Research Article

Study on the Influence of Connected Vehicle Fog Warning Systems on Driving Behavior and Safety

Wei Guan,1 Haolin Chen,2 Xuewei Li,2 Haijian Li,3 and Xin You4

1Beijing Sutong Technology Co. Ltd., Beijing 100161, China
2Beijing Key Laboratory of Traffic Engineering, College of Metropolitan Transportation, Beijing University of Technology, Beijing 100124, China
3Beijing Engineering Research Center of Urban Transport Operation Guarantee, College of Metropolitan Transportation, Beijing University of Technology, Beijing 100124, China
4Beijing Eroadshine Technology Co. Ltd., Beijing 100073, China

Correspondence should be addressed to Haijian Li; lihaijian@bjut.edu.cn

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Driving speeds are higher on freeways, and the visibility reduction occurring in freeway fog zones often increases traffic accidents. This study aims at assessing the impact of different levels of connected vehicle fog warning systems on driving behavior and safety. A connected vehicle fog warning system is developed based on driving simulators, and virtual scenes are developed based on fog zones. The connected vehicle technology includes three levels: a normal level, a level including a human-machine interface, and a level with both a human-machine interface and dynamic message signs. Speed and lateral deviation are chosen as assessment indicators and combined with sample entropy to evaluate the impact of the connected vehicle fog warning system on safety. The deceleration ratio of the warning point is used to evaluate the efficiency of the connected vehicle fog warning system. Results show that the connected vehicle fog warning system can significantly reduce driving speed, and that there are differences in the speed-reduction effectiveness for different technical levels. The connected vehicle fog warning system can reduce the lateral deviation and improve the lateral driving safety. From the perspective of change stability, speed safety entropy and lateral deviation safety entropy are increased, which indicates that the connected vehicle fog warning system will negatively impact safety because of the additional workload. Drivers’ responses are more pronounced in the human-machine interface group compared to the group with dynamic message signs, where the drivers maintained a lower speed. This study provides a reference for the studies on connected vehicle technology based on driving simulators and supports the optimization, design, and evaluation of connected vehicle fog warning systems.

1. Introduction

The likelihood of traffic accidents significantly increases under adverse weather conditions. Specifically, in foggy zones, drivers cannot accurately judge surrounding traffic conditions due to limited visibility, which increases the risks of driving [1]. Advanced driver assistance systems (ADAS) can reduce human error by providing surrounding information to the driver [2]. With the development of intelligent transportation, fog zone warning systems based on connected vehicle technology provide new opportunities to improve driving safety in fog zones [3].

Connected vehicle technology has proven its ability to substantially improve traffic safety [4–7]. It mainly consists of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, which carry out active vehicle safety control and road collaboration management based on the collection and fusion of dynamic traffic information, in full time and space. The technical optimization of V2V and V2I has been widely studied [8, 9] and demonstrated to significantly improve the safety, efficiency, and ecology of transportation systems [10–13]. According to the National Highway Traffic Safety Administration (NHTSA), V2V and V2I warning systems can reduce traffic accidents by about
Based on the meta-analysis method, Xiao et al. [7] found that the anticipated reduction in the number of fatal crashes would be 5% in 2025 and 13% in 2035, with the increase in the market penetration rate of connected vehicles. V2I and V2V warning systems mainly interact with drivers through Dynamic Message Signs (DMS) and a Human-Machine Interface (HMI).

