Lighting Traffic Ahead: Tunnel Lighting for Hazard Response and Car-Following Safety among Novice Drivers

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Tunnels create a constrained car-following environment in which rear-end crashes remain a major safety concern. This is especially challenging for novice drivers, who may have difficulty anticipating traffic changes further ahead. Existing warning systems mainly reflect the state of the immediate lead vehicle, while vehicle-to-vehicle approaches for upstream information are limited by technology adoption. This paper investigates an infrastructure-based approach that uses ceiling-mounted tunnel lighting to present beyond-visual-range (BVR) traffic information. A driving simulator study with 24 novice drivers was conducted to evaluate two designs: a headway-based representation of traffic spacing (THW-HMI) and a dynamic-state representation of vehicle deceleration (DYN-HMI). The results showed that both HMIs were associated with earlier braking responses, larger temporal safety margins, and lower subjective workload than baseline. Outside the emergency events, car-following behavior remained comparable across conditions. These findings indicate that infrastructure-based ambient cues may contribute to safer tunnel driving for novice drivers.

CCS Concepts: • **Human-centered computing** → **Empirical studies in interaction design**; **User interface design**.

Additional Key Words and Phrases: Tunnel Safety, Beyond-Visual-Range Information, Infrastructure-to-Vehicle Communication, Novice Drivers, Car Following Behavior

1 Introduction

Road tunnels are a demanding driving environment. Their confined geometry, high speed, and limited space make lane changes difficult or impossible, so drivers are often forced into sustained car-following (CF) mode. In this setting, longitudinal control becomes the main task [23, 28]. As a result, rear-end crashes are one of the most common crash types in tunnels [30, 40], leading to traffic congestion and making rescue and emergency response difficult [2, 30, 38]. Reducing rear-end risk in tunnels is therefore important for traffic safety.

Existing technologies typically attempt to reduce rear-end collisions in general traffic scenarios through ego-vehicle forward collision warnings [3, 20]. However, these warnings mainly reflect the state of the immediate lead vehicle and provide little information about traffic further upstream [21]. Their effectiveness can also be limited by false or nuisance alerts [24, 27]. In tunnel CF scenarios, this limitation is particularly evident because the tunnel environment reduces

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visual cues to support speed perception, hazard anticipation, and longitudinal control. Thus, drivers have to rely on the limited lead-vehicle information or the alerts [28]. In recent years, Beyond-Visual-Range (BVR) information has been identified as playing a positive role in mitigating rear-end risks [11, 17]. Building upon this line of work, some studies have tried to explore vehicle-to-vehicle (V2V) communication to provide drivers with information about upstream vehicles or traffic flow, in order to support safer following behavior [8, 36]. Although such approaches have shown promise, their practical value still depends heavily on the adoption and market penetration of V2V technology [1, 35].

Tunnels, however, offer a unique opportunity to embed BVR information directly into the driving environment. Because the tunnel ceiling extends continuously along the road, it can be used to convey traffic information from farther ahead to following drivers. Further, sensors can be easily installed in tunnels to provide BVR information. This creates an opportunity for an infrastructure-led interaction approach, rather than a purely vehicle-based one [15, 16, 33]. Previous work suggests that different types of upstream information may influence drivers in different ways [12]. For example, headway information may help drivers understand traffic spacing, while deceleration states information may help them interpret immediate risk [29, 34]. Based on this distinction, we examined two ceiling-mounted HMI designs: a distance-based design that visualizes the headway distribution (THW-HMI) of upstream traffic, and a dynamic-state design that visualizes the deceleration status (DYN-HMI) of lead vehicles. These two designs allow us to examine whether different forms of upstream information affect CF behaviors differently in tunnel driving.

Furthermore, given that novice drivers have a higher risk of accidents and lower capabilities to anticipate hazards ahead compared to experienced drivers [14, 31], especially under demanding driving conditions, novice drivers are the main focus of our current research [4]. In general, we aim to answer two research questions (RQs): whether infrastructure-led BVR information in tunnels can improve CF safety in tunnels (RQ1), and whether the two display designs lead to different driving and workload outcomes among novice drivers (RQ2). Based on prior BVR-related research [7, 8], it is hypothesized that BVR information in the tunnel may facilitate improved safety outcomes compared to the baseline condition (H1). However, the DYN-HMI may be perceived as more acceptable (H2), as the DLV's deceleration information was perceived as more useful than the DLV's headway information in a previous study [7], though it is unknown whether this applies to the BVR information of the leading traffic flow.

2 METHOD

2.1 Participants

Participants were recruited in local residential areas and through social media posts. Before the experiment, all participants completed a screening questionnaire that gathered demographic information, including gender, age, and driving experience. Novice drivers were required to have held a valid driver's license for less than 12 months and to have driven less than 5,000 kilometers in the past year. A total of 24 participants (12 male and 12 female) completed the study, exceeding the required number of participants (i.e., 19), assuming a medium effect size (Cohen's f = 0.25), a type I error of 0.05, and a power of 0.8 based on GPower (3.1). The participants' ages ranged from 18 to 27 years, with a mean age of 20.92 and a standard deviation (SD) of 2.67 years. Post-hoc effect analysis indicated that our sample can reach a power of 0.853 even for the smallest effect size we detected, i.e., Cohen's f of 0.23 (equivalent to partial eta squared η_p^2 of 0.05) for the Average Time Headway (which is defined in later sections).



Fig. 1. The driving simulator.

