

Article

Framing Effects in Personalized In-Vehicle Freeway Traffic Messaging: A HUD-Based Approach

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Abstract

Effective communication of traffic information is critical for freeway safety. Yet, Traditional road signs and variable message displays often fail to capture drivers' attention, as evidenced by persistent speeding-related crashes on highways. Advances in connected-vehicle technology and head-up displays (HUDs) now enable real-time, personalized in-vehicle warnings, offering new opportunities to enhance speed compliance. At the same time, these systems introduce an important design challenge: the effectiveness of warnings may depend on how messages are framed (e.g., emphasizing benefits versus risks), particularly under time pressure and varying driver characteristics. Despite its theoretical importance, the impact of message framing in real-time, HUD-based speed warning contexts remains insufficiently understood. This study proposes and evaluates a Freeway-Centered Dynamic Speed Warning System (F-DSWS) that delivers real-time speed warnings via vehicle-to-infrastructure communication and HUD interfaces. Two message-framing strategies were examined: gain-framed messages emphasizing positive and socially relevant outcomes, and loss-framed messages highlighting safety risks. A driving simulator experiment was conducted with 39 licensed drivers aged 19–78 years across multiple freeway scenarios. Results indicate that HUD-based warnings significantly outperformed traditional roadside signs in reducing speeding, lane-deviation extremes, and harsh braking. Moreover, gain-framed messages consistently produced greater improvements in driving performance than loss-framed messages across all evaluated metrics. These findings suggest that the proposed F-DSWS provides measurable safety benefits and demonstrate that framing choice is a critical design factor in personalized in-vehicle freeway traffic messaging. These results offer evidence-based guidance on framing selection within HUD-based in-vehicle freeway warnings, and support future field deployment of the proposed F-DSWS to improve freeway safety.



Academic Editor: José Santa

Received: 31 December 2025

Revised: 13 February 2026

Accepted: 13 February 2026

Published: 3 March 2026

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Keywords: personalization; heads-up display (HUD); Safety reminder; in-vehicle traffic messaging; freeway-centered dynamic speed warning system (F-DSWS); framing effects

1. Introduction

Freeway safety remains a significant concern, as crash rates on freeways are substantially higher than on other road types [1]. Speeding is widely recognized as a major

contributor to these high freeway crash rates [2,3]. Therefore, developing effective methods to curb speeding on freeways is imperative for improving traffic safety.

With advances in connected-vehicle technology and head-up displays (HUDs), real-time personalized in-vehicle speed warnings are increasingly feasible. Compared to traditional roadside signs, in-vehicle systems can deliver timely, situation-specific alerts directly to drivers. However, the effectiveness of such systems depends not only on technological capability but also on message design. In particular, message framing (e.g., gain-framed versus loss-framed messaging) may significantly influence drivers' attention and compliance, especially under high-speed and time-pressured freeway conditions. Current approaches to freeway speed management exhibit two key limitations.

First, most speed control measures rely on external variable message signs (VMS) or static signs along the roadway [4,5]. drivers may overlook or miss information on roadside signs, thus limits the effectiveness of this approach [6]. Factors such as sign placement, information overload, and limited driver attention can further undermine the impact of roadside warnings [7]. Consequently, there is a clear need for solutions that more effectively capture drivers' attention and promote timely speed reduction.

In-vehicle warning systems made possible by connected vehicle (CV) technology present a promising alternative [8–11]. By providing real-time speed alerts directly within the vehicle, these systems can deliver highly relevant information tailored to each driver's context such systems can provide highly relevant alerts tailored to each driver's situation, making compliance more likely [9,12,13]. Yet, relocating warnings from the roadside into the vehicle introduces an important design challenge: the same advisory message may produce different behavioral responses depending on how it is framed (gain vs. loss), particularly in fast-paced freeway environments. This study proposes such an in-vehicle system specifically designed to guide drivers to reduce speed on freeways, with the goal of improving safety beyond what roadside signs can achieve. If proven effective in simulation, the system could be considered for field implementation, bringing practical benefits to real-world freeway operations [14].

Second, the optimal design and framing of speed warning messages remain unresolved. Safety messages can be framed in terms of gains (emphasizing the benefits of safe behavior) or losses (highlighting the consequences of risky behavior) [15]. Prior research indicates that individuals may respond differently to gain- and loss-framed messages across domains such as public health, climate communication, marketing, and travel behaviors [16–19]. However, findings are inconsistent regarding which framing strategy is more effective in influencing driving behavior [20,21]. In the context of in-vehicle speed warnings, it is important to determine whether message framing has a significant impact on driver compliance and performance. Addressing this gap will provide insight into how best to design the content of in-vehicle messages for maximum persuasive effect. These insights could inform automobile manufacturers and interface designers in developing in-vehicle information systems that more effectively engage drivers and promote safer driving behavior on freeways.

To address these gaps, this research aims (i) to propose a freeway-centered dynamic speed warning system (F-DSWS) that is specialized for freeway segments with connected vehicle technology enabled, and (ii) to validate the effectiveness of the proposed system in a simulation environment. The F-DSWS focuses on guiding drivers to reduce speed on the freeway, with varying message framings to encourage speed reduction on freeways. The effectiveness of the proposed system is validated by comparing it to existing practices from both longitudinal (speed, maximum deceleration rate) and lateral (lane deviation) perspectives.

The simulation results show that the proposed system significantly outperforms the existing system in terms of speed control, lane deviation, and maximum deceleration rate. Given the promising performance of the proposed system in the simulation environment, field implementation is recommended so that it can be further evaluated and used in real-world practice.

The remainder of this manuscript is organized as follows. Section 2 reviews the literature review. Section 3 describes the methods. Section 4 presents the results and discussion. Section 5 concludes the manuscript and outlines future work.

2. Literature Review

2.1. Current Practice of Freeway Safety Solutions

Current freeway safety solutions can be broadly divided into passive safety facilities and intelligent safety systems [22,23]. Passive safety facilities include rolling guardrails, anti-glare devices, and similar roadside infrastructure [24]. While such facilities can mitigate crash severity, they require regular inspection for corrosion and deformation, as well as timely repair or replacement of damaged components [25]. In practice, the lack of routine maintenance on some sections of the highway leads to the accumulation of hidden hazards [26]. Moreover, these passive facilities do not remind drivers in real time to adjust their speed in response to changing conditions [24].

Intelligent safety systems include variable message signs and traffic flow detection systems [27]. Variable message signs dynamically display traffic and safety information, but drivers may still overlook or disregard the messages, especially in visually complex environments or under high workload [28]. Traffic flow detection systems can be affected by adverse weather conditions (e.g., rain, snow, fog) and lighting conditions (e.g., backlight, nighttime), resulting in degraded detection accuracy [29]. These limitations highlight the need for more robust, driver-centered solutions. Recent connected-vehicle (CV) and in-vehicle HMI advances enable warnings to be delivered inside the vehicle with higher salience and richer context than roadside devices. Importantly, once warnings move from infrastructure to a personalized in-vehicle interface (e.g., HUD), effectiveness is no longer only a sensing/placement problem but also a communication problem: the same advisory can be perceived differently depending on its wording, tone, and framing under high workload. This shift motivates a joint view of system capability and message design, where framing becomes a first-order factor in realizing safety benefits.

2.2. Gain-Framed and Loss-Framed Message Types

Gain- and loss-framed messages are well-established strategies in communication research, with extensive applications in health promotion, marketing, and public policy. Framing effects are grounded in Prospect Theory, which shows that individuals evaluate equivalent information differently depending on whether outcomes are presented as gains or losses [16,30,31]. In health domains, gain-framed appeals tend to be more effective when targeting preventive behaviors (e.g., exercise, healthy diet), whereas loss-framed appeals may be more effective when targeting detection behaviors (e.g., cancer screening) [16,30,31]. In marketing, gain- and loss-framed appeals do not always differ significantly in persuasiveness, for instance in charity advertising [32–34]. In public policy contexts such as climate change communication, loss-framed messages can more effectively increase support for policy [35–37].

In transportation safety, however, evidence on the relative effectiveness of gain- versus loss-framed messaging for reducing speeding and enhancing compliance remains inconclusive and highly context-dependent. For example, a study conducted in France demonstrated that drivers reduced their speed more effectively when encountering gain-

framed messages compared to loss-framed ones. Notably, these findings were derived from messages presented on signs along the highway, rather than on in-vehicle displays and gender as a factor was also explored. Regarding the temporal impact of these framing strategies, evidence suggests that while negative appeals or loss-framed messages may result in greater persuasiveness immediately upon exposure, positive appeals are linked to greater behavioral improvements over time [38]. Recent efforts have sought to translate these findings inside the vehicle to support Level 2 automated driving. In this study, researchers developed an “affective message concept” (AMC) that utilized message framing and emoticons displayed via a Head-Up Display (HUD) to maintain driver attention. The messages in this concept were primarily designed to induce a positive mood and coping appraisal. However, this study was limited in that it only tested this specific affective messaging concept against a baseline (no messages); it did not utilize a distinct experimental condition to test negative or loss-framed messages against the positive affective concepts [21].

Overall, prior research suggests that the relative effectiveness of gain- versus loss-framed messaging is context-dependent and may interact with individual characteristics such as risk perception, motivation, and demographic factors. However, evidence from health, marketing, or policy communication does not directly translate to safety-critical driving, where messages must be processed within seconds and may interact with workload, trust in automation, and real-time risk perception.