Many researchers have studied the efficiency of DMS and HMI in fog zones. In terms of DMS, Zhao et al. [15] collect driving behavior data under DMS through fog zone driving simulation experiments. The results indicate that DMS is beneficial in reducing the speed before drivers enter a heavy fog zone. DMS also reduces the tension of drivers entering a heavy fog zone and helps them operate the vehicles more smoothly. Wu et al. [16] show that DMS can affect drivers’ brake reaction at the beginning of the reduced visibility area. Sui and Young [17] analyze the existing DMS implemented by the Wyoming Department of Transportation (WYDOT), finding that DMS message signs are effective at reducing drivers’ speeds along rural interstate corridors from 8 to 32 km/h. A technology acceptance model (TAM) is developed to evaluate the drivers’ acceptance of connected vehicle technology, with results showing that drivers’ acceptance of on-road DMS is significantly higher than that of on-board devices [18]. In terms of HMI, Zhao et al. [19] evaluate the compliance level of fog warning systems, concluding that HMI can efficiently reduce driving speed and improve speed-limit adherence. When the fog concentration increases, the compliance level of fog warning systems with only HMI is higher than others. Based on a driving simulator, Zhao et al. [20] show that drivers reduce their driving speeds after receiving the HMI warning information. Under adverse weather conditions, the participants state that the HMI provides them with improved road condition information and increases their feeling of safety while driving [21]. Studies have found that the HMI does not introduce significant distraction from the main driving task, but it tends to introduce an additional visual workload [22, 23]. These studies indicate that connected vehicle technology has a positive impact on driving safety in fog zones, and it contributes to understanding the efficiency and influence mechanisms of DMS and HMI on driving behavior and safety. It remains necessary to explore the combination of HMI and DMS in fog zones to further improve driving behavior and safety.

The driving simulator has become the most used test tool for the study of connected vehicle technology because of its real-time data acquisition, controllable events and driving trajectory, and human-machine dual-in-loop capabilities [24]. Driving simulators have proven to be effective tools for connected vehicle technology and driving behavior analysis [25–27]. They are widely used for studying the effect of connected vehicle technology on driving behavior in fog zones, such as the response behavior of drivers [24] and the impact on vehicle operating eco-characteristics [28]. Moreover, a test platform that can realize real-time data exchange between driving simulators and external terminals through a User Datagram Protocol (UDP) and deliver real-time messages to drivers through the HMI is developed based on the driving simulator [29]. Due to these attributes, the driving simulator is selected as an experimental tool in this study.

To summarize, it is particularly important to study the combined form of HMI and DMS using a driving simulator and demonstrate its effect on driving behavior and safety in fog zones. In this study, a test platform for a connected vehicle fog warning system and a virtual scene of dense fog are developed based on driving simulators, to explore the influence of three different combinations of connected vehicle fog warning systems (normal, HMI, and HMI & DMS) on driving behavior and safety. This study can offer guidance for the design of a connected vehicle fog warning system and provide a platform development and case study reference for future studies on connected vehicle technology.

2. Research Method

2.1. Test Platform Development of Connected Vehicle Technology

The connected vehicle technology test platform is developed based on the AutoSimAS driving simulator at Beijing University of Technology. The system structure is shown in Figure 1.

The test platform includes four parts: (i) a driving simulation system, (ii) a V2V terminal: HMI, (iii) a Sensor Motoric Instruments Eye Tracking Glasses 2 Wireless (SMI ETG2w) eye-tracking system, and (iv) a data collaborative processing center. The apparatus adopts the AutoSimAS driving simulator of Beijing University of Technology. The driving simulator consists of four parts: a real vehicle, a central control equipment, an audio-visual system, and a projection device. The road scenario is projected onto three big screens, providing a 130-degree view field. The screen resolution of the driving simulator is 1920 × 1080, and the driving simulator records the vehicle operating data (e.g., acceleration, speed, and lateral placement) at the rate of 1–60 times per second. The key connection technologies include (1) the application program interface (API), which adds the simulator script language to create the different roads, weather, and traffic conditions in the experimental scenario; (2) the user data protocol (UDP) interface, which realizes data interaction between the control center and the data collaborative processing center; (3) wireless communication technology (Wi-Fi), which enables data communication between the computer and the HMI (V2V terminal) to realize the interconnection between the vehicle and driver.

