 (1580 m)	9	43.71	5.69	30.3	50.84
	10	44.07	5.17	35.25	52.07
	11	43.41	3.6	34.38	47.77
	12	42.33	5.05	33.49	48.65

ANOVA was performed at each of the four locations to test whether differences in speeds across scenarios were statistically significant. The null hypothesis (that there is no difference in mean speeds across scenarios) was rejected if the p-value was less than 0.05. The Tukey's Confidence Intervals were also calculated to determine which pairs of scenarios exhibited significantly different average speeds. If any confidence interval did not cover zero, it indicated a significant difference between the means. The ANOVA results are shown in Table 4.

TABLE 4. ANOVA RESULTS FOR THE FOUR FREE-FLOW EXPERIMENTAL SCENARIOS

Location	F-Value	p-value	Tukey's CI not covering zero	Interpretation
1	0.33	0.805	None	No differences in speeds
2	3.07	0.037	# 11 (audio and image) and # 12 (no ADAS)	Speeds with ADAS Audio and Image were significantly lower than speeds with no ADAS variant.
3	3.30	0.029	#10 (image) and # 12 (no ADAS)	Speeds with ADAS Image were significantly lower than speeds with no ADAS variant
4	0.28	0.841	none	No differences in speeds

The ANOVA results yield the following:

- At Locations 1 and 4 (680m and 1580m), the null hypothesis was not rejected, indicating that there were no significant differences in speeds across scenarios. This suggests that, at these locations, the presence of ADAS variants did not influence driver speeds.
- At Locations 2 and 3 (980m and 1280m), the null hypothesis was rejected, suggesting that at least one of the group means was significantly different. Tukey's test identified significant differences between the following pairs:
    - At Location 2, experimental scenario # 11 (audio and image) had significantly lower speeds (43.8 mph) compared to experimental scenario # 12 (no ADAS), which had higher speeds (50.4 mph). The difference of 6.6 mph was statistically significant.
    - At Location 3, experimental scenario # 10 (image) had significantly lower speeds (43.7 mph) compared to experimental scenario # 12 (No ADAS), where speeds were higher (51.5 mph). The difference of 7.8 mph was statistically significant.

The analysis suggests that ADAS Image or ADAS Audio and Image variants are related to lower operating speeds when compared to the No ADAS setup, although this was not observed consistently across all locations. Further analyses, incorporating additional variables such as the presence of opposing traffic or changes in roadway geometry, are recommended to explore other factors influencing driver speeds. Future studies could also focus on examining the standard deviation of speeds, as experimental scenario # 11 (audio and image) showed lower variability in speeds, which could be beneficial given its potential relationship with vehicle crashes.

VI. Conclusions and Recommendations

The study utilized the UPRM driving simulator to evaluate various ADAS alternatives on rural roads in western Puerto Rico. The results revealed that drivers responded more effectively to image sensors, particularly those that displayed both the speed limit and the driver’s current speed. This was followed by the combined audio and image sensor, which was the second-most effective. In contrast, the audio-only sensor proved to be the least effective in promoting safe driving behaviors. These results suggest that visual cues are more actionable for drivers, enabling them to make immediate adjustments to their speed compared to auditory signals, which can be interpreted ambiguously and may be more easily ignored.

The study’s conclusions emphasize the importance of image sensors in enhancing driver safety, particularly because they offer clear, actionable visual feedback that helps drivers adhere to posted speed limits. On the other hand, audio sensors were found to be less effective in achieving speed compliance, potentially due to a delay in interpretation or drivers not responding promptly to the auditory alerts. However, when both audio and image alerts were combined, the ADAS variant showed improved performance, ranking better than audio-only sensors in ensuring drivers maintained safe speeds.

To further improve the effectiveness of ADAS technologies, several recommendations are made. First, the design of audio signals could be enhanced by using voice messages instead of simple warning sounds. Voice messages would be more likely to capture the driver’s attention and reduce the chances of the alerts being ignored. Another recommendation is to optimize the placement of ADAS screens, ensuring they are within the driver’s field of view without obstructing their vision. This would maximize their effectiveness in promoting speed limit compliance. Additionally, future research should explore the integration of advanced ADAS technologies, such as real-time computer vision systems like YOLO, to provide better pedestrian recognition and analyze road conditions, thus enabling anticipatory decision-making that can further enhance driver safety.

The study also suggests investigating the impact of climatic factors, such as nighttime visibility or adverse weather conditions, on ADAS performance. Understanding how these factors influence ADAS systems will be crucial for developing adaptive driving modes that improve safety under various conditions.

In summary, the findings of the study highlight that image sensors are the most effective for ensuring driver safety, especially when it comes to speed limit compliance. The incorporation of image sensors into vehicles on rural roads is highly recommended, as it aligns with previous research that also supports the superiority of image sensors over auditory cues in reducing speeding and improving driver concentration. Future ADAS designs should prioritize the use of image sensors and consider integrating auditory cues as complementary features rather than standalone systems. Finally, the study notes that speed dispersion is another important factor to consider when evaluating ADAS performance. The combination of image and audio alerts was shown to reduce speed variability, and future studies should include this measure to assess the broader impact of ADAS on driver behavior.

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REFERENCES

[1] National Highway Traffic Safety Administration, "Traffic Safety Facts: 2018 Data," May 2020. DOT HS 812 957. Available at https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812957
[2] National Highway Traffic Safety Administration, "Traffic Safety Facts: 2022 Data," July 2024. DOT HS 813 582. Available at https://www.nhtsa.gov/risky-driving/speeding
[3] C. Satterfield and R. B. Albin, "Public Roads – Autumn 2020," Federal Highway Administration. Volume 4, No. 3. FHWA-HRT-21-001. Available at https://highways.dot.gov/public-roads/autumn-2020/moving-forrrwd-focus-reducing-rural-roadway-departures
[4] A. Eser, "Global ADAS Industry Statistics: Explosive Growth and Technological Advancements Ahead." *Zipdo Education Report*, 2024. Available at https://zipdo.co/adas-industry-statistics/
[5] National Highway Traffic Safety Administration, "2020 Fatality Data Show Increased Traffic Fatalities During Pandemic," NHTSA Media. Available at https://www.nhtsa.gov/press-releases/2020-fatality-data-show-increased-traffic-fatalities-during-pandemic
[6] Puerto Rico Highways and Transportation Authority, "Puerto Rico Highway Safety Improvement Program: 2021 Annual Report," US DOT. FHWA. Available at https://highways.dot.gov/media/21226
[7] B. Colucci and Y. Rivera, "Observational Study of Centerline Rumble Strips in Puerto Rico: PR-114 Case Study," Proceedings of the *13th Latin American and Caribbean Conference for Engineering and Technology: Engineering Education Facing the Grand Challenges, What Are We Doing?* July 2015.
[8] E. T. Aarts, "Advanced driver assistance systems (ADAS) for road safety." Transportation Research Part F: Traffic Psychology and Behaviour, pp 1-10. 2010.
[9] J. S. Hickman, et al, "Onboard Safety System Effectiveness Evaluation Final Report," (Report No. FMCSA-RRT12-012). Washington, D.C.: Federal Motor Carrier Safety Administration, 2013.
[10] F. Lai, O. Carsten, and F. Tate, "How much benefit does Intelligent Speed Adaptation deliver: An analysis of its potential contribution to safety and environment," *Accident Analysis & Prevention*, Volume 48. pp 63-72, 2012.
[11] J. B. Cicchino, "Effectiveness of forward collision warning and autonomous emergency braking systems in reducing front-to-rear crash rates", *Accident Analysis and Prevention*, pp 142-152, 2017.