Impact of connected vehicle environment on driving performance: A case of an extra-long tunnel scenario

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Funding information
Natural Science Foundation of Beijing Municipality, Grant/Award Number: 9202001; National Natural Science Foundation of China, Grant/Award Number: 51608017; National Key R&D Program of China, Grant/Award Number: 2019YFB1600500

Abstract
In view of the benefits and a promising prospect of the emerging connected vehicles (CV), more and more vehicles will be equipped with the in-vehicle human-machine interface (HMI). This study aims to assess the comprehensive impacts of HMIs on individual driving performance, traffic safety, and eco-driving behaviour based on a driving simulator. In order to explore how a driver responds to warnings when approaching a tunnel, this study divided the experimental road into five zones according to warning positions. A comparative analysis was conducted to examine the changes in driving comfort, speeding behaviour, the standard deviation of speed, time headway (THW), fuel consumption, and emissions. Results showed that the HMI could be beneficial to speed adjustment before entering a tunnel. Meanwhile, HMI may affect the THW of vehicles. Drivers were usually more cautious when the HMI was on. However, no significant effects of the HMI for driving comfort and eco-driving behaviour can be observed. It is expected that more efficient technology and different warning strategies can be developed to enhance eco-safe driving for different zones because they have different effects. The findings of this study are also helpful for active safety management and for evaluating the effectiveness of CV systems.

1 INTRODUCTION

Traffic systems are composed of human, vehicle, road, infrastructure, and environment, in which drivers are the main part. Previous research has consistently shown that inappropriate human manoeuvre is responsible for about more than 80% of all traffic crashes and traffic congestions [1–3]. Human factors are an important topic on the way of seeking for traffic safety and efficiency. The development of information and communication technologies has provided opportunities to adjust driving behaviour in improving traffic safety and capacity and in reducing fuel consumption and emissions [4–7]. Connected vehicle (CV) technologies, in which vehicles communicate with other vehicles, roadway infrastructure, and traffic management entity in real time, can give abundant and accurate information to drivers. These information help drivers make more preparations for the upcoming traffic emergency events or the changing environments of driving situations.

Road tunnels are usually designed to reduce travel time and protect natural resources and the environment. The number of road tunnels is increasing rapidly due to the above advantages and the development of construction technologies in China. As such, due to the unique physical structure of tunnels, the driving situation changes sharply when approaching a tunnel. Previous studies indicated that crashes in tunnels are lower than road crashes [8]. Nevertheless, crashes occur more frequently with serious and severe consequences for tunnel users [9, 10]. For example, a crash happened in Shanxi Qinling No.1 tunnel in August 2017; 36 people died and 13 people were injured [11]. Therefore, it is necessary to explore how road tunnel conditions affect driving performance and to develop efficient methods to help drivers get prepared to adjust their manoeuvres when driving on a road tunnel section.

The driving situation transition has a significant effect on perceptual response and driving performance, which needs to be understood to design warning strategies. Several studies have been conducted to investigate driving performance corresponding to tunnel in a series of simulator experiments such as drivers’ speed, car-following behaviour, lateral movement, and driving physiological performance [12–16]. However, almost all current studies related to the driving behaviour of road tunnels only compared the differences between normal and in-tunnel...
situations. The research on driving adjustments when approaching a tunnel is rare. Some other studies examined the impact of tunnels’ features on visual characteristics and driver behaviour, including the length of road tunnels and the entrance light [17, 18]. The results revealed that the length of a tunnel is a major factor in influencing driving performance that can lead to traffic crashes. In addition, despite the crash rate in longer tunnels is lower, once it happens it would often have serious human and economic consequences [19]. Statistical results showed that 63.7% of tunnel crashes occur in the tunnel entrance zone [20]. Also, it has been suggested that drivers’ attention was focused on the tunnel entrance almost neglecting all the roadside signs from 150 m before entering the tunnel [21]. Although drivers are likely to reduce speed to obey the legal speed limit when entering the tunnel, the speed reduction is found to be insufficient for them and drivers are forced to decelerate too quickly that easily makes drivers exposed to safety problems [22, 23].