In this study, HMI and DMS are used to deliver information from the connected vehicle fog warning system, and the warning information is received from the data collaborative processing center. The design and functions of the HMI (Figure 2) and DMS (Figure 3) are described in the sequel.

A Huawei MediaPad M3 tablet is developed as an HMI, which sends speed limits, road traffic conditions, and warnings in the form of voice, text, and images. The HMI consists of four parts as follows:

Part 1. Text Warning Prompt Module: if the distance between the vehicle and the front vehicle is more than 200 m, the module displays “>200 m”; otherwise, the real-time distance is displayed.
Part 2. Variable Speed Limit Control Module: if the system detects that the driver is speeding up, then it triggers a voice prompt.

Part 3. Warning Module: if the time to collision (TTC) is less than the threshold value [30], then the warning sign and prompt of a red triangle exclamation mark appear. If the vehicle is in transition or fog zones, then the warning sign of a yellow triangle mark is continuously displayed.

Part 4. Traffic Environment Module: a green arrow mark is displayed if the distance between the vehicle and the surrounding vehicles exceeds 200 m; otherwise, a yellow arrow appears. A red arrow appears if the TTC is less than the threshold value.

In this study, four sets of DMS are set in the fog zone, with an interval of 500 m (according to the rule of providing navigation prompts every 500 m). The location of the DMS is shown in Figure 4. Under normal conditions (no fog), the DMS displays “welcome to freeway” (green font); under warning conditions (foggy weather), the DMS shows the fog level and distance from the fog zone (yellow font).

2.2. Experimental Design

2.2.1. Scenario Design of Fog Zone. A freeway fog zone is chosen as the experimental scenario to explore the effect of different connected vehicle fog warning systems (normal, HMI, and HMI & DMS) on driving behavior and safety. The fog zone scenario is shown in Figure 4.

1) Road Condition. The length of the study section is 5500 m, which is divided into three parts: a speed-up zone (1500 m), a warning zone (2000 m), and a fog zone (2000 m). The cross section of the road is 26 m (four lanes with lane width = 3.75 m, median width = 2 m, and shoulder width = 4.5 m). The speed limit is 120 km/h in the speed-up and warning zones and 60 km/h in the fog zone.

2) Traffic Flow State. The traffic flow is set as free flow with an average headway of 36 s. The average speed of the other vehicles is 100 km/h in the speed-up and warning zones and 55 km/h in the fog zone.

3) Visibility. According to the “Grade of fog forecast (GBT 27964-2011)” standard [31], visibility is more than 10,000 m in a clear state (speed-up and warning zones) and 125 m in a dense fog state (fog zone). In the transition zone (500 m) designed as part of the fog zone, the visibility is gradually reduced, promoting the adaptability of drivers and the authenticity of the scenario experience.

4) Connected Vehicle Fog Warning Systems. The fog warning system sends warning information to the driver through the HMI and DMS. The combination of warning systems is divided into three levels (normal, HMI, and HMI & DMS). The corresponding warning information is prompted when the vehicle passes the warning position (Figure 4).

2.2.2. Participants. The driving simulation experiment consists of 43 drivers from a group of designated drivers and college students. The drivers’ information is listed in Table 1. Referring to the method that determines the required sample size of drivers [24], the number of drivers in this study is more than 32, which meets the sample size requirements.
2.2.3. Experimental Procedure. The experimental steps are listed in Table 2.

2.3. Data Preprocessing, Indicator Selection, and Analytical Method

2.3.1. Data Preprocessing. This study analyzes the impact of different levels of connected vehicle technology on driving behavior and safety in fog zones. The speed-up zone is set to ensure that drivers have reached a stable driving state before entering the warning zone. The data collection range in the whole zone starts at 200 m before DMS1 and finishes at the end of the fog zone (from point A to point H in Figure 4). Data are collected from 43 drivers in three scenarios (normal, HMI, and HMI & DMS), resulting in 129 records.