2.2 Apparatus

The experiment was conducted on a driving simulator, as shown in Fig. 1. The simulated environment was built in SILAB 7.1 (WIVW GmbH, Germany) and was run on hardware supplied by Info Tech, Shanghai. The cabin setup featured a steering wheel, pedals, and a three-screen display. The scenario was displayed on three 43-inch screens, each with a resolution of 1920x1080, and was positioned approximately 1 meter from the participant, yielding a 150° horizontal and 47° vertical field of view. The study was approved by the university's institutional ethics committee (protocol no. HSP-2025-0236).

2.3 Scenario Design

The experiment was conducted in a simulated straight highway environment that included a section leading into a 2-kilometer-long two-lane tunnel. The participant's task was to follow a direct leading vehicle (DLV) that followed an indirect leading vehicle (ILV) and executed a pre-scripted sequence of dynamic behaviors containing multiple events. The entire scenario was designed to evaluate driver responses across two primary traffic phases: a Free-Flow phase and a subsequent Congested Traffic phase, as depicted in Fig. 2 and Fig. 3.

The scenario commenced with the DLV accelerating to a high-speed cruising state of approximately 100 km/h (27.78 m/s) to simulate Free-flow Traffic. 500 meters before entering the tunnel, the DLV performed a slight and natural deceleration to approximately 80 km/h (22.22 m/s). In the tunnel, the traffic consisted of two sections: free-flow traffic (FT, with an average speed of 100 km/h) and congested traffic (CT, with an average speed of 60 km/h). During each section, there were two emergent braking (EB) events: the DLV executed an abrupt, high-intensity deceleration of $-5.5\,\mathrm{m/s^2}$, sustained for 3 seconds, to simulate a response to a sudden hazard [39]. Outside the EB events, the remaining intervals were normal drive segments, during which the DLV exhibited two mild speed reductions, with a deceleration of $-1.5\,\mathrm{m/s^2}$ sustained for 3 seconds, followed by a recovery to prior speed. Additionally, there were random speed

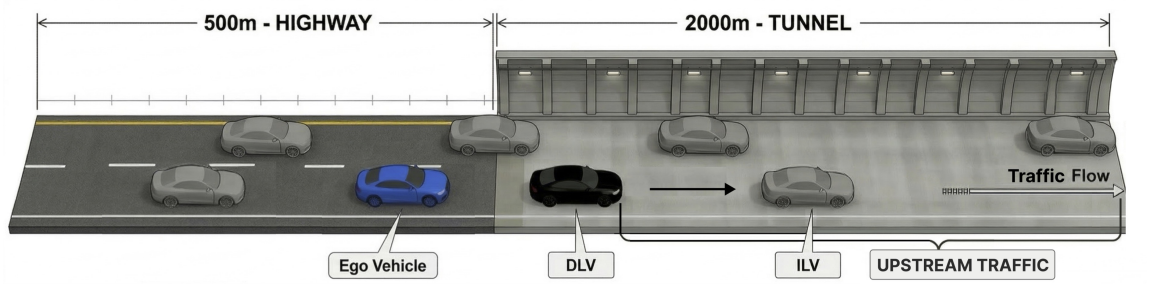


Fig. 2. The tunnel scenario design.

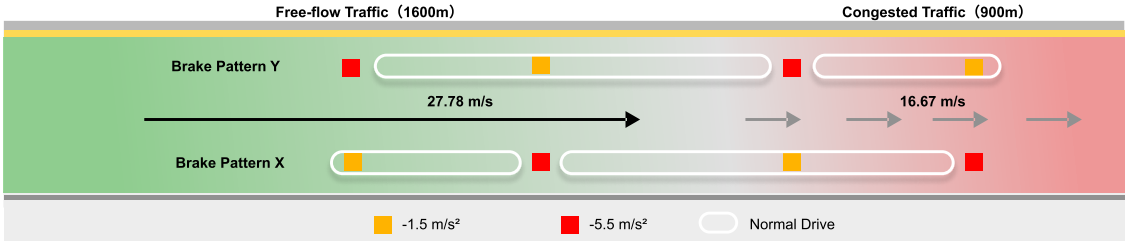


Fig. 3. Definition of braking events and normal drive segments.

variations in traffic, with an SD of 0.28 m/s and a maximum deceleration of ≤ -0.50 m/s^2, without brake light activation. These two mild speed reductions and random speed variations were used to represent common and foreseeable speed adjustments in traffic. As shown in Fig. 3, two event patterns were used in the experiment: in Pattern X, the two EB events appeared in the second and fourth positions; whereas in Pattern Y, they appeared in the first and third positions.