Efforts to enhance the safety of road tunnels are necessary. The tunnel warning (TW) system serves as an important CV system to inform drivers ahead and help them get ready to respond for the tunnel driving situation. Human–machine interfaces (HMIs) represent a promising approach for informing drivers to adjust their driving behaviour and to maintain an eco-safe driving style, which includes driving behaviours aimed at reducing both fuel consumption and emissions, as well as safe driving behaviours [24]. However, little effort has been made to quantify their integrated effects on driving behaviour, including drivers’ speed adjustment, driving comfort, speeding behaviour, time headway (THW), and eco-driving (eco-driving, the concept of changing driving behaviour and vehicle maintenance practices to improve fuel efficiency and reduce greenhouse emissions of existing vehicles, has been demonstrated to have a great potential in reducing fuel consumption and emissions) [25]. Hence, more detailed investigations are required to evaluate the impact of such HMI application. Existing studies have paid attention mainly to the effects evaluation of speed limit warning, forward collision warning, and fog warning on driving behaviour and driving stress [26–30]. To investigate the effects of CV technology on driving performance on road tunnels, Vashitz et al. evaluated the potential benefits of in-vehicle HMI that showed that the level of distraction was relatively minor and could reduce drivers’ anxiety and boredom [31]. Moreover, Fu et al. found that the HMI was valid for safety improvement and the effects varied in different zones of the tunnel entrance [32]. However, the effects of TW on driving speed adjustment when approaching a tunnel, driving comfort, and eco-driving behaviour have rarely been studied [31–33]. There is also a lack of systematic analysis of the effect of HMI deployment. Therefore, the objective of this study is to evaluate the effect of road tunnel condition on driving performance and fuel consumptions with and without HMI. This study carried out this research using a driving simulator from Chinese drivers and driving environment perspective. Moreover, the validity of driving simulator used in this study in studying driving behaviour, traffic safety, and eco-driving has been established in previous research [34–39].

2 | METHOD

2.1 | Participants

Based on the distribution of ages and driving experience of licensed drivers in China [40], 35 participants (15 females) between 23 and 55 years of age (mean age ± SD = 35.8 ± 11.3 years; mean driving experience ± SD = 12.1 ± 8.9 years, range 2 to 30 years) participated in the experiment. The test drivers were recruited from taxi drivers (13 male and nine female drivers) and university students (seven male and six female drivers). Each participant held a Chinese class C driver’s license. The participants were provided written informed content before the experiment. Meanwhile, in order to reduce other factors on driving performance, participants were made sure to avoid intake of stimulating food or drink and had no health or motion problems before the experiment. They were paid 200 Chinese RMB after the whole experiment.

2.2 | Apparatus

2.2.1 | CV environmental platform structure

A study method formed by Zhao et al. and Chang et al. was referred, a fixed-base driving simulator of Beijing University of Technology (BJUT) and a portable android device (PAD) were used to build the simulation CV environment [41, 42]. Figure 1 shows the apparatus used in the experiment. As shown
in Figure 1(a), the BJUT driving simulator consists of a full-size vehicle cabin with a real operation interface linked to system software with five computers and three big screens providing a 130-degree field of view. The simulator records the driving behaviour (e.g. steering wheel angle, brake pedal depth, gas pedal depth, sampling time, position, driving speed, acceleration, lateral position, the distance to the front vehicle within 250 m, and the speed of the front vehicle) at a frequency of 20 Hz. One of the key components of this CV system is the in-vehicle HMI that is designed as a PAD software. The HMI was installed at a fixed position that did not affect the driving field of view as shown in Figure 1(b). The HMI displayed and broadcast warning messages according to the data collected by the simulator. The developed CV warnings were classified into four status, and four priority levels were defined in the order of (1) forward collision warning (FCW), (2) speeding warning (SW), (3) TW, and (4) normal traveller information (NTF) [43].

2.2.2 HMI display layout

Figure 2 illustrates the architecture of the HMI display layout. The HMI includes five parts. Area 1 provides navigation information. The content of areas 2–4 change according to warning types. Area 5 is setting buttons of the CV system. As mentioned before, the CV warnings are classified into four categories: FCW, SW, TW, and NTF, and they are triggered based on the driving situations.

FCW is used when the distance between the test and the front vehicles is less than a certain value. The FCW has two warning levels: The cautionary level (HMI displays a red warning when the distance is greater than safety distance and less than 250 m) and the alert level (HMI displays a red warning with a series of loud ‘di, di, di’ sounds when the distance is less than safety distance, and the text ‘pay attention to the front vehicle’ will be displayed in area 2). The safety distance algorithm used is shown in Equation 1:

\[
S = \frac{(V_1 - V_2)}{3.6} \times T + \frac{(V_1 - V_2)^2}{254(\psi + i)} + s_0
\]

where \(S\) is the safety following distance (FD, see Figure 3), \(s_0\) is the minimum FD when standstill, \(V_1\) is the speed of the test vehicle, \(V_2\) is the speed of the front vehicle, \(T\) is the reaction time, \(\psi\) is the coefficient of friction of the road, \(i\) is the slope of the road.