2.3.2. Indicator Selection. Safe driving is the primary objective in adverse weather conditions. Thus, indicators based on the safety and efficiency of the connected vehicle fog warning system are selected, and safety entropy is introduced as an index to further quantify driving safety:

(1) **Speed** ($V$, km/h). Speed is the most intuitive indicator to reflect the driving state on the road. A lower driving speed means a higher level of safety that a driver is in.

(2) **Lateral Deviation** ($L_d$, m). The lateral deviation is the distance between the vehicle’s central axis and the
Driving Practice. Drivers practice using the driving simulator for 4–5 minutes to enhance their proficiency using the driving simulator and connected vehicle environment.

Formal Experiments. When participating in the experiment, the drivers are not disturbed by external factors, and driving information is obtained through HMI prompts and observation. To prevent fatigue, drivers are required to take a break for 5–10 min after each scenario, and the driving time does not exceed 25 min for any scenario.

End of the Experiment. Participants fill in the subjective questionnaire and receive a financial reward of 200 Chinese Yuan (about 31.68 US dollars).

### Table 1: Drivers’ information.

<table>
<thead>
<tr>
<th>Gender</th>
<th>Numbers/ratio</th>
<th>Average age M/SD</th>
<th>Average driving age M/SD</th>
<th>Average driving mileage M/SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>28/65%</td>
<td>37.5/13.1</td>
<td>16/10.2</td>
<td>18,524/3548.22</td>
</tr>
<tr>
<td>Female</td>
<td>15/35%</td>
<td>25.0/12.97</td>
<td>13/9.3</td>
<td>9584/5514.21</td>
</tr>
</tbody>
</table>

Note: M, mean; SD, standard deviation. Average age and average driving age are provided in years; average driving mileage is provided in km per year.

### Table 2: Experimental steps.

<table>
<thead>
<tr>
<th>Step</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Participants fill out personal information and subjective physiological questionnaires.</td>
</tr>
<tr>
<td>2</td>
<td>Pretesting is performed using three drivers to locate and solve any problems.</td>
</tr>
<tr>
<td>3</td>
<td>Driving Practice. Drivers practice using the driving simulator for 4–5 minutes to enhance their proficiency using the driving simulator and connected vehicle environment.</td>
</tr>
<tr>
<td>4</td>
<td>Formal Experiments. When participating in the experiment, the drivers are not disturbed by external factors, and driving information is obtained through HMI prompts and observation. The drivers randomly finish experimental scenarios. To prevent fatigue, drivers are required to take a break for 5–10 min after each scenario, and the driving time does not exceed 25 min for any scenario.</td>
</tr>
<tr>
<td>5</td>
<td>End of the Experiment. Participants fill in the subjective questionnaire and receive a financial reward of 200 Chinese Yuan (about 31.68 US dollars).</td>
</tr>
</tbody>
</table>

(3) Speed Safety Entropy and Lateral Deviation Safety Entropy. The speed safety entropy and the lateral deviation safety entropy are derived by calculating safety-related indices using the sample entropy method. The lower the safety entropy is, the higher the safety will be. The MATLAB programming is used to calculate sample entropy as follows:

1. Let the original data be $x(1)$ and $x(2)$, for a total of $N$ numbers.
2. Make up the $m$ vector, and subtract every two vectors:
   \[
   X(i) = [x(i), x(i+1), \ldots, x(i+m-1)];
   \]
   \[i = 1, 2, \ldots, N - m + 1, \ldots,\]
   where $m$ is the embedded dimension and $N$ represents the data length. In general, $m$ is taken as 1 or 2. When $m > 2$, the sample demand increases greatly. In this study, $m$ is chosen to be 2, and the value of $N$ is within the range of 100–5000, chosen as 1000.
3. Define the distance $d_{x(i), x(j)}$ between the vectors $x(i)$ and $x(j)$:
   \[
   d_{x(i), x(j)} = \max|x(i+k) - x(j+k)|, k = 0, 1, 2, \ldots, m + 1, \]
   where $d_{x(i), x(j)}$ is the maximum distance parameters of the difference between elements $x(i)$ and $x(j)$.
4. The parameter $m$ can be obtained by equations (3) and (4):
   \[
   B_{mn}(r) = \frac{\text{Num}[d_{x(i), x(j)} < r]}{N - m + 1}, \quad (3)
   \]
   \[
   B_m(r) = \frac{1}{N - m + 1} \sum_{i=1}^{N-m+1} B_{mn}(r), \quad (4)
   \]
   where $B_{mn}(r)$ is the ratio of the number of times that $d_{x(i), x(j)}$ is less than $r$ and the total number of distances $N - m + 1$. $r$ is the tolerance error of similarity, and the value of $r$ is generally expressed as follows:
   \[
   r = 0.1 \sim 0.25E, \quad (5)
   \]
   where $E$ is the variance of the original data, $0.1e$ or $0.25e$. In this study, $r = 0.25e$ is selected.
5. Add 1 to the parameter dimension and repeat the above steps to get $B_{m+1}(r)$, when $n < \infty$ (equation (6)):
   \[
   S(m, r, N) = -\ln \left( \frac{B_{m+1}(r)}{B_m(r)} \right), \quad (6)
   \]
   where $S(m, r, N)$ expresses sample entropy.

(4) Deceleration Ratio of Warning Point (%).

A driver is considered decelerating if the driving speed keeps decreasing within 50 m before and after the warning point. The deceleration ratio of warning point represents the percentage of decelerating drivers, which can evaluate the drivers’ response to fog warning information prompts. A higher deceleration ratio indicates a higher compliance level of the fog warning system.

2.3.3. Analytical Method. After testing normality and homogeneity of variance, the test method is selected according to the data characteristics. Within the same group, the one-way ANOVA method is used for the speed and lateral deviation comparison, while the Friedman test is selected for comparing the speed safety entropy and the lateral deviation safety entropy.

### 3. Results

This section explores the effect of the connected vehicle fog warning system (normal, HMI, and HMI & DMS) in terms of safety and efficiency.
3.1. Safety Analysis. Statistical characteristics and changing trends of speed and lateral deviation under different connected vehicle fog warning systems are respectively shown in Table 3 and Figure 5.

It can be seen from Table 3 that in the whole zone and segmented zones, the technical level of the connected vehicle fog warning system is statistically different from the speed \( (p \leq 0.001) \). It can also be observed that the normal group and the HMI group on one hand, and the normal group and the HMI&DMS group on the other hand, have intergroup significance, which further proves that the connected vehicle fog warning system significantly affects speed. Furthermore, the normal group has the highest speed in all zones, indicating that the connected vehicle fog warning system can constructively reduce the vehicle’s speed, thus improving the driving safety in adverse weather conditions. In the clear zone (A–F), the speed of the HMI & DMS group is lower than that of the HMI group \( (p = 0.018) \), which indicates the deceleration effect of the HMI&DMS group is better. Upon entering the dense fog zone (G–H), the deviation of the HMI&DMS group is significantly higher than that of the HMI group \( (p = 0.001) \). Therefore, it is inferred that the warning information must be given continuously in adverse weather conditions for a more efficient connected vehicle fog warning system. Figure 5(a) shows that speed fluctuations in the normal group are significantly higher than those in the HMI and HMI & DMS groups. The connected vehicle fog warning system has spatial significance for speed in the clear and transition zones. In the transition zone, the three groups of vehicles all exhibit obvious deceleration. The normal group’s deceleration is faster, which shows that the connected vehicle fog warning system improves the driver’s predicting ability and enables a better response to adverse weather conditions, such as fog.