2.3. Summary

In summary, the core challenge in freeway safety messaging is to deliver timely, reliable, and behavior-effective speed guidance under dynamic conditions while ensuring that drivers actually notice and comply with the information. Current practice has made progress along two complementary directions. On the system side, passive roadside facilities can mitigate crash severity but offer limited real-time behavioral guidance and depend heavily on routine maintenance. Intelligent infrastructure-based solutions (e.g., variable message signs and traffic detection systems) improve information timeliness, yet their effectiveness can be constrained by drivers’ limited attention in complex visual environments and by degraded sensing performance under adverse weather or lighting conditions. These limitations collectively highlight a practical gap: freeway safety still lacks driver-centered, context-aware messaging that remains salient and actionable when driving workload is high.

On the message-design side, framing research provides a theoretical foundation for shaping behavioral responses through gain- versus loss-framed appeals, but the evidence is largely context-dependent and has been established mainly in domains outside in-vehicle freeway safety. Prior studies suggest that framing effectiveness can vary with task type (e.g., preventive vs. detection behaviors) and may interact with individual characteristics (e.g., risk perception and demographics), implying that results cannot be directly extrapolated to real-time driving. Therefore, the key difficulty for in-vehicle freeway messaging lies in bridging system capability and behavioral communication: even if real-time speed information can be delivered to the vehicle, it remains unclear which framing strategy is most effective for improving speed compliance and driving stability in a freeway context, and whether such effects differ across driver groups. In particular, for personalized HUD-based in-vehicle warnings, there is limited controlled evidence showing whether gain-versus loss-framed messages produce measurably different safety benefits in freeway-like scenarios, as evaluated by objective driving metrics (e.g., speeding, lane deviation and maximum deceleration rate). These gaps motivate the present study to integrate a Connected Vehicle-enabled, HUD-based warning system with framing-based message design and to empirically examine their combined impacts on freeway driving behavior.

3. Methods

3.1. System Architecture and Warning Logic

The proposed Freeway-Centered Dynamic Speed Warning System (F-DSWS) integrates roadside sensing infrastructure with an in-vehicle head-up display (HUD) to deliver real-time, context-aware speed warnings. As a connected vehicle approaches a monitored freeway segment, the roadside controller (RSC) continuously receives speed and position data from the vehicle. When predefined triggering conditions are met, such as entering a detection zone or exceeding a speed threshold, the RSC transmits a safety message directly to the vehicle's HUD.

In total, there are two message-framing strategies implemented:

- **Gain-framed message**, emphasizing the positive and personal benefits of safe driving (e.g., "Please drive carefully, your family is waiting for you.").
- **Loss-framed message**, highlighting the negative consequences of unsafe behavior (e.g., "Speeding is the leading cause of traffic accidents.").

Moreover, two delivery mechanisms were evaluated:

- **Roadside single-point triggering**, in which the RSC dispatches a one-time warning when the vehicle passes a fixed roadside location.
- **Dynamic HUD-based triggering**, in which the RSC monitors vehicle speed in real time and issues warnings immediately once speeding occurs.

These configurations allow direct comparison between (i) roadside versus in-vehicle message delivery and (ii) gain-framed versus loss-framed message content. The overall system architecture is illustrated in Figure 1.

Compared with conventional roadside signs, HUD-based in-vehicle warnings are designed to mitigate (i) missed or delayed perception of safety messages due to limited driver attention and sign legibility at freeway speeds, (ii) insufficient timing/actionability when warnings must be acted upon quickly, and (iii) lack of personalization to the driver's current speed and context. These issues are consistent with connected-vehicle human-factors goals that emphasize driver comprehension and appropriate response to warnings. Accordingly, the proposed F-DSWS places concise warnings in the forward field of view and standardizes message format and timing to limit cognitive load while improving detectability and response efficiency.

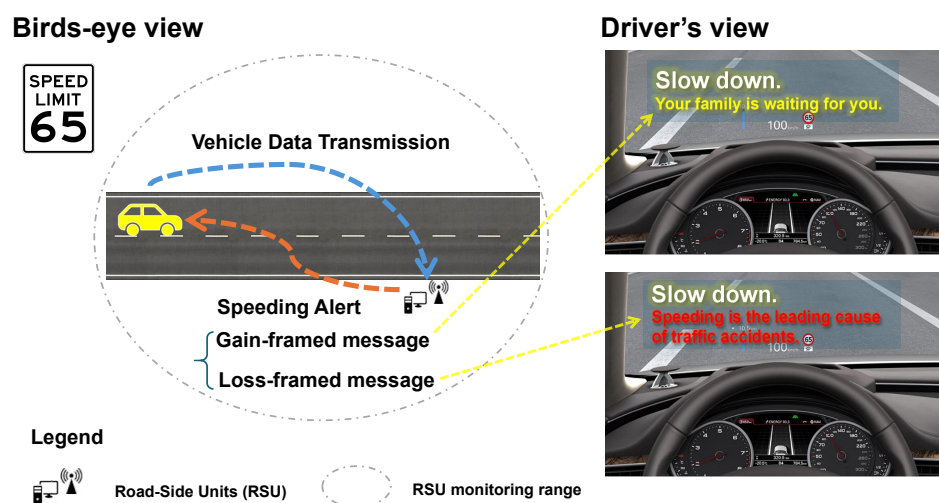


Figure 1. System architecture.

3.2. Modeling Techniques

3.2.1. Data Analysis

All driving performance data were collected at a sampling frequency of 60 Hz and processed to compute longitudinal and lateral behavior indicators. Raw time-series data were first screened to remove missing points, simulator artifacts, and anomalous readings caused by signal noise. For each experimental section, performance measures—including maximum, minimum, and average driving speed; maximum, minimum, and average lane deviation; and both maximum and average maximum deceleration rates—were extracted as summary metrics. These indicators were selected to reflect overall speed compliance, lane-keeping stability, and braking intensity under different message-framing and warning-delivery conditions.

To statistically evaluate differences between paired experimental conditions, both parametric and nonparametric methods were employed. When performance measures met normality assumptions, one-tailed paired *t*-tests were applied based on the directional hypotheses that HUD-based warnings and gain-framed messages would lead to safer driving outcomes. When normality was violated, the Wilcoxon signed-rank test was used as a distribution-free alternative for paired comparisons. These complementary tests allowed robust inference across a variety of outcome distributions.

3.2.2. Regression and Classification Tree (CART) Modeling

To explore heterogeneity in framing effects across demographic segments, we developed a Classification and Regression Tree (CART) classifier using age and gender as predictors. The tree was designed to predict which message framing condition (gain vs. loss) yields a larger safety benefit with respect to *minimum lane deviation*. Specifically, for each participant *j*, we computed the pre–post improvement under each framing condition as

$$\Delta_{j,\text{gain}}^{\min} = LD_{j,\text{pre,gain}}^{\min} - LD_{j,\text{post,gain}}^{\min}, \quad \Delta_{j,\text{loss}}^{\min} = LD_{j,\text{pre,loss}}^{\min} - LD_{j,\text{post,loss}}^{\min}, \quad (1)$$

where a positive $\Delta^{\min}$ indicates a reduction in minimum lane deviation and thus improved lane-keeping performance.

The outcome variable (*Target*) was then encoded based on the relative effectiveness of gain- versus loss-framed messages:

$$\text{Target}_j = \begin{cases} 1, & \Delta_{j,\text{gain}}^{\min} > \Delta_{j,\text{loss}}^{\min} \quad (\text{gain-framed more effective}), \\ 0, & \Delta_{j,\text{gain}}^{\min} \leq \Delta_{j,\text{loss}}^{\min} \quad (\text{loss-framed more effective}). \end{cases} \quad (2)$$

For classification trees, the impurity of a node *t* was measured by the Gini index [39,40]:

$$G(t) = 1 - \sum_{k=1}^K p_k(t)^2, \quad (3)$$

where $p_k(t)$ denotes the proportion of class *k* among samples in node *t*, and *K* is the number of classes. For a candidate split *s* that partitions node *t* into left and right child nodes (*t_L*, *t_R*), the impurity reduction is

$$\Delta G(s, t) = G(t) - \frac{N_L}{N} G(t_L) - \frac{N_R}{N} G(t_R), \quad (4)$$

where *N* is the sample size of node *t*, and *N_L* and *N_R* are the sample sizes of the two child nodes. The split maximizing $\Delta G(s, t)$ was selected.

Given the relatively small sample size and the risk of overfitting in tree-based models, cost-complexity pruning was applied:

$$R_{\alpha}(T) = R(T) + \alpha|T|, \quad (5)$$

where $R(T)$ denotes the resubstitution misclassification error, $|T|$ is the number of terminal nodes (leaves), and $\alpha \geq 0$ controls the trade-off between goodness-of-fit and model complexity. The complexity parameter was determined using 10-fold cross-validation. Because the resulting splits can become fine-grained when only a small number of predictors are available, the CART-based subgroup findings are interpreted as exploratory and hypothesis-generating rather than prescriptive.

Normally, the classification models are built from a training data set in which trends of explanatory and response variables are identified and used to predict the value of the dependent variable for the testing datasets. In this study, these tree graphs can assist understand the underlying cognitive mechanisms behind the consistent out-performance of gain-framed messages compared to loss-framed messages.

Furthermore, The reason why choosing “r-part” in R studio to build these decision tree models is due to the function of cross-validation [41]. Given the relatively limited sample size and the tendency of tree-based models to over-fit, cross-validation was employed to obtain more reliable estimates of out-of-sample performance and to guide the selection of an appropriate tree complexity. The data set was partitioned using 10-fold stratified cross-validation to preserve the class distribution within each fold [42]. For each setting, nine folds were used for training and one fold for testing. This process was repeated ten times so that each fold served as the test set once.

3.3. Driving Simulator Configuration

The experiment was conducted using the miniSim driving simulator, a high-fidelity research platform capable of replicating realistic freeway driving environments. The system integrates computer-controlled vehicle dynamics, multi-screen visual projection, and synchronized audio feedback to immerse participants in a controlled yet lifelike driving scenario. The simulator records more than 100 driving-related variables, including speed, acceleration, steering input, and lane position, at a 60 Hz sampling rate.