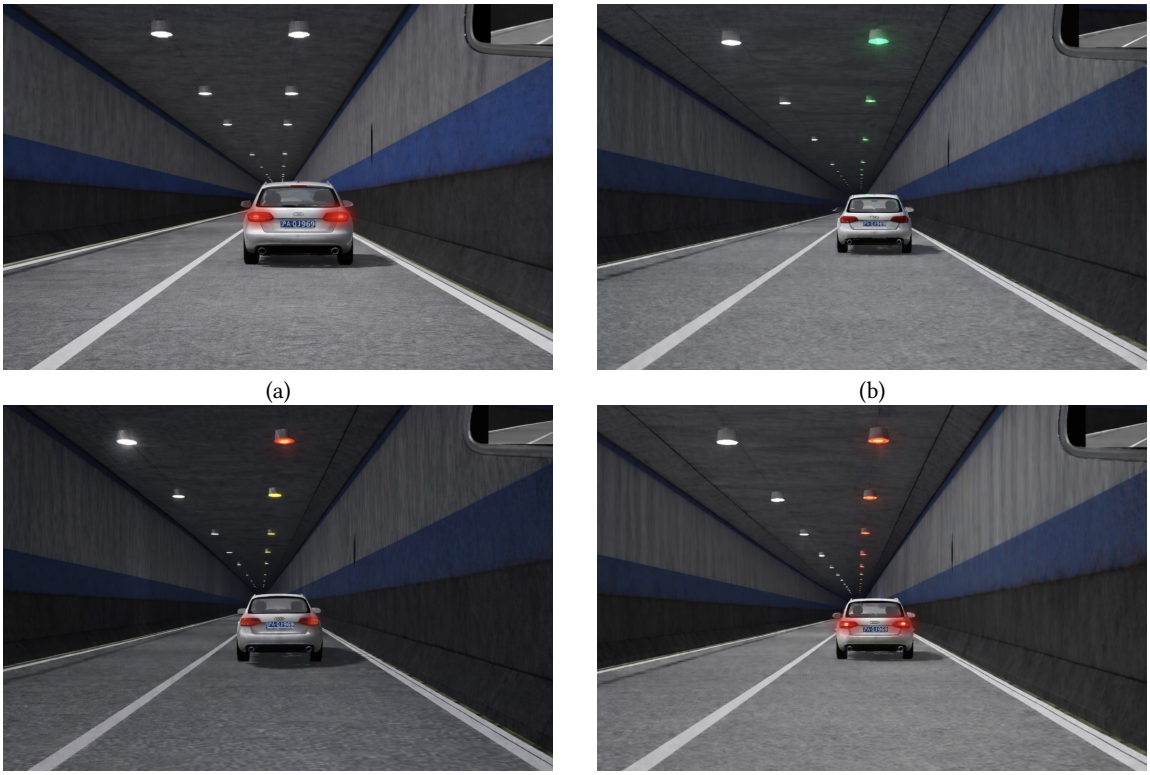
2.4 Driving Task

In the experiment, participants were required to follow the traffic on a simulated two-lane highway to safely navigate through the tunnel and follow the leading traffic. The driving scenario featured a single DLV traveling ahead of the ego vehicle. The task emphasized the importance of longitudinal control and did not impose explicit speed or distance targets on participants, thereby encouraging naturalistic driving behavior.

2.5 Lighting HMI Design

As shown in Fig. 4, the ceiling-light cues were designed to provide upstream information while limiting interference with driving. Their overhead placement used the continuous tunnel structure and kept the information outside the driver's central focal area. In practice, the spacing of the lights in the tunnel is determined by specific lighting requirements and can vary between tunnel zones [26]. In our experiment, however, the spacing was simplified, but remained within a realistic range.

This study designed and evaluated two novel ambient-lighting HMIs to provide participants with information about upstream traffic flow, i.e., BVR information, within the tunnel: a Headway-Based HMI (THW-HMI) and a Dynamic



(a) (b) (c) (d)

Fig. 4. Representative views in the tunnel scenario: (a) Baseline without color changes, and (b)–(d) showing gradual changes in upstream traffic conditions.

State-Based HMI (DYN-HMI), along with a Baseline condition without additional visual cues. The lighting effects are illustrated in Fig. 4.

2.5.1 THW-HMI Design. The THW-HMI was designed to provide real-time visualization of the following-distance chain for the entire lead-vehicle platoon. The color of each overhead light strip was determined by the Time Headway (THW) of the vehicles beneath it, shown in Fig. 5. The encoding scheme was founded on the "two-second rule" and leveraged the universal traffic light color metaphor [32]:

- Green indicated a safe Time Headway of at least 2.0 seconds.
- Yellow indicated a cautionary Time Headway of 1.0–2.0 seconds.
- Red signified a dangerous Time Headway of less than 1.0 seconds.

2.5.2 DYN-HMI Design. The DYN-HMI provided the dynamic state of vehicles in the platoon ahead. The color of each overhead light was determined in real time by the speed and longitudinal acceleration of the vehicle directly beneath it, shown in Fig. 6 [5, 39]:

- Red (Emergency State): Triggered by an emergency braking event, defined as a longitudinal deceleration over $4.0\,\mathrm{m/s^2}$.

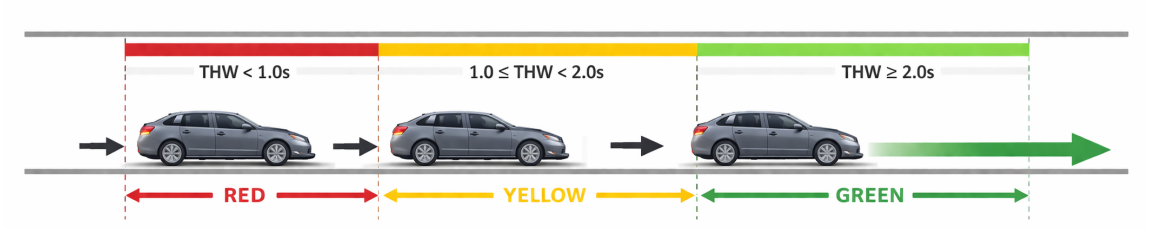


Fig. 5. Conceptual illustration of the THW-HMI design based on THW.