SW is usually triggered when a vehicle is speeding. The speed limit is displayed for the existing road. TW aims to alert drivers of the road condition ahead, including distance to the tunnel entrance or exit and the speed limit in the tunnel. The TW will be broadcasted at fixed positions: 1000 m ahead from the tunnel entrance (TW 1), 500 m ahead (TW 2), near the entrance (TW 3), and 2000 m ahead from the tunnel exit (TW 4). An NTF will appear on the HMI when the vehicle is in a safety situation.

Detailed descriptions of each CV warnings, including its warning signs, text messages that will be displayed on the HMI, are presented in Table 2.

| Parameter |
|----------|
| \(s_0\) |
| \(T\) |
| \(\psi\) |
| \(i\) |
| Values 8 m 2 s 0.4 0 |

TABLE 1 Parameter values

2.2.3 Scenario design

The road in the simulated scenario is part of the Xingyan Freeway (located northwest of Beijing), which includes the Shixia Tunnel (length = 3600 m). The entire experimental road is a four-lane divided freeway with two lanes in each direction, and each lane width is 3.75 m. The tunnel is a two-hole tunnel divided with two lanes in each direction. The road signs and road surface markings comply with the Chinese road rules (GB5768, 2009). In order to reduce the interference of other factors, the traffic condition (density and speed) was kept constant during each experiment. In addition, the experimental traffic flow is free flow so that drivers can freely control the vehicle according to their driving habits and situations. The experimental route has three sections: Starting section A-B (0.5 km), experimental transition section B–C (1.0 km), and formal experimental section C–H (7.1 km, including 3.6 km tunnel F–G) as shown in Figure 4.

2.2.4 Experiment procedure

The experiment was designed as a comparison test under two conditions: The HMI is on and the HMI is off. In order to eliminate drivers’ familiarity with the experimental road,
participants were asked to do the experiment two times, and the order was arranged randomly.

Upon arrival, participants were asked to sign an informed consent form and fill out a before-drive questionnaire (social characteristics). Then, the HMI function was introduced to them through PowerPoint. In order to make sure all of the drivers were familiar with the CV warning systems to avoid priming and experimental bias, we only introduced the function of the CV warning systems, which was more like a product description. Moreover, we also designed the questions to verify that all of the drivers understand the messages of the CV warning systems. However, we did not interfere with the driver’s use of the system. Meanwhile, a questionnaire about the HMI and the 10-min training session were provided to make sure that participants all understand the HMI function and become familiar with the simulator’s steering and braking dynamics. Participants were advised to adhere to traffic laws and drive normally but were not notified of the condition setting of the experiment.
3 | DEPENDENT MEASURES

3.1 | Zone division

In order to better understand the effects of CV warnings on driving manoeuvre adjustment, similar to recent studies [32, 44, 45], this study divided the road into five zones (TW-1, TW-2, entrance, inner, and exit zones) according to the positions of TW warnings and the Shixia Tunnel (see Figure 5). Except for the inner zone, each zone was defined as the area from 200 m in front of the points D, E, F, and G to 300 m after those points, respectively. The observation indicators were analysed to identify variations in different zones with and without the CV system. The observation indicators in this study are described below.

3.2 | Observation indicators

3.2.1 | Speed adjustment

To evaluate the driving performance, speed difference in zones, the speeding behaviour of the inner zone (the proportion of space that was speeding (Pss) and the proportion of exceeding the speed limit (Pes), were calculated; see Equations 2 and 3), the number of deceleration at sharp events ($a_j < -3 \text{ m/s}^2$), and the driving comfort of the whole travel ($C$) were analysed (see Equation 4) [46]:

\[ P_{ss} = \frac{\sum_{i}^{n} S_{PI}}{L_{T}} \]  
(2)

\[ P_{es} = \frac{\sum_{i}^{n} \bar{v}_{SPi} - SL}{n} \]  
(3)

where $S_{PI}$ is the speeding space distance of driver no. $i$, $L_{T}$ is the length of the inner zone, $n$ is the total number of test drivers, $\bar{v}_{SPi}$ is the average speed that is speeding, $SL$ is the speed limit in the tunnel:

\[ C = \left( \frac{1}{m} \sum_{j=1}^{m} a_j^2 \right)^{\frac{1}{2}} \]  
(4)

where $m$ is the length of the data analysed road and $a_j$ is the acceleration at per metre.