The virtual roadway environment was constructed using high-resolution surface tiles and standardized freeway geometry to ensure consistency across participants. All experimental scenarios were designed to maintain identical roadway curvature, lane width, traffic-free conditions, and speed-limit signage to isolate the effects of message framing and display modality. During each drive, the simulator continuously captured longitudinal and lateral performance metrics for subsequent analysis.

Figure 2 illustrates the miniSim simulator used in this study.

3.4. Participant Recruitment

A total of 35 licensed drivers were recruited for the study. The sample was designed to capture a broad range of demographic and driving experience characteristics to enhance the generalizability of the findings. Participants ranged in age from 18 to 78 years, with driving experience varying from 1 to 64 years. The sample included 16 female drivers (45.7%) and 19 male drivers (54.3%).

All participants reported normal or corrected-to-normal vision and no history of motion sickness or medical conditions that could impair safe simulator use. Each participant provided informed consent prior to the experiment and received a briefing on simulator operation and the experimental procedures. The study protocol was reviewed internally to ensure adherence to ethical standards for human-subjects research.

Table 1 summarizes the demographic characteristics of the participant sample.



Figure 2. Driver simulator.

3.5. Experimental Design

A within-subjects experimental design was adopted to examine how message framing (gain-framed vs. loss-framed) and warning delivery modality (roadside vs. HUD-based) influence driving behavior. We considered a fixed position as the baseline control condition. Each participant completed three experimental rounds, and each round contained two free-way road sections. Road geometry, speed limits, environmental visibility, and the absence of surrounding traffic were held constant across all sessions to ensure that differences in driver performance were attributable solely to the experimental manipulations.

The whole experiment session lasts approximately 1 hour per participant. To better replicate the real-world driving conditions, the scenarios were designed based on the “Springfield Road Network” provided by the Driving Safety Research Institute, University of Iowa. The “Springfield Road Network” was chosen because it contains freeway scenery inspired by real-world locations [43].

Two independent variables were controlled. The first was message framing, comparing gain-framed wording that emphasized positive outcomes with loss-framed wording highlighting negative consequences. The second was delivery modality, including a single-point roadside triggering mechanism and a dynamic HUD-based mechanism that issued warnings immediately when the vehicle exceeded a predefined speed threshold. This structure allowed systematic comparison between content effects (gain vs. loss) and interface effects (roadside vs. HUD).

In the first driving task, all warnings were gain-framed. During the first road section, a gain-framed message (“Please drive carefully, your family is waiting for you.”) was delivered once when the vehicle passed a fixed roadside controller location. In the second section, the same gain-framed message was triggered dynamically when speeding occurred. This round was designed to reveal how delivery modality affects drivers’ responses to gain-framed information.

The second driving task mirrored the structure of Round 1 but used loss-framed messages (“Speeding is the leading cause of traffic accidents.”). The first section again involved fixed roadside triggering, while the second section adopted speed-threshold-based HUD triggering. By maintaining identical procedures except for message framing, this round isolated the interface effect within the context of loss-framed information.

The third driving task was designed to compare framing effects directly under a constant delivery modality. Both road sections adopted dynamic HUD-based triggering; the first presented the gain-framed message, and the second presented the loss-framed message. With the delivery method held constant, this round enabled a clear assessment of the relative effectiveness of the two framing strategies.

Driving performance was continuously recorded at 60 Hz. The analysis focused on longitudinal and lateral behavior, including maximum, minimum, and average speeds; lane deviation metrics; and maximum and average maximum deceleration rates. These measures captured drivers’ speed control, lane-keeping stability, and braking intensity under each experimental condition. Figure 3 illustrates the research framework.

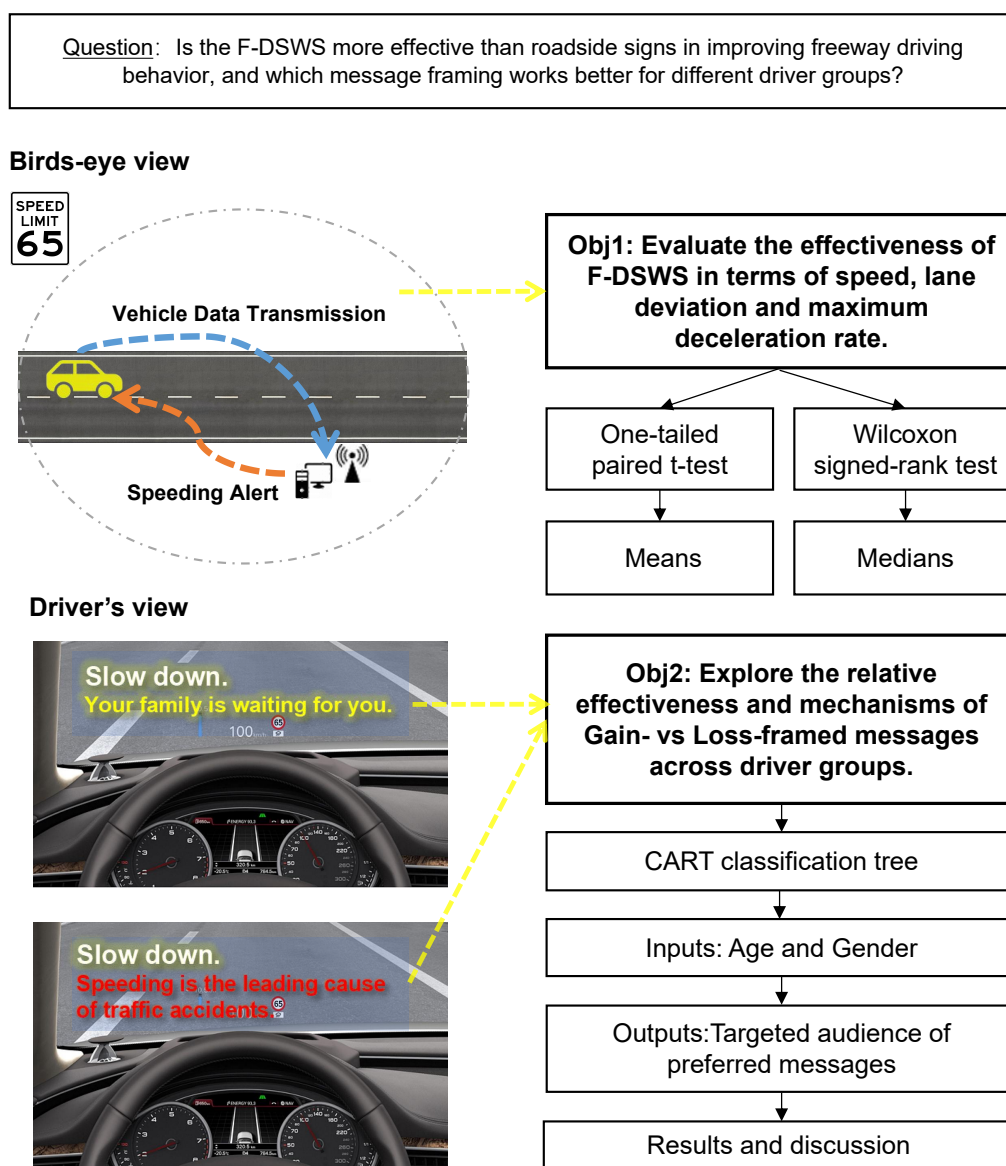


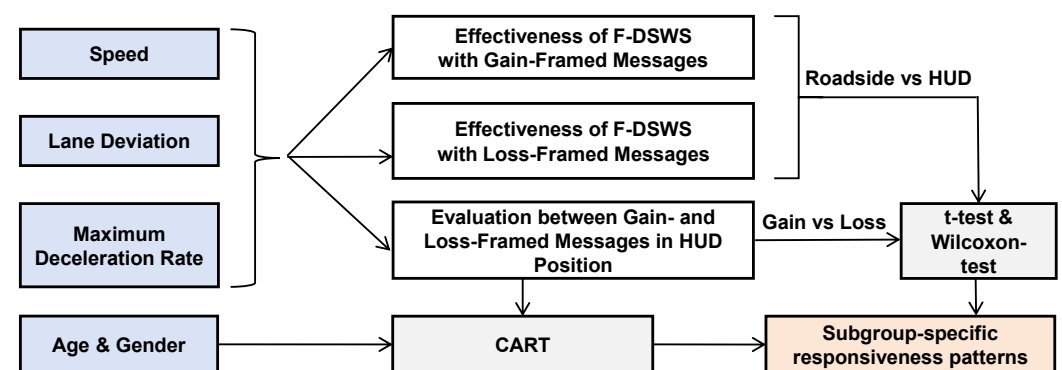
Figure 3. Research framework.

Table 1. Driver information.

Variable	Description	Type	Category	N	Percentage (%)
Age	Age of participants	Discrete variable	(18, 30)	24	68.6
			(31, 40)	5	14.3
			(41, 50)	2	5.7
			(51, 79)	4	11.4
Gender	Gender of participants	Binary variable	Female	19	54.3
			Male	16	45.7
Accident history	Number of accidents being involved	Discrete variable	0	29	76.3
			1	7	18.4
			2	1	2.6
			3	1	2.6

4. Results and Discussion

In this study, roadside refers to a fixed roadside location equipped with a Roadside Unit (RSU) that detects an approaching vehicle and delivers a single gain- or loss-framed warning message at that predetermined point. In contrast, the HUD condition involves an in-vehicle head-up display through which the RSU transmits the same types of messages in real time whenever the vehicle exceeds the designated speed threshold. The freeway-centered HUD delivery and event-triggered warning logic produced a clearer and more consistent behavioral differentiation attributable to message framing, as reflected in speed profiles, lane deviation, and maximum deceleration rate. These findings suggest that the proposed system enhances the measurable behavioral impact of gain- versus loss-framed warnings compared to existing approaches. All statistical analyses were conducted in RStudio version 4.5.1, and the *rpart* package was used to model relationships between message framing and driving performance outcomes. Figure 4 illustrates the overall framework of these experimental conditions.