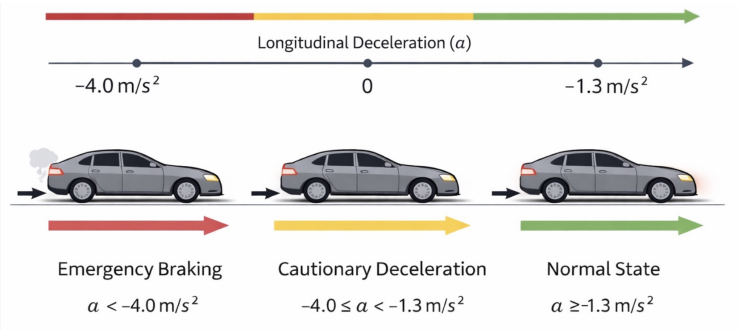


Fig. 6. Conceptual illustration of the DYN-HMI design based on longitudinal deceleration.

- Yellow (Cautionary State): Triggered by a moderate braking event, defined as a longitudinal deceleration between $1.3\,\mathrm{m/s^2}$ and $4.0\,\mathrm{m/s^2}$.
- Green (Normal State): The default state for normal driving, triggered when longitudinal deceleration is less than $1.3\,\mathrm{m/s^2}$.

2.6 Experiment Design

A within-subject design was employed, in which each of the 24 participants experienced all three HMI conditions: Baseline, THW-HMI, and DYN-HMI. To mitigate order effects, a 3×3 Latin square was used to create three counterbalanced presentation orders. Within each order, participants were further split into two subgroups to balance the brake event patterns (X vs. Y), resulting in a fully crossed design for scenario and condition orders. Each participant completed three trials, one per experimental condition, with each trial consisting of two braking events. Thus, in total, there were 24 participants (3 HMI orders, 2 brake pattern orders, and 2 genders per order). Data for reaction-based metrics were collected from a total of 144 braking events (24 participants $\times$ 3 conditions $\times$ 2 braking events per condition).

2.7 Procedures

Upon arrival, participants were briefed on the study's objectives and signed an informed consent form. They then received pre-experiment instructions detailing the driving task, the simulated tunnel environment, and the overall experimental requirements.

Training on the experimental tasks commenced with a five-minute demo driving session in the simulator. This familiarization drive did not include any HMI systems and was designed to allow participants to acclimate to the

simulator's controls and vehicle dynamics. After the demo, the formal experiment started, consisting of three drives, one for each HMI condition (Baseline, THW-HMI, DYN-HMI). Before each drive featuring an HMI, participants received standardized oral instructions explaining the meaning of the different light colors.

Following each of the three drives, participants completed a series of subjective questionnaires to assess their perceptions of the HMI and cognitive workload (using the NASA-Task Load Index [9]). Upon completion of all three drives, participants took part in a brief post-drive interview, in which they were asked whether they preferred the proposed HMIs over having no additional information, which of the two HMI designs they preferred and why, and whether they had any additional feedback regarding the HMIs.

2.8 Dependent Variables and Statistical Analysis

To evaluate HMI effects in tunnel CF scenarios, driving performance measures were extracted from two periods of interest: EB braking events and normal drive segments. The EB-braking-related measures captured drivers' responses to emergency braking, whereas the normal drive measure characterized routine CF behavior. In total, three driving performance metrics were extracted in this study:

Braking Response Time (BRT): The time interval between the onset of the DLV's emergency brake and the driver's first braking action [6]. Notably, if the driver responded before the DLV's braking event had begun, the value could be negative.

Minimum Time-to-Collision (MinTTC): The minimum value of TTC recorded during the interval from DLV's emergency braking until the DLV terminated deceleration, representing the most critical temporal safety margin between the ego and the DLV [10].

Average Time Headway (MeanTHW): The mean value of time headway (THW) recorded within the normal drive segments in each drive, where THW was calculated as the ratio of headway distance to ego vehicle speed [32].

We followed the standard approach for calculating the weighted NASA-TLX score from all six sub-dimensions, ranging from 0 (low workload) to 100 (high workload) [9]. As for the comments in the post-drive interview, the responses were reviewed descriptively to identify recurring observations and common perceptions reported by participants. No formal qualitative coding was conducted for the post-drive interview results, as the interviews were designed to provide supplementary context for interpreting the quantitative results. The study was not designed or powered to support demographic subgroup analyses; therefore, no formal comparisons of interview responses were performed across participant groups.

All statistical analyses were conducted in RStudio. Linear mixed-effects models (LMMs) were fitted separately for the driving performance measures and the NASA-TLX. The model adopted HMI condition (Baseline, THW-HMI, and DYN-HMI) as fixed effects, and participant ID as a random intercept to account for repeated measures. Post-hoc pairwise comparisons were conducted for significant effects ($p < .05$) using the Tukey adjustment method. The effect sizes of all main effects are reported as the partial eta squared (η_p^2, [19]).

3 Results

3.1 Driving Performance

As shown in Fig. 7, MinTTC differed significantly across HMI conditions, $F(2, 99.15) = 5.54$, $p = .005$, $\eta_p^2 = 0.10$. Tukey-adjusted post-hoc comparisons showed that MinTTC was higher in THW-HMI than in the baseline condition, with an estimated difference (Δ) of 1.03, 95% confidence interval (95%CI) between [0.15, 1.91], $t(98.9) = -2.78$, $p = .018$,

and higher in DYN-HMI than in the baseline condition ($\Delta = 1.15$, 95% CI [0.24, 2.05], $t(98.4) = -3.01$, $p = .009$). No significant difference was found between THW-HMI and DYN-HMI ($p = .946$).