3.2.2 | Traffic safety

The speed SD and the THW were selected to analyse the effects of HMI on traffic safety. The speed SD and the THW were calculated and compared at different zones. The FD and the speed of the front vehicle were collected by the simulator when the FD is less than 250 m. The THW was calculated by Equation 5:

\[ THW = \frac{FD}{V_1} \]  
(5)

3.2.3 | Eco-driving behaviour

The characteristics of drivers’ eco-driving behaviour in fuel consumption and emissions were estimated. Based on the second-by-second data provided by the driving simulator, emissions could be estimated through microscopic emission models. Then, vehicle fuel consumption could be calculated by the carbon balance method [47].

The microscopic emission model was established based on vehicle-specific power (VSP) distribution. The VSP was calculated by Equation 6. Then, based on the corresponding relationship between VSP and the base emission rate in VSP bins, the total emissions of the whole travel time were acquired. More details of the base emission rate in VSP bins could be
TABLE 3  Summary of the CV warnings

|                 | Pss | Pes | Number of sharp events | C   | THW (s) |
|-----------------|-----|-----|------------------------|-----|---------|
| Human–machine interface (HMI) ON | 0.11 | 0.01 | 1.28 | 0.32 | 8.66 |
| HMI OFF         | 0.25 | 0.04 | 1.63 | 0.35 | 7.63 |
| t-test (p-value) | –   | –    | –   | –   | –0.946 | 1.791 |

Note: THW is time headway.

found in [47]. Next, the fuel consumption per 100 km (FC) could be calculated through the carbon balance method (see Equation 7). According to the general public’s concern, CO₂ was selected as the representation of emissions [48]:

\[ VSP = 0.156461 v + 0.00200193v^2 + 0.000492646v^3 + 1.4788v_{ab} = 1.4788 \]  

(6)

where \( v \) is the vehicle speed per second (m/s) and \( v_{ab} \) is the vehicle acceleration per second (m/s²):

\[ FC = \left( 0.866M_{HC} + 0.4286M_{CO} + 0.2727M_{CO_2} \right) \times 0.156 \]  

(7)

where \( M_{HC} \) is the emissions of HC per kilometres (g/km), \( M_{CO} \) is the emissions of CO per kilometres (g/km), \( M_{CO_2} \) is the emissions of CO₂ per kilometres (g/km).

4 RESULTS

The data of 35 participants were used in the following analysis. To evaluate the systematic impacts of in-vehicle HMI on driving behaviour, a series of analysis of variances (ANOVA) were conducted. Tables 3 and 4 present a summary of the driving performance, traffic safety, and vehicle emissions for each scenario.

4.1 Driving performance

After the experiment, the driving performance data were collected. From Table 3, it was found that the Pss, the Pes, and the number of sharp deceleration at events for HMI-OFF were higher than that of HMI-ON. The results indicated that HMI could lead to decrease in the proportion of speeding behaviour (Pss: 0.11 with warning vs. 0.25 without warning; Pes: 0.01 vs. 0.04) and the number of deceleration at sharp events (1.28 vs. 1.63). Furthermore, as shown in Table 4, the results showed a significant main effect of HMI on speed (except the exit zone). It suggested that drivers were usually more cautious when the HMI was on. The average speed of the HMI-ON scenario is lower than that of HMI-OFF:

Figure 6(a) illustrates that drivers would reduce their speed when entering a tunnel. Moreover, the average speed of HMI-ON at the entrance zone was ready for the lower speed limit of the in-tunnel road. However, the average speed was still higher than 80 km/h at zones 5 and 6 when the HMI was off. Another interesting finding was that the driver would reduce their speed at zone 3 when the HMI was on, which was earlier than that of HMI-OFF condition. The results also revealed that the HMI was beneficial for drivers to get prepared when approaching a tunnel.

The driving comfort was also analysed in this study. According to [46], the comfort levels were divided into five levels (see Table 5). Under the experimental traffic flow condition, the results showed that there was no significant difference in the comfort level. The comfort levels were all at level 4 (0.32 with HMI and 0.35 without HMI).