Legend blue: collected data, white: primary analyses, grey: modeling techniques, orange: results

Figure 4. Result framework.

4.1. Effectiveness of F-DSWS with Gain-Framed Messages

This section presents the performance outcomes associated with gain-framed messages when delivered through either a single roadside trigger or the dynamic HUD-based system. The comparison focuses on speed behavior, lane deviation, and maximum deceleration rate.

4.1.1. Speed-Related Performance Measures

Roadside vs. HUD

The one-tailed paired *t*-tests showed that both maximum speed and average speed were lower under the HUD condition than under the roadside condition, although these differences did not reach statistical significance at the 0.05 level. The Wilcoxon signed-rank test revealed a marginally significant difference in minimum speed, suggesting that drivers maintained slightly higher minimum speeds with the HUD-based warnings than with a single roadside alert ($p < 0.1$). This pattern suggests that real-time HUD feedback helps drivers avoid excessively low speeds and promotes smoother deceleration behavior.

Influence of Driver Demographics on Speed Behavior

To further examine the sources of variation in minimum-speed behavior, the analysis was stratified by age and gender. Among younger drivers (below 29 years), the HUD condition produced a higher median minimum speed and a more compact distribution, with fewer instances of abrupt slowing. This indicates that HUD-based gain-framed messages help younger drivers maintain smoother and more controlled deceleration. For drivers aged 29 years and older, the medians under the two conditions were similar; however, the HUD distribution remained slightly tighter, suggesting modest improvements in speed stability even among more experienced drivers.

Gender differences followed a similar pattern. Male drivers exhibited a clear increase in minimum speed under the HUD condition, accompanied by reduced variability and fewer extremely low-speed observations. Female drivers showed a smaller upward shift in median minimum speed, indicating that while HUD guidance helped minimize very low speeds, the stabilizing effect was less pronounced than that observed among males. Overall, the HUD-based gain-framed warning system enhanced minimum-speed stability across demographic groups, with stronger improvements among younger and male drivers.

Figure 5 suggests the distribution of minimum speeds under roadside and HUD conditions for gain-framed messages, stratified by age group and gender.

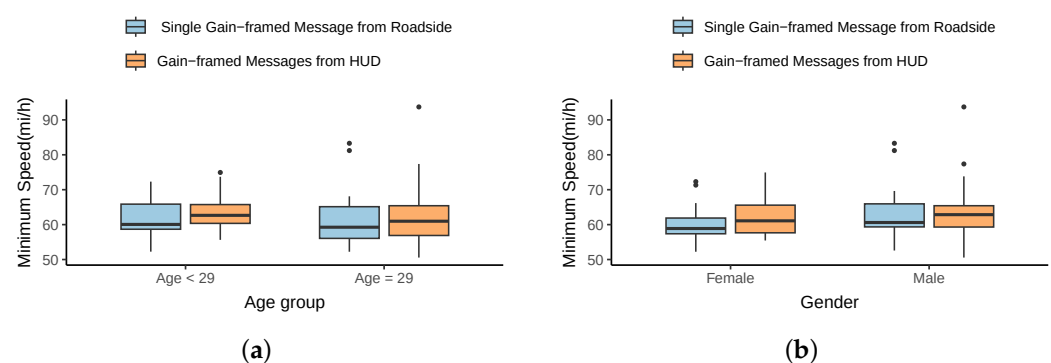


Figure 5. Minimum speed under Roadside-position and HUD-position with gain-framed messages: (a) comparisons by age group and (b) comparisons by gender.

4.1.2. Lane Deviation-Related Performance Measures

Roadside vs. HUD

The results for lane-deviation behavior under gain-framed messages reveal a mixed pattern. The one-tailed paired *t*-test showed that the mean lane deviation was slightly higher under the HUD condition than under the roadside condition, indicating that typical lateral positioning did not improve with HUD-based warnings. However, the Wilcoxon signed-rank tests indicated that both maximum and minimum lane deviations were significantly lower under the HUD condition ($p < 0.1$). This suggests that while overall averages

remained similar, the HUD system helped reduce extreme deviations, thereby constraining the most pronounced instances of lateral drift.

Additional Wilcoxon tests showed that the standard deviations of maximum lane deviations were markedly lower when warnings were delivered through the HUD ($p < 0.1$). Moreover, minimum and average lane deviations were markedly lower when warnings were delivered through the HUD ($p < 0.01$). These reductions in variability indicate that the HUD-based gain-framed system contributed to more stable lateral control, even if the average deviation itself did not decline.

Influence of Driver Demographics on Lane Deviation Behavior

Age-stratified analyses revealed heterogeneous responses to HUD-based gain-framed messages. Among younger drivers (below 29 years), maximum lane deviations were slightly higher and more dispersed under the HUD condition, suggesting that real-time warnings may have introduced momentary lateral adjustments that increased variability. For drivers aged 29 years and older, median maximum deviations were similar across conditions, though HUD distributions remained somewhat more spread out. These patterns imply that the stabilizing effect of the HUD system on extreme lane deviations is not uniform and may depend on how different age groups allocate attention between speed management and lateral control.

Minimum lane deviation further illustrates the age divide. Younger drivers displayed consistently small minimum deviations across both conditions, with tight distributions near zero, indicating strong lane-centering performance regardless of warning delivery method. Older drivers, by contrast, exhibited higher minimum deviations with greater dispersion, and the HUD condition produced slightly larger and more variable minimum deviations. This suggests that HUD-based gain-framed messages may impose additional attentional load on older drivers, making precise lane-centering somewhat more difficult.

Gender differences also emerged. Female drivers maintained relatively small minimum lane deviations in both conditions, with the HUD condition exhibiting a slightly lower median and narrower interquartile range. This pattern suggests that HUD-based messages helped reinforce lane-centering for most female drivers. Male drivers, however, showed a shift toward larger and more variable minimum deviations under the HUD system, indicating that real-time gain-framed messages may have diverted attention away from lateral control. Taken together, these results indicate that HUD-based gain-framed warnings improve lane-centering consistency primarily among female drivers, whereas male drivers may experience increased variability under the same conditions.

Figure 6 suggests maximum lane deviation under roadside and HUD conditions for gain-framed messages, stratified by age group and gender.

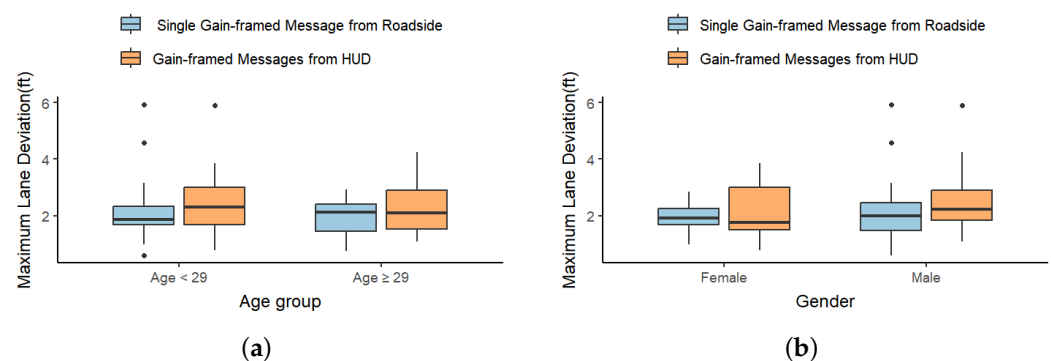


Figure 6. Maximum lane deviation under Roadside-position and HUD-position with gain-framed messages: (a) comparisons by age group and (b) comparisons by gender.

4.1.3. Deceleration-Related Performance Measures

Roadside vs. HUD

The one-tailed paired *t*-test indicated that the mean maximum deceleration rate after implementing the HUD system was significantly lower than under the roadside condition ($p < 0.1$). The mean average maximum deceleration rate was also significantly lower with the HUD system ($p < 0.1$). These results support that, on average, HUD-based gain-framed messages reduce the severity of peak braking events. Table 2 suggests the *t*-test comparison of vehicle metrics under Roadside-position and HUD-position with gain-framed messages.

The Wilcoxon Signed-Rank test showed that median maximum deceleration rate and median average maximum deceleration rate were both significantly lower under the HUD condition than under the roadside condition ($p < 0.1$). Additionally, the median standard deviations of maximum and average maximum deceleration rates were significantly lower under the HUD condition ($p < 0.01$), indicating that the HUD system reduces both the level and variability of harsh braking. Table 3 suggests the W-test comparison of vehicle metrics under Roadside-position and HUD-position with gain-framed messages.

Table 2. *t*-test comparison of vehicle metrics under Roadside-position and HUD-position with gain-framed messages.

Metric	Average Value		<i>p</i> -Value	Significance
	Roadside	HUD		
Maximum Speed	71.64	70.51	0.278	NS
Minimum Speed	61.94	63.49	0.196	NS
Average Speed	67.21	66.89	0.428	NS
Maximum Gas Pedal Position	0.59	0.61	0.250	NS
Minimum Gas Pedal Position	0.11	0.20	0.009	$p < 0.01$ ***
Average Gas Pedal Position	0.37	0.51	0.001	$p < 0.01$ ***
Maximum Brake Force	0	0.45	0.162	NS
Minimum Brake Force	0	0	/	/
Average Brake Force	0	0.01	0.162	NS
Maximum Lane Deviation	2.09	2.32	0.175	NS
Minimum Lane Deviation	0.13	0.23	0.143	NS
Average Lane Deviation	1.13	0.97	0.105	NS
Maximum Deceleration	0.21	0.35	0.055	$p < 0.1$ *
Average Maximum Deceleration	−1.48	−1.23	0.061	$p < 0.1$ *

/ No data available. NS: not significant. * $p < 0.1$, *** $p < 0.01$.