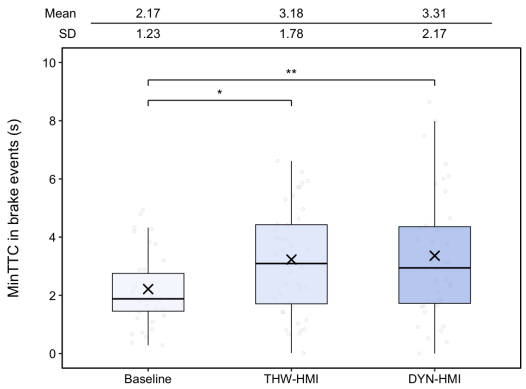


Fig. 7. MinTTC across different HMI conditions during EB events. In the figure and following figures, the boxplot shows the median, interquartile range, and minimum–maximum values; "×" indicates the mean, asterisks indicate significant pairwise comparisons, and the values above the plot report the mean and standard deviation for each condition.

As shown in Fig. 8, HMI condition had a significant effect on BRT, $F(2, 97.14) = 8.56$, $p < .001$, $\eta_p^2 = 0.15$. Tukey-adjusted post-hoc comparisons indicated that, relative to the baseline condition, both HMIs were associated with earlier braking responses. Specifically, BRT was shorter in THW-HMI ($\Delta = -2.22$, 95% CI [-3.80, -0.65], $t(99.0) = 3.37$, $p = .003$), and shorter in DYN-HMI ($\Delta = -2.58$, 95% CI [-4.20, -0.96], $t(98.5) = 3.80$, $p < .001$) compared to the baseline condition. Notably, negative BRT values were observed either due to drivers' earlier speed adjustment responses to the BVR information in the THW-HMI and DYN-HMI conditions, or to drivers' speed adjustments occurring before the DLV braking in the baseline conditions. No significant difference was observed between THW-HMI and DYN-HMI ($p = .850$).

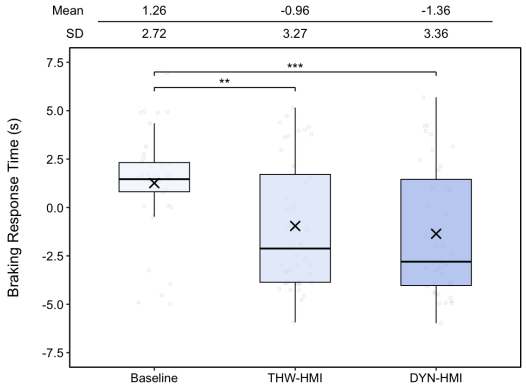


Fig. 8. BRT across different HMI conditions during EB events.

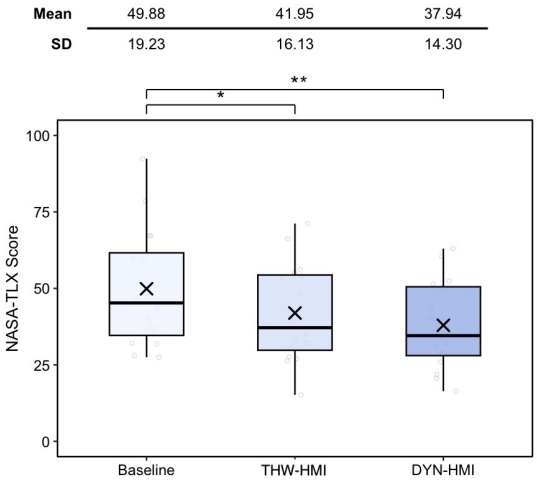


Fig. 9. NASA-TLX workload scores across different HMI conditions during EB events.

For the normal driving section, the effect of HMI condition on MeanTHW did not reach significance, $p = .077$, $\eta_p^2 = 0.05$.

3.2 Overall Workload

As shown in Fig. 9, HMI condition had a significant effect on NASA-TLX scores, $F(2, 30) = 7.38$, $p = .002$, $\eta_p^2 = 0.09$. Post-hoc comparisons showed that, compared with the baseline condition, subjective workload was significantly lower in THW-HMI ($\Delta = -7.93$, 95% CI [-15.70, -0.13], $t(30) = 2.51$, $p = .046$) and in DYN-HMI ($\Delta = -11.94$, 95% CI [-19.70, -4.14], $t(30) = 3.78$, $p = .002$). The difference between THW-HMI and DYN-HMI was not significant ($p = .424$).

3.3 Post-drive Interviews

Post-drive interviews indicated that nearly all participants preferred HMI support over the baseline condition, and only one participant reported that the difference between the HMI and baseline conditions was minimal: “I don’t think the difference was that big. In the baseline condition, I simply focused more on the car in front and drove more carefully.”

When comparing the two HMIs, preferences were relatively balanced, with 11 participants preferring the THW-HMI and 13 participants preferring the DYN-HMI. Participants who preferred the THW-HMI often emphasized its ability to provide a broader understanding of the traffic situation ahead. For example, one participant stated: “The THW-HMI gave me a clear idea of the distance I should maintain, which made it easier to control my speed and anticipate what might happen next.” Another participant commented: “With the THW-HMI, I could better understand the overall traffic situation ahead. It gave me additional information that I found useful.”

Participants who preferred the DYN-HMI frequently highlighted its directness and compatibility with their normal driving habits. One participant noted: “The DYN-HMI matched what I was already looking for while driving. It focused on information I naturally pay attention to, so it felt more consistent with my normal driving habits and didn’t require extra interpretation.” Another participant reported: “The DYN-HMI required less thinking on my part. The information was more direct, and it helped me anticipate the state of vehicles further ahead.”