TABLE 4  Summary of the CV warnings

| Index       | TW-1 zone | TW-2 zone | Entrance zone | Inner zone | Exit zone |
|-------------|-----------|-----------|---------------|------------|-----------|
|             | Total     | Zone 1    | Zone 2        | Zone 3     | Zone 4    |
|             |           |           |               |           |           |
|             |           |           |               | Zone 5    | Zone 6    |
|             |           |           |               |           | Zone 7    |
|             |           |           |               |           | Zone 8    |
|             |           |           |               |           | Zone 9    |
| Ave. speed (km/h) |          |          |               |           |           |
| HMI-ON      | 77.59     | 89.14     | 91.46         | 91.12      | 85.7      |
| HMI-OFF     | 82.69     | 101.47    | 104.4         | 104.73     | 101.67    |
| t-test      | –6.630*   | –4.343*   | –4.687*       | –5.260*    | –6.648*   |
| Speed SD    |           |           |               |           |           |
| HMI-ON      | 8.83      | 1.68      | 1.95          | 1.31       | 2.6       |
| HMI-OFF     | 12.51     | 1.68      | 1.33          | 0.82       | 3.1       |
| t-test      | –4.333*   | –0.010    | 1.873         | 1.893      | –0.872    |
| FC (L/100 km) |          |          |               |           |           |
| HMI-ON      | 7.66      | 9.17      | 7.97          | 7.33       | 6.34      |
| HMI-OFF     | 7.77      | 10.23     | 8.67          | 8.15       | 6.58      |
| t-test      | 0.667     | –2.649*   | –2.165*       | –1.831     | –0.627    |
| CO₂ (g/km)  |           |           |               |           |           |
| HMI-ON      | 179.51    | 214.66    | 186.72        | 171.72     | 148.52    |
| HMI-OFF     | 181.87    | 239.17    | 202.93        | 190.86     | 154.13    |
| t-test      | 0.689     | –2.632*   | –2.147*       | –1.827     | –0.614    |

*Difference is significant at the 95% level.
FIGURE 6 The effect of HMI on driving behaviour. (a) The effect of HMI on speed, (b) the effect of HMI on speed SD, (c) the effect of HMI on FC, and (d) the effect of HMI on CO₂ emissions.
4.2 Traffic safety

THW and speed SD were selected as indicators of traffic safety [49]. Table 1 shows the increasing trend of THW for HMI-ON, compared to HMI-OFF (8.66 vs. 7.63 s), which is consistent with previous studies [50, 51].

Overall, the effect of HMI on speed SD is statistically significant according to the result of ANOVA in Table 4. Figure 6(b) illustrates the increasing trend of speed SD before entering a tunnel. It was found that the speed SD was higher at zones 2 and 3 but was lower from zones 4 to 6 (especially near the tunnel entrance) for HMI-ON compared to the HMI-OFF condition. The results also demonstrated that the HMI may help drivers get a more stable speed in the tunnel, especially at the entrance zone.

4.3 Eco-driving behaviour

Based on the second-by-second driving parameters (e.g. speed and acceleration) collected and the vehicle emissions calculation methods, the fuel consumption, and CO₂ emissions were obtained as listed in Table 2. Although there were no significant interactions with and without HMI, the differences in vehicle emissions were observed in different zones. As presented in Figures 6(c) and (d), it was found that the FC and the CO₂ of HMI-ON were higher than that of HMI-OFF condition at the entrance and exit zones. The reason may result from HMI’s effect on visual perception abilities at the entrance and exit zones. In addition, the design and development of such a CV system, also for improving eco-driving behaviour, should be considered. The results were helpful to design a system for improving eco-driving behaviour.

5 CONCLUSION AND FUTURE WORK

Based on a driving simulator study, this study addressed the comprehensive effects of in-vehicle HMI, including driving speed adjustment, driving comfort, driving safety, and eco-driving behaviour, from Chinese drivers and driving environment perspective. The findings from the current experiment suggested that HMI involving both advice and feedback messages (FCW, SW, and TW) may help drivers be better prepared when approaching a tunnel and have the potential to improve traffic safety, especially near the tunnel entrance, as previously described. The impacts of HMI on driving comfort and vehicle emissions were also analysed. Nevertheless, no significant effects of HMI on driving comfort, CO₂ emissions, and fuel consumption were found. The current study highlights the potential benefits of such a CV system. The findings improve our knowledge by proving a systematic analysis of the effects of in-vehicle HMI. However, the challenges remain how best to design an HMI and to provide real-time feedback to drivers. Future research should give more attention to explore optimal ways of proving proper feedback to drivers. Moreover, it would be of great value to further evaluate the impacts of such systems on traffic flow capacity and proactive safety management strategies. Last but not least, though driving simulators are considered effective tools for human factor analysis, future work is needed to validate these findings in the empirical study.

ACKNOWLEDGEMENTS

This study was supported by the National Key R&D Program of China (2019YFB1600500) and the National Natural Science Foundation of China project (51608017).

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