Influence of Driver Demographics on Deceleration Behavior

The following section explores the underlying mechanisms from the perspectives of age and gender.

From the perspective of age, the box plots of maximum deceleration show a systematic shift toward values closer to zero under the HUD condition, particularly for drivers younger than 29 years. For this group, the median maximum deceleration is less negative under the HUD condition than under the roadside condition, indicating milder peak braking maneuvers. For drivers aged 29 years and older, the HUD median is again slightly closer to zero and the distribution spreads upward, suggesting somewhat softer braking overall. These patterns indicate that HUD-based gain-framed messages help both younger and older drivers avoid excessively harsh braking, with a more pronounced effect among younger drivers.

From the perspective of gender, the median average maximum deceleration rate of female drivers under the HUD condition is less negative than under the roadside condition, and the HUD distribution shifts toward values closer to zero, although several outliers

remain. This suggests that for most female drivers, gain-framed HUD messages lead to softer braking. For male drivers, medians under the two conditions are similar, and the HUD distribution is somewhat more dispersed. Overall, HUD-based gain-framed messages markedly reduce braking intensity for female drivers, while the effect for male drivers is more modest. Figure 7 depicts average maximum deceleration rate under roadside and HUD positions for gain-framed messages, stratified by age group and gender.

Table 3. W-test comparison of vehicle metrics under Roadside-position and HUD-position with gain-framed messages.

Metric	V Statistic	<i>p</i> -Value	Estimated Median Diff.	99% CI	Significance
Max Speed	260	0.126	−0.754	$(-\infty, +4.456)$	NS
Max Speed SD	414	0.102	0.223	$(-0.683, +\infty)$	NS
Min Speed	415	0.099	2.161	$[-\infty, +\infty]$	$p < 0.1$ *
Min Speed SD	304	0.324	−0.683	$[-\infty, +\infty]$	NS
Average Speed	284	0.221	−0.493	$[-\infty, +\infty]$	NS
Average Speed SD	392	0.177	0.501	$(-0.946, +\infty)$	NS
Max LD	424	0.076	0.399	$(-\infty, +\infty)$	$p < 0.1$ *
Max LD SD	423	0.079	0.202	$(-0.133, +\infty)$	$p < 0.1$ *
Min LD	419	0.088	0.004	$(-\infty, +\infty)$	$p < 0.1$ *
Min LD SD	506	0.003	0.090	$(0.071, +\infty)$	$p < 0.01$ ***
Average LD	390	0.1853	−0.012	$[-\infty, +\infty]$	NS
Average LD SD	505	0.003	0.193	$(0.038, +\infty)$	$p < 0.01$ ***
Max DR	423	0.079	0.078	$(-0.105, +\infty)$	$p < 0.1$ *
Max DR SD	521	0.001	0.265	$(0.071, +\infty)$	$p < 0.01$ ***
Average Max DR	425	0.074	0.062	$(-0.102, +\infty)$	$p < 0.1$ *
Average Max DR SD	521	0.002	0.271	$(0.066, +\infty)$	$p < 0.01$ ***

SD: standard deviation LD: lane deviation DR: deceleration rate. NS: not significant. * $p < 0.1$, *** $p < 0.01$.

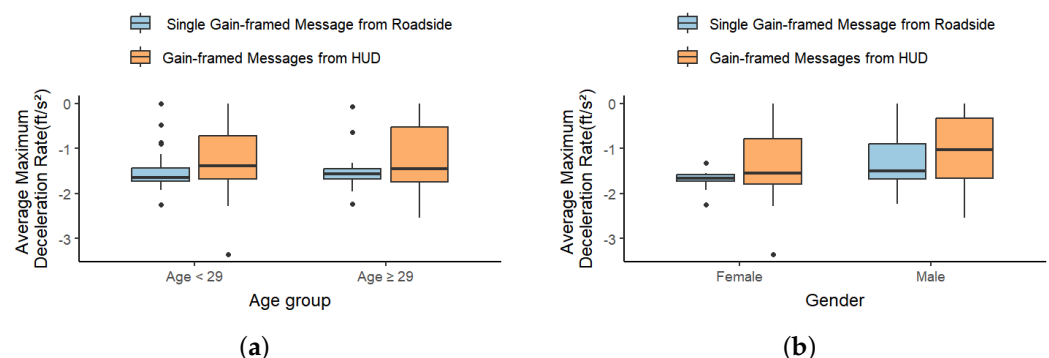


Figure 7. Average maximum deceleration rate under Roadside-position and HUD-position with gain-framed messages: (a) comparisons by age group and (b) comparisons by gender.

4.1.4. Summary

This subsection evaluates the effectiveness of the HUD system with gain-framed messages compared to roadside triggers, integrating analyses of speed, lane deviation, and deceleration behaviors. The findings demonstrate that the HUD system enhances driving smoothness and safety: for speed, the HUD marginally increased minimum speed ($p < 0.1$), reducing excessive deceleration, particularly among younger and male drivers; for lane deviation, while average deviation did not improve, the HUD significantly reduced extreme deviations (max/min deviation, $p < 0.1$) and variability, improving lateral stability, though effects varied by age and gender (with better outcomes for females); for deceleration, the HUD significantly lowered maximum deceleration rates and variability ($p < 0.1$), mitigating harsh braking, especially among younger and female drivers. These results

indicate that the HUD system effectively addresses the challenge of reducing extreme driving behaviors through dynamic messaging.

4.2. Effectiveness of F-DSWS with Loss-Framed Messages

This subsection presents the comparative results for loss-framed warnings delivered through a fixed roadside trigger versus the dynamic HUD-based system. The analysis focuses on drivers' speed behavior, lane-deviation patterns, and maximum deceleration rates under the two delivery conditions.

4.2.1. Speed-Related Performance Measures

Roadside vs. HUD

The one-tailed paired *t*-test indicated that the mean driving speed after using the HUD speed-warning system with loss-framed messages was slightly higher than before. This result suggests that, on average, loss-framed messages do not reduce overall freeway speed.

However, the Wilcoxon Signed-Rank test indicated that median minimum driving speeds under the HUD condition were significantly higher than under the roadside condition ($p < 0.05$). This suggests that the HUD system helps drivers maintain a higher and more stable minimum speed, avoiding excessive speed drops.

The Wilcoxon Signed-Rank test further indicated that the median standard deviations of maximum, minimum, and average speeds after implementing the HUD system were significantly lower compared with the standard deviations before implementation ($p < 0.1$). These results suggest that the HUD system effectively reduces the variability of freeway speed under loss-framed messages, even if average speeds do not decrease.

Influence of Driver Demographics on Speed Behavior The following section explores the underlying mechanisms from the perspectives of age and gender.

From the perspective of age, the box plots of minimum speed show a fairly consistent upward shift for the HUD condition across age groups. For drivers younger than 29 years, the median minimum speed with HUD-based loss-framed messages is slightly higher than under the roadside condition, and the central part of the HUD distribution is shifted toward faster minimum speeds, with only a few high and low outliers. This suggests that, under loss-framed warnings, younger drivers tend to avoid dropping to very low speeds and decelerate in a somewhat smoother and more controlled manner when the messages are presented on the HUD rather than at the roadside. For drivers aged 29 years and older, the HUD median is again higher than the roadside median, indicating milder reductions in speed, although occasional very low minimum speeds still appear in both conditions. Overall, this implies that, under loss-framed information, HUD-based warnings help both younger and older drivers maintain a slightly higher and more stable minimum speed compared with roadside signs.

From the perspective of gender, both female and male drivers show higher minimum speeds under the loss-framed HUD condition than under the roadside condition. Among female drivers, the median minimum speed with HUD-based loss-framed messages is clearly higher than with a single roadside loss-framed message, and the bulk of the HUD distribution is concentrated at moderately higher speeds, even though one extreme low outlier remains. This indicates that HUD delivery encourages most female drivers to avoid over-braking in response to loss-framed warnings. For male drivers, the HUD median is also higher than the roadside median, and the HUD box is shifted upward with some high-speed outliers at the upper end. In summary, under loss-framed messages, HUD-based warnings generally lead to smoother deceleration, with the effect being slightly more pronounced among female drivers. Figure 8 suggests minimum speed under roadside and HUD positions for loss-framed messages, stratified by age group and gender.

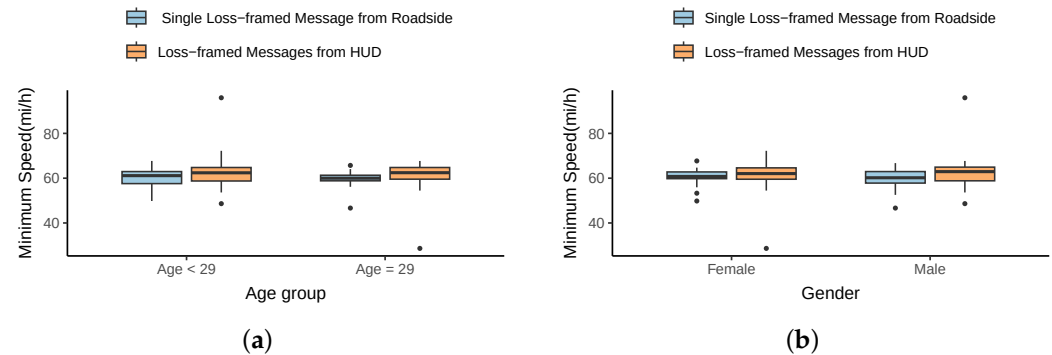


Figure 8. Minimum speed under Roadside-position and HUD-position with loss-framed messages: (a) comparisons by age group and (b) comparisons by gender.