4 Discussion

This study examined whether tunnel lighting could be used to present upstream traffic information and support driving in a tunnel CF scenario. Across the objective and subjective measures, the results showed a consistent pattern. In response to RQ1 and in line with H1, compared with the baseline condition, both HMI designs were associated with earlier braking responses and larger temporal safety margins during EB events. Subjective workload was also lower under both HMI conditions. Taken together, these findings suggest that tunnel lighting may have improved CF safety in the tunnel without overloading the drivers.

This is in line with our expectations: in tunnel CF scenarios without additional BVR information, drivers may have to adjust their speed in response to the vehicle directly ahead. The tunnel lighting used in this study has extended this local view by making upstream traffic variations ahead of the DLV available. Thus, they may take actions or prepare to take actions earlier, leading to earlier braking responses and larger temporal safety margins. Similar trends have also been reported in previous studies showing that access to downstream traffic information can support safer and more stable CF behavior [8, 22]. This may be especially relevant for novice drivers, who are more likely to rely on immediate traffic cues (i.e., the state of the DLV) when no additional information is provided [37].

Notably, 7 negative BRT values were observed even under the baseline condition. This is likely due to drivers' speed-adjustment behaviors, in which participants may occasionally slow down to maintain a safe following distance from the DLV. Thus, braking may happen to occur prior to the onset of the DLV's emergency braking event as part of normal speed control rather than as a direct response to the event. Keeping them in the analysis should have led to a more conservative estimate of the HMI effects. However, both HMIs have still resulted in significantly earlier braking responses than baseline, suggesting that the BVR information has robustly facilitated timely driver responses.

Next, no clear difference in MeanTHW between conditions was observed during the normal driving segment. This indicates that the effects of the HMIs were likely limited to emergency braking events and may not have disrupted routine CF behavior. The positive effect of BVR information on driving performance during EB events, without affecting CF behaviors in non-urgent CF scenarios, is consistent with observations from an external human-machine interface study [8]. Thus, our study provides additional support for the potential value of the BVR information in CF scenarios.

In addition, we noticed that both HMI conditions were associated with lower NASA-TLX scores than the baseline condition. This finding suggests that presenting BVR information through tunnel lighting may not increase the overall perceived workload. One possible explanation is that the additional information enabled drivers to become aware of developing traffic conditions earlier, reducing the need for reactive decision-making during emergencies. This interpretation is broadly consistent with previous research suggesting that enhanced situational awareness can support driver performance while reducing cognitive demands [25].

In response to RQ2, when comparing the two HMIs, although DYN-HMI consistently produced numerically better outcomes than THW-HMI across several measures, the differences were not statistically significant. It is possible that both interfaces enabled drivers to be aware of traffic conditions beyond the DLV, even though they conveyed different types of BVR information. As a result, both may have supported anticipatory responses to developing traffic situations, leading to broadly comparable behavioral outcomes. However, practitioners may remain cautious when interpreting the non-significant differences between the two HMIs, as nuanced differences may exist and warrant further investigation. Specifically, in response to H2, although we did not observe a difference in perceived workload between the THW-HMI and DYN-HMI, post-drive interview responses suggested that some participants perceived the two interfaces somewhat differently. In their comments, THW-HMI was associated with a broader understanding of

traffic flow, whereas DYN-HMI was perceived as providing more direct information about braking activity ahead. This indicates the need to further explore suitable scenarios when these two types of information should be provided.

Finally, from a practical perspective, the findings suggest that tunnel lighting may have potential as a medium for conveying BVR information in tunnel environments. However, real-world challenges should be addressed before deploying our proposed HMIs, including integration with traffic management systems, information standardization, and compliance with existing tunnel lighting regulations. Future research should therefore investigate the feasibility and effectiveness of the proposed approach in real-world tunnel environments.

5 Limitations and Future Work

It should be noted that this study has several limitations. First, the experiment was conducted in a driving simulator in a two-lane straight tunnel with a fixed set of traffic events and only two tunnel-lighting designs; thus, the findings may not fully reflect driver behavior in real tunnel environments. Second, the sample included only novice drivers, who generally exhibit less developed hazard-perception abilities than experienced drivers [37], and therefore the findings should be interpreted as preliminary and may not generalize directly to other driver groups. Third, though we conveyed the BVR information through dynamic spatial-temporal lighting patterns, our design still relied on color changes, and color-blind drivers may have difficulty using it. Future work should evaluate our designs in more diverse tunnel settings and traffic conditions, in on-road or naturalistic studies with more diverse driver groups, including color-blind drivers.

Finally, previous studies have shown that tunnel lighting characteristics can influence drivers' behavior and driving safety. For example, He et al. reported changes in drivers' visual behavior across different tunnel-lighting environments [13], and Kang et al. found associations among lighting conditions, reaction performance, and visual fatigue [18]. Researchers also found that changing the ambient light color alone, without conveying BVR information, can already affect drivers' performance [13, 18]. In our study, although dynamic lighting patterns have shown benefits in certain events in a relatively short tunnel, the role of lighting design warrants further evaluation in long tunnels, particularly from the perspectives of attention allocation (e.g., based on eye-tracking data), driver states, and overall safety impact. Future research should also differentiate the potential influence of overall lighting conditions from that of BVR information.