The technical level of the connected vehicle fog warning system is statistically different from the lateral deviation \( (p = 0.016) \) throughout the whole zone. The normal group has the largest lateral deviation, while the HMI & DMS group has the smallest one. This shows that the connected vehicle fog warning system can significantly improve the lateral deviation of the vehicle under adverse weather conditions, and the lateral safety is improved. The lateral deviation is not significant in the clear (A–F) and dense (G–H) fog zones. In the transition zone (F–G), the lateral deviation is significant \( (p \leq 0.001) \), and the lateral deviation is significant between groups, considering the normal and HMI groups on one side, and normal and HMI & DMS groups on the other side, which indicates that the connected vehicle fog warning system has a considerable impact on the lateral deviation when the connected vehicle enters the fog zone. The lateral deviation of the normal, HMI, and HMI & DMS groups gradually decreases, indicating that a higher level of connected vehicle fog warning system better improves driving safety. After the vehicle enters the dense fog zone (G–H), the deviation between the HMI & DMS group and the HMI group becomes insignificant, which further proves the importance of continuous warning information. In Figure 5(b), the lateral deviation fluctuation of the normal group is higher than that of the HMI and HMI & DMS groups. In the clear zone, the lateral deviation is spatially significant when the vehicle passes through the HMI and DMS warning points. In conclusion, the connected vehicle fog warning system can improve lateral stability under adverse weather conditions, and the continuous provision of warning information is an important factor for improved driving safety.

Figure 6 shows speed safety entropy in clear (A–F, \( p = 0.001 \)) and fog (F–H, \( p = 0.049 \)) zones. It can be noticed

### Table 3: Statistical analysis of index under fog zone.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Levels</th>
<th>Speed (km/h)</th>
<th>Difference between groups, ( p ) value</th>
<th>Lateral deviation (m)</th>
<th>Difference between groups, ( p ) value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean (SD)</td>
<td>( p ) value</td>
<td>Mean (SD)</td>
<td>( p ) value</td>
</tr>
<tr>
<td>Whole zone (A–H)</td>
<td>Normal</td>
<td>88.954 (19.571)</td>
<td>( p \leq 0.001 )</td>
<td>1.741 (0.127)</td>
<td>( p \leq 0.001 )</td>
</tr>
<tr>
<td></td>
<td>HMI</td>
<td>82.068 (17.443)</td>
<td>( p \leq 0.001 )</td>
<td>1.729 (0.094)</td>
<td>( p \leq 0.001 )</td>
</tr>
<tr>
<td></td>
<td>HMI&amp;DMS</td>
<td>82.393 (18.010)</td>
<td>( p \leq 0.001 )</td>
<td>1.711 (0.093)</td>
<td>( p \leq 0.001 )</td>
</tr>
<tr>
<td>Clear zone (A–F)</td>
<td>Normal</td>
<td>100.592 (0.894)</td>
<td>( p \leq 0.001 )</td>
<td>1.711 (0.159)</td>
<td>( p \leq 0.001 )</td>
</tr>
<tr>
<td></td>
<td>HMI</td>
<td>106.421 (9.588)</td>
<td>( p \leq 0.001 )</td>
<td>1.711 (0.081)</td>
<td>( p \leq 0.001 )</td>
</tr>
<tr>
<td></td>
<td>HMI&amp;DMS</td>
<td>98.481 (2.752)</td>
<td>( p \leq 0.001 )</td>
<td>1.683 (0.116)</td>
<td>( p \leq 0.001 )</td>
</tr>
<tr>
<td>Transition zone (F–G)</td>
<td>Normal</td>
<td>92.157 (6.710)</td>
<td>( p \leq 0.001 )</td>
<td>1.769 (0.048)</td>
<td>( p \leq 0.001 )</td>
</tr>
<tr>
<td></td>
<td>HMI</td>
<td>94.319 (7.586)</td>
<td>( p \leq 0.001 )</td>
<td>1.675 (0.109)</td>
<td>( p \leq 0.001 )</td>
</tr>
<tr>
<td></td>
<td>HMI&amp;DMS</td>
<td>70.433 (4.346)</td>
<td>( p \leq 0.001 )</td>
<td>1.777 (0.064)</td>
<td>( p \leq 0.001 )</td>
</tr>
<tr>
<td>Dense fog zone (G–H)</td>
<td>Normal</td>
<td>64.767 (2.527)</td>
<td>( p \leq 0.001 )</td>
<td>1.777 (0.091)</td>
<td>( p \leq 0.001 )</td>
</tr>
<tr>
<td></td>
<td>HMI</td>
<td>66.643 (4.204)</td>
<td>( p \leq 0.001 )</td>
<td>1.775 (0.069)</td>
<td>( p \leq 0.001 )</td>
</tr>
<tr>
<td></td>
<td>HMI&amp;DMS</td>
<td>70.433 (4.346)</td>
<td>( p \leq 0.001 )</td>
<td>1.777 (0.091)</td>
<td>( p \leq 0.001 )</td>
</tr>
</tbody>
</table>