4.2.2. Lane-Deviation-Related Performance Measures

Roadside vs. HUD

The one-tailed paired *t*-test indicated that the mean lane deviation after using the HUD speed-warning system with loss-framed messages was slightly higher than before, suggesting that, on average, loss-framed HUD messages do not reduce typical lane deviation.

Nevertheless, the Wilcoxon Signed-Rank test indicated that the median standard deviations of maximum lane deviations under the HUD condition were significantly lower than those before implementation ($p < 0.1$). In addition, the median standard deviation of minimum lane deviations with the HUD system was significantly lower than before ($p < 0.01$). These results suggest that the HUD system effectively reduces the variability of freeway lane deviation under loss-framed messages, even though mean deviation does not improve.

4.2.3. Deceleration-Related Performance Measures

Roadside vs. HUD

The one-tailed paired *t*-test indicated that the mean maximum deceleration rate after implementing the HUD system with loss-framed messages was somewhat lower compared to the maximum deceleration rate before implementation, whereas the mean average maximum deceleration rate after using the HUD speed-warning system was slightly higher than before. These results suggest that, on average, loss-framed messages do not consistently reduce freeway maximum deceleration rate. Table 4 summarizes the *t*-test comparison of vehicle metrics under Roadside-position and HUD-position with loss-framed messages.

However, the Wilcoxon Signed-Rank test indicated that the median standard deviations of maximum deceleration rate after implementing the HUD system were significantly lower than before ($p < 0.05$). In addition, the median standard deviations of average maximum deceleration rate with the HUD system were significantly lower than before ($p < 0.05$). These findings suggest that the HUD system effectively reduces the variability of maximum deceleration rate under loss-framed messages, even if mean levels are not clearly improved. Table 5 summarizes the W-test comparison of vehicle metrics under Roadside-position and HUD-position with loss-framed messages.

4.2.4. Summary

This subsection evaluates the HUD system's performance with loss-framed messages compared to roadside triggers across speed, lane deviation, and deceleration metrics. Key findings show that while average speed and lane deviation did not improve significantly, the HUD system demonstrated effectiveness in reducing variability: minimum speed was significantly higher ($p < 0.05$) and speed variability (max/min/average standard deviations)

was reduced ($p < 0.1$), indicating smoother speed maintenance; lane deviation variability (max/min standard deviations) was also significantly lower ($p < 0.1$ – 0.01), suggesting improved lateral stability; deceleration results were mixed—mean maximum deceleration showed inconsistent changes, but variability (standard deviations) was significantly reduced ($p < 0.05$), indicating more consistent braking patterns. Age and gender analyses revealed consistent benefits across demographic groups, with HUD helping drivers avoid excessive speed drops and extreme deviations. These results suggest the HUD system with loss-framed messages primarily addresses “reducing driving behavior variability” rather than lowering absolute values.

Table 4. *t*-test comparison of vehicle metrics under Roadside-position and HUD-position with loss-framed messages.

Metric	Average Value		<i>p</i> -Value	Significance
	Roadside	HUD		
Maximum Speed	68.25	70.45	0.118	NS
Minimum Speed	59.96	61.78	0.146	NS
Average Speed	64.67	65.96	0.160	NS
Maximum Gas Pedal Position	0.59	0.65	0.072	$p < 0.1$ *
Minimum Gas Pedal Position	0.17	0.19	0.036	$p < 0.05$ **
Average Gas Pedal Position	0.41	0.45	0.090	$p < 0.1$ *
Maximum Brake Force	0	0	/	/
Minimum Brake Force	0	0	/	/
Average Brake Force	0	0	/	/
Maximum Lane Deviation	2.20	2.33	0.289	NS
Minimum Lane Deviation	0.04	0.06	0.296	NS
Average Lane Deviation	0.93	0.95	0.373	NS
Maximum Deceleration	−0.62	−0.89	0.377	NS
Average Maximum Deceleration	−1.26	−1.21	0.391	NS

/ No data available. NS: not significant. * $p < 0.1$, ** $p < 0.05$.

4.3. Evaluation Between Gain- and Loss-Framed Messages in HUD Position

This subsection compares gain-framed and loss-framed messages directly under HUD conditions from the perspectives of speed, lane deviation, and maximum deceleration rate, and further examines age- and gender-specific patterns using CART models.

4.3.1. Speed-Related Performance Measures

The one-tailed paired *t*-test indicated that the mean maximum and minimum driving speeds with gain-framed messages were lower than those with loss-framed messages, although the differences were not statistically significant at the 0.05 level. This suggests that gain-framed messages may have a modest advantage in reducing freeway speed under HUD conditions, but the effect size is limited. Table 6 summarizes the *t*-test comparison of vehicle metrics under HUD-position with gain-framed and loss-framed messages.

4.3.2. Lane-Deviation-Related Performance Measures

Gain-Framed vs. Loss-Framed

The one-tailed paired *t*-test indicated that the mean minimum lane deviation after using gain-framed messages was significantly lower than when using loss-framed messages ($p < 0.1$). This result supports that, on average, gain-framed messages reduce freeway lane deviation more effectively than loss-framed messages under HUD conditions.

Table 5. W-test comparison of vehicle metrics under Roadside-position and HUD-position with gain-framed messages.

Metric	V Statistic	<i>p</i> -Value	Estimated Median Diff.	99% CI	Significance
Max Speed	395	0.165	0.578	$[-\infty, +\infty]$	NS
Max Speed SD	422	0.081	0.874	$(-0.84, +\infty)$	$p < 0.1$ *
Min Speed	461	0.022	1.846	$(-0.72, +\infty)$	$p < 0.05$ **
Min Speed SD	421	0.083	0.901	$(-0.72, +\infty)$	$p < 0.1$ *
Average Speed	395	0.165	0.397	$[-\infty, +\infty]$	NS
Average Speed SD	415	0.099	1.187	$(-0.908, +\infty)$	$p < 0.1$ *
Max LD	326	0.544	-0.088	$[-\infty, +\infty]$	NS
Max LD SD	427	0.070	0.063	$(-0.142, +\infty)$	$p < 0.1$ *
Min LD	293	0.265	-0.001	$[-\infty, +\infty]$	NS
Min LD SD	538	0.0006	0.021	$(0.015, +\infty)$	$p < 0.01$ ***
Average LD	331	0.488	-0.022	$[-\infty, +\infty]$	NS
Average LD SD	395	0.165	0.049	$(-0.078, +\infty)$	NS
Max DR	361	0.330	-0.028	$(-0.173, +\infty)$	NS
Max DR SD	518	0.002	0.189	$(0.048, +\infty)$	$p < 0.05$ **
Average Max DR	361	0.330	-0.028	$(-0.173, +\infty)$	NS
Average Max DR SD	518	0.002	0.189	$(0.048, +\infty)$	$p < 0.05$ **

SD: standard deviation; LD: lane deviation; DR: deceleration rate. NS: not significant. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 6. *t*-test comparison of vehicle metrics under HUD-position with gain-framed and loss-framed messages.

Metric	Average Value		<i>p</i> -Value	Significance
	Gain	Loss		
Maximum Speed	69.01	70.45	0.391	NS
Minimum Speed	61.62	61.78	0.411	NS
Average Speed	69.78	67.02	0.473	NS
Maximum Gas Pedal Position	0.59	0.65	0.250	NS
Minimum Gas Pedal Position	0.22	0.19	0.009	$p < 0.01$ ***
Average Gas Pedal Position	0.50	0.46	0.001	$p < 0.01$ ***
Maximum Brake Force	0.45	0.47	0.162	NS
Average Brake Force	0.01	0.02	0.162	NS
Maximum Lane Deviation	2.58	2.33	0.370	NS
Minimum Lane Deviation	0.22	0.09	0.051	$p < 0.1$ *
Average Lane Deviation	1.19	0.41	0.117	NS
Maximum Deceleration	0.35	0.28	0.268	NS
Average Maximum Deceleration	-1.23	-0.99	0.114	NS

NS: not significant. * $p < 0.1$, *** $p < 0.01$.

The Wilcoxon Signed-Rank test indicated that median minimum lane deviations with gain-framed messages were significantly lower compared to those with loss-framed messages ($p < 0.1$). In addition, the median average lane deviations with gain-framed messages were significantly lower than with loss-framed messages ($p < 0.1$). These results suggest that gain-framed messages effectively reduce both the level and variability of freeway lane deviation.

The Wilcoxon Signed-Rank test further indicated that the median standard deviations of minimum lane deviations with gain-framed messages were significantly lower compared to those with loss-framed messages ($p < 0.01$). The median standard deviations of average lane deviations with gain-framed messages were also significantly lower than with loss-framed messages ($p < 0.01$). These findings suggest that gain-framed messages provide more stable lane-keeping performance.

Influence of Driver Demographics on Lane Deviation Behavior

The following section explores the underlying mechanisms from the perspectives of age and gender.

Minimum Lane Deviation

From the perspective of age, drivers younger than 29 years show very small minimum lane deviations under both gain- and loss-framed HUD messages, with medians near zero and extremely narrow boxes, except for a few isolated outliers. This indicates that younger drivers can keep the vehicle very close to the lane center regardless of the framing of the HUD message. In contrast, drivers aged 29 years and older exhibit larger minimum deviations overall, and the gain-framed condition shows a taller box and a longer upper whisker than the loss-framed condition. Thus, older drivers' lane-keeping episodes are farther from the lane center and more variable when exposed to gain-framed HUD messages. Overall, loss-framed messages are slightly more supportive of precise lane centering in the age group older than 29 years.