6 Conclusions

This study investigated whether tunnel lighting could be used to present beyond-visual-range traffic information and support novice drivers in tunnel car-following scenarios. In a driving simulator study, we found that HMIs showing the time headway (THW-HMI) and the vehicles' deceleration (DYN-HMI) ahead were both associated with earlier braking responses, larger temporal safety margins, and lower subjective workload than the baseline condition during emergency events. These findings show that beyond-visual-range information provided by the infrastructure can be useful in tunnels, where drivers have a constrained visual field. The participants' differing preferences for THW-HMI and DYN-HMI suggest a direction for future work on fusing headway-related traffic cues and vehicle-dynamics-related cues, or adaptively selecting them, to provide more suitable BVR information. Overall, this work provides initial evidence that tunnel lighting may serve as a practical, infrastructure-based channel to actively support drivers in tunnels.

References

[1] Ghadeer Abdelkader, Khalid Elgazzar, and Alaa Khamis. 2021. Connected vehicles: Technology review, state of the art, challenges and opportunities. *Sensors* 21, 22 (2021), 7712.

[2] Shy Bassan. 2016. Overview of traffic safety aspects and design in road tunnels. *IATSS Research* 40, 1 (2016), 35–46. doi:10.1016/j.iatssr.2016.02.002

[3] Jessica B Cicchino. 2017. Effectiveness of forward collision warning and autonomous emergency braking systems in reducing front-to-rear crash rates. *Accident Analysis & Prevention* 99 (2017), 142–152.

[4] Hamish A Deery. 1999. Hazard and Risk Perception among Young Novice Drivers. *Journal of Safety Research* 30, 4 (1999), 225–236. doi:10.1016/S0022-4375(99)00018-3

[5] John G Gaspar and Daniel V McGehee. 2019. Driver brake response to sudden unintended acceleration while parking. *Transportation Research Interdisciplinary Perspectives* 2 (2019), 100039.

[6] Marc Green. 2000. " How long does it take to stop?" Methodological analysis of driver perception-brake times. *Transportation Human Factors* 2, 3 (2000), 195–216.

[7] Feiqi Gu, Yufan Chen, Zhenyu Wang, Zhixiong Wang, Jiahui Li, Hongling Sheng, and Dengbo He. 2026. Optimizing followers' car-following behaviors using rear-facing eHMIs. *Accident Analysis & Prevention* 231 (2026), 108475.

[8] Feiqi Gu, Zhixiong Wang, Zhenyu Wang, and Dengbo He. 2026. Supporting car-following behavior through V2V-based beyond-visual-range information display. *Transportation Research Part F: Traffic Psychology and Behaviour* 118 (2026), 103551.

[9] Sandra G Hart and Lowell E Staveland. 1988. Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In *Advances in psychology*. Vol. 52. Elsevier, 139–183.

[10] John C. Hayward. 1972. Near-Miss Determination Through Use of a Scale of Danger. *Highway Research Record* 384 (1972), 24–35. https://onlinepubs.trb.org/Onlinepubs/hrr/1972/384/384-004.pdf

[11] Dengbo He and Birsen Donmez. 2022. The influence of visual-manual distractions on anticipatory driving. *Human factors* 64, 2 (2022), 401–417.

[12] Dengbo He, Dina Kanaan, and Birsen Donmez. 2021. In-vehicle displays to support driver anticipation of traffic conflicts in automated vehicles. *Accident Analysis & Prevention* 149 (2021), 105842.

[13] Shiyong He, Bo Liang, Guobing Pan, Feng Wang, and Lulu Cui. 2017. Influence of dynamic highway tunnel lighting environment on driving safety based on eye movement parameters of the driver. *Tunnelling and underground space technology* 67 (2017), 52–60.

[14] Chunxi Huang, Zuyuan Wang, and Dengbo He. 2024. The effect of dual training on the hazard response and attention allocation of novice drivers when driving with advanced driver assistance system. *Accident Analysis & Prevention* 208 (2024), 107802.

[15] Hongwei Huang, Jiateng Li, Xuejing Feng, Jun Ma, and Bruce Mehler. 2025. Characteristics of Driver Peripheral Vision: How Drivers Respond to Ubiquitous Information on Wide-Area In-Vehicle Displays. In *Proceedings of the Extended Abstracts of the CHI Conference on Human Factors in Computing Systems*. 1–8.

[16] Fangtong Jiao, Zhigang Du, Yiik Diew Wong, Shiming He, and Zehao Jiang. 2022. Influence of different visual guiding facilities in urban road tunnel on driver's spatial right-of-way perception. *Accident Analysis & Prevention* 172 (2022), 106688.

[17] I Ge Jin, Sergei S Avedisov, Chaozhe R He, Wubing B Qin, Mehdi Sadeghpour, and Gábor Orosz. 2018. Experimental validation of connected automated vehicle design among human-driven vehicles. *Transportation research part C: emerging technologies* 91 (2018), 335–352.

[18] Cheng Kang, Guojun Lin, Lei Ye, Chi Zhang, Zhiyi Huang, and Ke Wu. 2023. Influence of luminance and luminance longitudinal uniformity of tunnel lighting on drivers' comprehensive visual performance. *Tunnelling and Underground Space Technology* 140 (2023), 105282.

[19] Daniël Lakens. 2013. Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. *Frontiers in psychology* 4 (2013), 62627.

[20] John D Lee, Daniel V McGehee, Timothy L Brown, and Michelle L Reyes. 2002. Collision warning timing, driver distraction, and driver response to imminent rear-end collisions in a high-fidelity driving simulator. *Human factors* 44, 2 (2002), 314–334.