*Significant values at 95% confidence level.
that in both zones, the technical level of the connected vehicle fog warning system is significant to the speed safety entropy. In the clear zone, the normal group and the HMI group ($p = 0.002$) have intergroup significance, as well as the normal group and the HMI & DMS group ($p \leq 0.001$), while the speed safety entropy for the normal group is the lowest. This shows that the connected vehicle fog warning system has an adverse effect on the speed safety entropy in the clear zone. As the technical level rises, the value and fluctuations of the speed safety entropy also increase. In the fog zone, the HMI group has the highest speed safety entropy, which is significant compared to the normal group ($p = 0.031$) and the HMI & DMS group ($p = 0.049$). It is therefore inferred that the safety is reduced because the HMI and DMS create driver interference. Consequently, the design and delivery method of the connected vehicle fog warning system need to be further studied.

In Figure 7, it can be observed that the technical level of the connected vehicle fog warning system in the clear (A–F) and fog (F–H) zones has no significant impact on the lateral deviation safety entropy, and the abnormal values of the HMI group and HMI&DMS group are larger than those of the normal group. This implies that the connected vehicle fog warning system will have a negative impact on safety in terms of drivers’ change stability.

3.2. Effectiveness Analysis. Figure 8 shows that at the warning point, the deceleration ratios of the HMI and HMI & DMS groups are higher than that of the normal group, thus indicating that driving safety is improved under adverse weather conditions. Furthermore, the deceleration ratio of the HMI group (51.85%) is higher than that of the HMI & DMS group (27.78%) at point 1, while the opposite is observed at points 2 (47.06% < 50.00%) and 3 (39.29% < 46.43%). This implies that the initial deceleration effect of the HMI group is the best, and the deceleration effect of the HMI & DMS is lagging. At points 4 and 5, the deceleration ratio of the HMI group is higher than that of the HMI & DMS group. However, the deceleration ratio in the HMI group shows an increasing trend, while the HMI & DMS
group has a decreasing trend. Therefore, it can be concluded that the continuous deceleration effect of the HMI group is better than that of the HMI & DMS group. Additionally, the HMI group has a higher speed than the HMI & DMS group in the clear zone (points 1–5). The results also show that the drivers’ responses are more pronounced in the HMI group, while they remain at lower speeds in the HMI & DMS group. There is no statistical difference \( (p = 0.645) \) in the deceleration ratio between the normal, HMI, and HMI & DMS groups. In summary, the connected vehicle fog warning system shows a remarkable impact on speed reduction in fog zones, while there are variations in the speed-reduction efficiency at different technical levels.

4. Discussion

This study studies the impact of connected vehicle fog warning systems on driving behavior and safety at three technical levels, according to whether there is HMI and DMS, and compares and analyzes their efficiency. A driving simulator fully discussed in the previous study [24] is adopted in this study.