From the perspective of gender, female drivers exhibit very small minimum lane deviations under both gain- and loss-framed messages. The gain-framed messages show a slightly lower median and a somewhat tighter interquartile range, suggesting that gain-framed messages help female drivers maintain particularly accurate and stable lane centering. Male drivers, however, show a more dispersed pattern: under gain-framed messages, the box and upper whisker are clearly shifted upward, indicating larger and more variable minimum deviations, whereas the loss-framed condition yields minima closer to zero with a narrower spread. This implies that for males, loss-framed messages are relatively more conducive to tight lane centering. Figure 9 depicts minimum lane deviation under HUD positions for gain-framed and loss-framed messages, stratified by age group and gender.

Average Lane Deviation

From the perspective of age, younger drivers show generally lower deviations, with similar medians across gain- and loss-framed HUD messages. The gain-framed condition is only slightly higher, and both the box heights and whisker lengths remain moderate, indicating relatively smooth and stable lateral control for younger drivers under HUD assistance. For drivers aged 29 years and older, average lane deviations shift upward, and the gain-framed condition exhibits a taller box and a longer upper whisker than the loss-framed condition. This pattern suggests that older drivers' lateral trajectories are farther from the lane center and more variable when messages are gain-framed. Overall, loss-framed messages may be more effective in stabilizing overall lane position for older drivers.

From the perspective of gender, female drivers benefit more from gain-framed messages in terms of average lane deviation. For females, the gain-framed box shows a clearly lower median and a slightly tighter spread than the loss-framed box, indicating that gain-framed messages help them keep overall average deviation smaller and more stable. Male drivers exhibit the opposite pattern: under gain-framed messages, they show the highest median average deviation with a taller and wider box and whisker, whereas under loss framing, the median drops and the box becomes markedly narrower. This suggests that loss framing substantially reduces both the level and variability of males' average lane deviation. In summary, female drivers perform better with gain-framed messages, whereas male drivers benefit more from loss-framed messages. Figure 10 depicts average lane deviation under HUD positions for gain-framed and loss-framed messages, stratified by age group and gender.

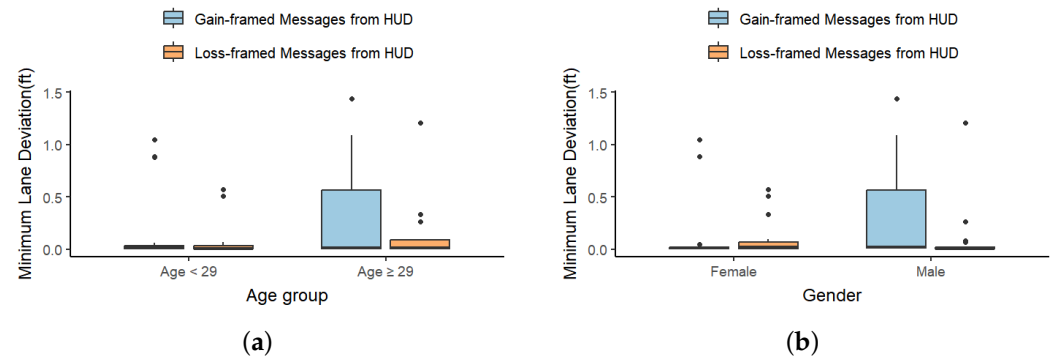


Figure 9. Minimum lane deviation under HUD-position with gain-framed and loss-framed messages: (a) comparisons by age group and (b) comparisons by gender.

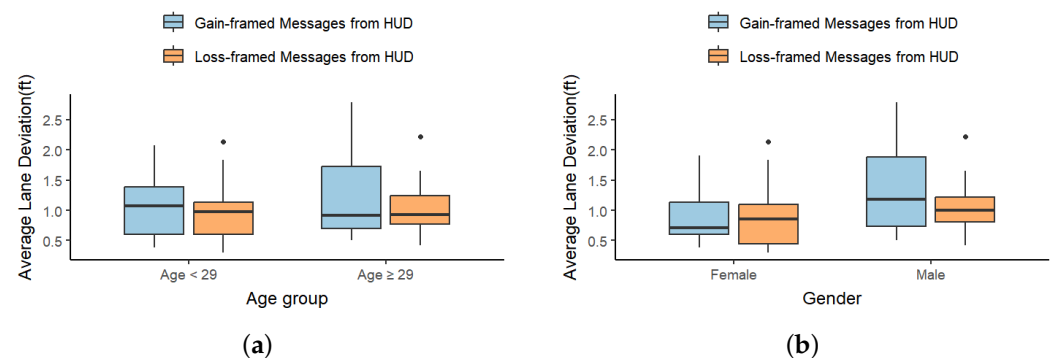


Figure 10. Average lane deviation under HUD-position with gain-framed and loss-framed messages: (a) comparisons by age group and (b) comparisons by gender.

4.3.3. Deceleration-Related Performance Measures

Gain-Framed vs. Loss-Framed

The Wilcoxon Signed-Rank test indicated that the median maximum deceleration rate after implementing gain-framed messages was significantly lower compared to that under loss-framed messages ($p < 0.05$). In addition, the median average maximum deceleration rate with gain-framed messages was significantly lower than with loss-framed messages ($p < 0.05$). These results suggest that gain-framed messages effectively reduce freeway maximum deceleration rate and produce milder peak braking than loss-framed messages. Table 7 summarizes the W-test comparison of vehicle metrics under HUD-position with gain-framed and loss-framed messages.

Influence of Driver Demographics on Deceleration Behavior

The following section explores the underlying mechanisms from the perspectives of age and gender.

Maximum Deceleration Rate

From the perspective of age, among drivers younger than 29 years, the loss-framed messages box is shifted upward relative to the gain-framed messages box, with a clearly less negative median. This suggests that younger drivers' hardest braking maneuvers are generally softer under loss-framed messages. For drivers aged 29 years and older, the same tendency is observed: the loss-framed messages median is slightly closer to zero than the gain-framed messages median, although both medians are more negative than those of younger drivers, indicating overall harsher maximum braking in this age group. In summary, loss-framed messages reduce maximum deceleration compared with

gain-framed HUD messages across both age groups, with a more pronounced effect among younger drivers.

Table 7. W-test comparison of vehicle metrics under HUD-position with gain-framed and loss-framed messages.

Metric	V Statistic	<i>p</i> -Value	Estimated Median Diff.	99% CI	Significance
Max Speed	284	0.221	0.023	$[-\infty, +\infty]$	NS
Max Speed SD	301	0.308	−0.728	$(-2.066, +\infty)$	NS
Min Speed	348	0.407	0.045	$[-\infty, +\infty]$	NS
Min Speed SD	342	0.444	0.220	$[-\infty, +\infty]$	NS
Average Speed	349	0.401	0.463	$[-\infty, +\infty]$	NS
Average Speed SD	306	0.336	−0.686	$(-1.311, +\infty)$	NS
Max LD	307	0.342	−0.116	$[-\infty, +\infty]$	NS
Max LD SD	347	0.413	−0.003	$(-0.276, +\infty)$	NS
Min LD	240	0.072	−0.004	$[-\infty, +\infty]$	$p < 0.1^*$
Min LD SD	62	0.00001	−0.129	$[-\infty, +\infty]$	$p < 0.01^{***}$
Average LD	239	0.070	−0.119	$[-\infty, +\infty]$	$p < 0.1^*$
Average LD SD	168	0.005	−0.144	$[-\infty, +\infty]$	$p < 0.01^{***}$
Max DR	443	0.042	0.310	$(-0.102, +\infty)$	$p < 0.05^{**}$
Max DR SD	289	0.756	−0.075	$(-0.225, +\infty)$	NS
Average Max DR	427	0.033	0.310	$(-0.097, +\infty)$	$p < 0.05^{**}$
Average Max DR SD	296	0.720	−0.078	$(-0.208, +\infty)$	NS

SD: standard deviation LD: lane deviation DR: deceleration rate. NS: not significant. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

From the perspective of gender, female drivers show a clear benefit from loss-framed messages. The loss-framed messages box lies above the gain-framed messages box, and its median is distinctly closer to zero while the interquartile ranges are of similar width. This indicates that females brake less harshly at their maximum deceleration under loss-framed messages. Male drivers exhibit the same directional pattern: the loss-framed messages median is less negative and the box is slightly shifted toward zero compared with gain-framed messages, but the magnitude of this shift is smaller than that observed for females. In summary, loss-framed messages soften maximum braking for both genders, with a stronger reduction in peak deceleration among female drivers and a more moderate effect among males. Figure 11 depicts maximum deceleration rate under HUD positions for gain-framed and loss-framed messages, stratified by age group and gender.