[21] Zihao Li, Yang Zhou, Danjue Chen, and Yunlong Zhang. 2024. Disturbances and safety analysis of linear adaptive cruise control for cut-in scenarios: A theoretical framework. *Transportation Research Part C: Emerging Technologies* 168 (2024), 104576.

[22] Lin Liu, Chunyuan Li, Yongfu Li, Srinivas Peeta, and Lei Lin. 2018. Car-following behavior of connected vehicles in a mixed traffic flow: Modeling and stability analysis. In *2018 IEEE 8th Annual International Conference on CYBER Technology in Automation, Control, and Intelligent Systems (CYBER)*. IEEE, 1085–1088.

[23] Michael P Manser and Peter A Hancock. 2007. The influence of perceptual speed regulation on speed perception, choice, and control: Tunnel wall characteristics and influences. *Accident Analysis & Prevention* 39, 1 (2007), 69–78.

[24] Michelle Nicolls, June Engeland, and Grégoire S Larue. 2026. A content analysis exploring adaptive cruise control and forward collision warning systems in vehicle manuals. *Transportation Research Part F: Traffic Psychology and Behaviour* 118 (2026), 103549.

[25] Luke Petersen, Lionel Robert, X Jessie Yang, and Dawn M Tilbury. 2019. Situational awareness, drivers trust in automated driving systems and secondary task performance. *arXiv preprint arXiv:1903.05251* (2019).

[26] PIARC (World Road Association). [n. d.]. Tunnel lighting system. PIARC Road Tunnels Manual. https://tunnelsmanual.piarc.org/en/equipment-systems-general-support/tunnel-lighting-system Accessed: 2026-04-07.

[27] Sean Seaman, Pnina Gershon, Linda Angell, Bruce Mehler, and Bryan Reimer. 2022. Evaluating the associations between forward collision warning severity and driving context. *Safety* 8, 1 (2022), 5.

[28] Ting Shang, Jiaxin Lu, Ying Luo, Song Wang, Zhengyu He, and Aobo Wang. 2024. Understanding the traffic flow in different types of freeway tunnels based on car-following behaviors analysis. *Tunnelling and Underground Space Technology* 143 (2024), 105494. doi:10.1016/j.tust.2023.105494

[29] Hongling Sheng, Tianyu Wei, Zhenyu Wang, Feiqi Gu, and Dengbo He. 2025. Seeing Beyond the Leading Vehicle: Designing V2V Braking Visualizations to Support Novice Drivers. In *Proceedings of the 17th International Conference on Automotive User Interfaces and Interactive Vehicular*

Applications. 19–25. doi:10.1145/3744333.3747815

[30] Per Strömgren and Svante Berg. 2018. Empirical tunnel traffic safety analysis in Sweden. In *18th International Conference Road Safety on Five Continents (RS5C 2018), Jeju Island, South Korea, May 16-18, 2018*. Statens väg-och transportforskningsinstitut.

[31] G. Underwood. 2007. Visual attention and the transition from novice to advanced driver. *Ergonomics* 50, 8 (2007), 1235–1249. doi:10.1080/00140130701318707

[32] Katja Vogel. 2003. A comparison of headway and time to collision as safety indicators. *Accident Analysis & Prevention* 35, 3 (2003), 427–433.

[33] Shoushuo Wang, Zhigang Du, Haoran Zheng, Lei Han, Xinhai Xia, and Shiming He. 2024. Improving driving safety in freeway tunnels: A field study of linear visual guiding facilities. *Tunnelling and Underground Space Technology* 143 (2024), 105489.

[34] WIM VAN WINSUM and Adriaan Heino. 1996. Choice of time-headway in car-following and the role of time-to-collision information in braking. *Ergonomics* 39, 4 (1996), 579–592.

[35] Guiming Xiao, Jaeyoung Lee, Qianshan Jiang, Helai Huang, Mohamed Abdel-Aty, and Ling Wang. 2021. Safety improvements by intelligent connected vehicle technologies: A meta-analysis considering market penetration rates. *Accident Analysis & Prevention* 159 (2021), 106234.

[36] Lin Xiao, Meng Wang, Wouter Schakel, and Bart van Arem. 2018. Unravelling effects of cooperative adaptive cruise control deactivation on traffic flow characteristics at merging bottlenecks. *Transportation research part C: emerging technologies* 96 (2018), 380–397.

[37] Weihua Zhang, Yajun Wang, Zhongxiang Feng, Shunying Zhu, Jianqiang Cui, Wei Hao, and Cheng Wang. 2022. A method to improve the hazard perception of young novice drivers based on Bandura's observational learning theory: Supplement to expert commentary training. *Transportation research part F: traffic psychology and behaviour* 85 (2022), 133–149.

[38] Yuxin Zhang and Xinyan Huang. 2024. A review of tunnel fire evacuation strategies and state-of-the-art research in China. *Fire Technology* 60, 2 (2024), 859–892.

[39] Weixuan Zhou and Xuesong Wang. 2022. Calibrating and comparing autonomous braking systems in motorized-to-non-motorized-vehicle conflict scenarios. *IEEE Transactions on Intelligent Transportation Systems* 23, 11 (2022), 20636–20651.

[40] Zichu Zhou, Fanyu Meng, Cancan Song, NN Sze, Zhongyin Guo, and Nan Ouyang. 2021. Investigating the uniqueness of crash injury severity in freeway tunnels: A comparative study in Guizhou, China. *Journal of Safety Research* 77 (2021), 105–113.