The obtained results show that the connected vehicle fog warning system can significantly reduce speed, enhance drivers’ awareness, and improve safety in fog zones. Zhao et al. [32] develop the variable speed limit application in a connected vehicle environment (CV-VSL) based on a
driving simulator, finding that the CV-VSL application is effective in reducing driver travel speeds in all three types of zones. Chang et al. [3] study the effectiveness of fog warning systems on driving performance and traffic safety in heavy fog conditions, finding that the warning systems are beneficial to speed reduction before entering a fog zone. Studies have also shown that connected vehicle technology plays a positive role in other adverse weather conditions. Speed variations under the connected vehicle scenarios are found to be significantly lower than the baseline scenarios, indicating that connected vehicle technology has the potential to harmonize speed variation [5]. From the above, it can be inferred that our finding that connected vehicle technology helps in improving driving behavior and safety in adverse weather conditions is consistent with the earlier study.

However, the efficiency of different connected vehicle technologies is different. In our study, the levels of connected vehicle technology are divided into three groups: normal, HMI, and HMI & DMS. Compared with the normal group, the HMI and HMI & DMS groups have remarkable deceleration effects. Drivers in the HMI group have a higher deceleration ratio at the beginning, while their high deceleration ratios appear relatively later in the HMI & DMS group. However, drivers in the HMI&DMS group have lower driving speeds. This can be due to the distraction of the driver caused by the HMI, in which the vocal warning causes the driver to react abruptly, resulting in an aggressive deceleration behavior. However, in the HMI & DMS group, drivers are more confident and cautious in driving and have better control over speed. Hu et al. [33] explore the influence of HMI on the driver’s visual characteristics in fog zones based on the AttenD algorithm, finding that HMI increases the driver’s visual workload and distraction. Comprehensive evaluation results show that the warning mode of the combined HMI and DMS has the highest level of compliance under light fog conditions [19]. This result supports the interpretation of our own conclusions. Thus, the connected vehicle technology helps improve driving safety in fog zones [34].

This study does not consider the market penetration rates of connected vehicles, and other vehicles are set as traditional vehicles. Combining driving simulator and microsimulation methods, Yang et al. [35] find that connected vehicles applications increase drivers’ situational awareness under adverse weather conditions, thus reducing the crash risk. The reduction in conflicts shows a decreasing trend with the increase of connected vehicles penetration rates. Under foggy conditions, it was found that an increase in the market penetration rates of connected vehicles enhances the safety performance [36]. Therefore, the market penetration rates of connected vehicles are closely related to the utility of connected vehicle technology.

### 5. Conclusions

In this study, a test platform for connected vehicle technology based on a driving simulator was developed. Fog zone simulation scenarios were designed, drivers participated in driving simulation experiments, and their driving data were collected. Combined with the safety entropy, this study explored the influence of different technical levels of a connected vehicle fog warning system on driving behavior and safety.

Compared with the normal group, the connected vehicle fog warning system (HMI and HMI & DMS groups) significantly reduced the driving speed. The HMI group had the highest speed reduction degree, which was beneficial to improve the longitudinal driving safety in fog zones. The connected vehicle fog warning system resulted in reducing the lateral deviation and improving lateral driving safety in fog zones.

Additionally, the connected vehicle fog warning system increased the speed safety entropy and lateral deviation safety entropy to some extent. From the perspective of change stability, the connected vehicle fog warning system had a negative impact on safety.

The deceleration ratio of the warning point in the HMI and HMI & DMS groups was significantly higher than that
in the normal group. Drivers’ responses were more pronounced in the HMI group, but the drivers maintained a lower speed in the HMI & DMS group. There were differences in the effectiveness of speed reduction at different technical levels.

This study provides a reference for the studies on connected vehicle technology based on driving simulators and supports the optimization, design, and evaluation of connected vehicle fog warning systems. As future work perspectives, the impact of connected vehicle technology on driving behavior and safety under different market penetration rates of connected vehicles will be further studied.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References


[24] X. Zhao, H. Chen, H. Li et al., "Development and application of connected vehicle technology test platform based on