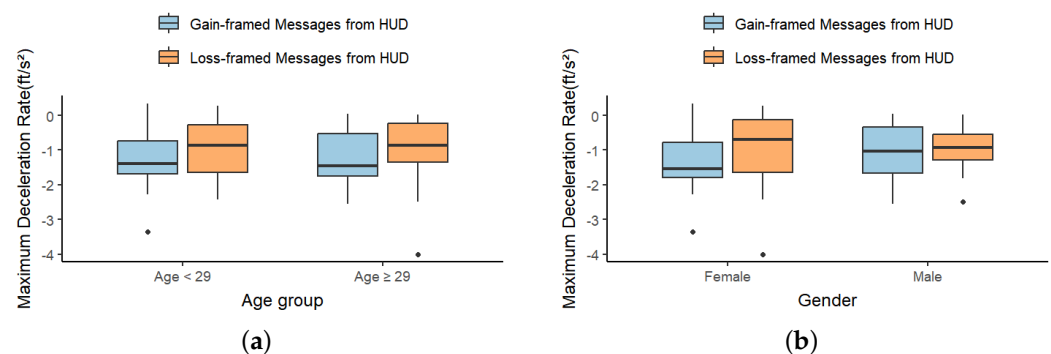
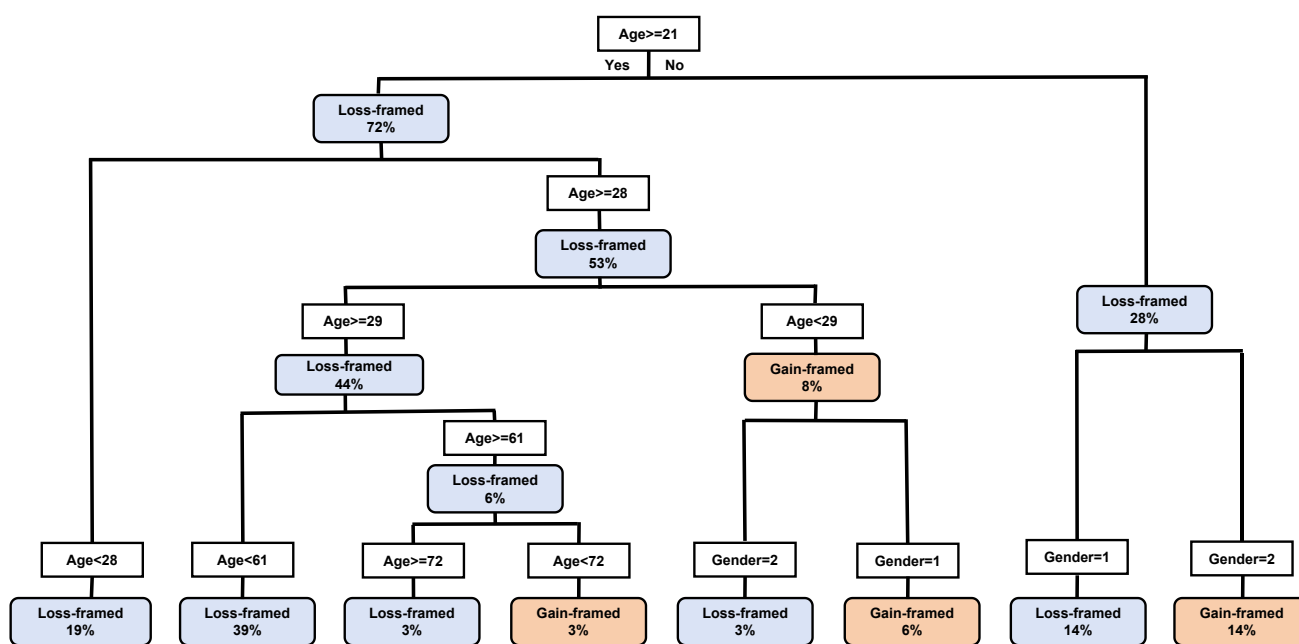


Figure 11. Maximum deceleration rate under HUD-position with gain-framed and loss-framed messages: (a) comparisons by age group and (b) comparisons by gender.

4.3.4. Decision Tree Analysis

The decision tree model based on age and gender for HUD-position suggests predicting the more effective framing condition (gain vs loss) with respect to minimum lane deviation is illustrated in Figure 12. In this model, the outcome variable *Target* is coded as 1 if gain-framed messages are more effective and 0 if loss-framed messages are more effective in reducing minimum lane deviation. The accuracy of cross-validation was 73.3%. Given the relatively small sample size and the fine-grained splits, the resulting subgroup classifications were framed as hypothesis-generating rather than prescriptive. Therefore, the CART-based subgroup analysis is exploratory in nature, and the identified age- and gender-specific patterns are interpreted with caution and considered hypothesis-generating.



The accuracy of cross-validation was 73.3%.

Figure 12. Decision tree of minimum lane deviation under HUD-position displays for gain-framed and loss-framed messages stratified by age and gender.

According to the decision tree, loss-framed messages are predicted to be more effective for several age- and gender-specific segments. Drivers aged 21–27 years and 29–60 years are generally classified into the loss-framed class regardless of gender. In the older population, drivers aged 72 years and above also tend to benefit more from loss-framed warnings. The model further identifies 28-year-old female drivers and male drivers younger than 21 years as additional subgroups for which loss-framed messages are preferable.

By contrast, gain-framed messages are predicted to be more effective for a smaller but clearly defined set of groups. In the older branch, drivers aged 61–71 years are classified as responding better to gain-framed messages, independent of gender. Around the 28-year threshold, 28-year-old male drivers are assigned to the gain-framed class. Among younger participants, female drivers younger than 21 years are also classified as more responsive to gain-framed messages.

Overall, the decision tree highlights that the relative effectiveness of gain-framed versus loss-framed messages is not uniform across the population and is strongly shaped by age and gender. These results underscore the potential value of tailoring in-vehicle message framing to specific driver segments to maximize safety benefits.

4.3.5. Summary

This subsection conducts a comprehensive comparison between gain- and loss-framed messages under HUD conditions, integrating speed, lane deviation, and deceleration metrics with demographic analyses and decision tree modeling. Key findings reveal a clear trade-off: gain-framed messages excel in lane-keeping stability, significantly reducing minimum and average lane deviation ($p < 0.1$) and their variability ($p < 0.01$), with female drivers showing the strongest benefits; conversely, loss-framed messages outperform in deceleration control, significantly reducing maximum and average maximum deceleration rates ($p < 0.05$) for all demographics, especially females and younger drivers. Decision tree analysis (73.3% cross-validation accuracy) further segments driver populations: loss-framed messages are more effective for younger drivers (21–27, 29–60 years), seniors (72+), and specific subgroups (e.g., 28-year-old females), while gain-framed messages benefit older adults (61–71 years), 28-year-old males, and females under 21. These results address the core challenge of “optimizing message framing for specific driving behaviors and demographics,” demonstrating that gain-framed messages enhance lateral stability, whereas loss-framed messages improve braking smoothness, with effectiveness contingent on age-gender profiles.

5. Conclusions

This study evaluated a Freeway-Centered Dynamic Speed Warning System (F-DSWS) that integrates Connected Vehicle technology with in-vehicle head-up display (HUD) interfaces, and examined how message framing shapes driver responses. Overall, the results demonstrate that delivering real-time, context-aware speed information directly through HUD warnings provides measurable safety benefits compared with conventional roadside warning signs. Across multiple indicators, HUD-based alerts improved driving behavior, and gain-framed messages—emphasizing positive, socially relevant outcomes such as family safety—consistently outperformed loss-framed messages. Specifically, gain framing was associated with lower maximum and average speeds, reduced lane-deviation extremes, and smoother deceleration patterns, suggesting that positive reinforcement can enhance compliance and promote more stable longitudinal and lateral control in dynamic in-vehicle traffic messaging.

Despite these promising findings, several limitations should be acknowledged and motivate future work. First, although the participant pool covered a broad age range, the oldest group (51–79 years) included only four drivers, which is insufficient for drawing reliable inferences about senior-driver responses; future studies should prioritize targeted recruitment and additional data collection among older adults to enable age-stratified analyses. Second, the simulator scenarios were intentionally “sterile”—with no surrounding traffic, consistently good visibility, and without adverse conditions such as night-time driving, rain, fog, or poor lighting—thereby limiting generalizability to complex real-world environments; subsequent experiments should systematically vary traffic density and environmental stressors (e.g., low illumination, weather degradation, and high-demand freeway situations). To strengthen external validity and practical deployment guidance, future research should conduct on-road field studies and naturalistic evaluations, while extending the current rule-based F-DSWS toward more adaptive and personalized warning strategies that account for driver state and contextual complexity, and explicitly evaluate safety–usability trade-offs (e.g., distraction, workload) under high traffic volumes and challenging visibility conditions. In addition, the study design may be subject to potential order effects. The gain- and loss-framed conditions were not randomized or counterbalanced due to system limitation, which may introduce sequence-related bias. Future research should randomize or counterbalance message framing conditions to more rigorously iso-

late framing effects. Last but not least, although in-vehicle warning messages have the potential to improve driving safety, they may also divert drivers' attention and introduce unintended distraction [44]. Future research should therefore focus on optimizing HUD design to maximize safety benefits while simultaneously minimizing driver distraction. Finally, given that the results are derived from a controlled driving simulator experiment, the claims regarding real-world effectiveness and policy implications are more cautiously. The results are exploratory and need a further field validation.

Author Contributions: Conceptualization, Y.W. and S.W.; methodology, Y.W. and S.W.; software, Y.L.; validation, Y.L. and S.W.; formal analysis, Y.L. and S.W.; investigation, Y.L. and S.W.; resources, Y.W.; data curation, Y.L. and S.W.; writing—original draft preparation, Y.L. and S.W.; writing—review and editing, Y.W., Z.L., and S.Z.; visualization, Y.L.; supervision, Y.W.; project administration, Y.W.; funding acquisition, Y.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Arts and Sciences Research and Creative Activities Grant Award at the University of Louisville. The paper reflects the authors' viewpoints only.

Institutional Review Board Statement: Approval of all ethical and experimental procedures and protocols was granted by the Human Subjects Research and Institutional Review Board at the University of Louisville on 10 January 2019.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding authors.

Acknowledgments: The authors would like to thank all drivers who participated in the driving simulator experiment.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

HUD	Heads-up Display
CV	Connected Vehicle
F-DSWS	Freeway-centered Dynamic Speed Warning System
RSC	Roadside Controller
CART	Classification and Regression Tree
SD	Standard Deviation
LD	Lane Deviation
DR	Deceleration Rate
CI	Confidence Interval
NS	Not Significant

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