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Investigation of Car following and Lane Changing Behavior in Diverging Areas of Tunnel–Interchange Connecting Sections Based on Driving Simulation

Zhenhua Sun [1,2], Jinliang Xu [1,*], Chenwei Gu [1,*], Tian Xin [1] and Wei Zhang [3]

[1] School of Highway, Chang'an University, Xi'an 710054, China; 2021021092@chd.edu.cn (Z.S.)
[2] Shaoxing Communications Investment Group Co., Ltd., Shaoxing 312000, China
[3] China Railway Tunnel Group Co., Ltd., Municipal Engineering Company, Hangzhou 310000, China
* Correspondence: xujinliang@chd.edu.cn (J.X.); 2020021051@chd.edu.cn (C.G.)

Abstract: Tunnel–interchange connecting sections pose significant safety challenges on mountainous expressways due to their high incidence of accidents. Improving road safety necessitates a comprehensive understanding of driver behavior in such areas. This study explores the influences of road characteristics, signage information volume, and traffic conditions on drivers' car-following and lane-changing behavior in tunnel–interchange diverging areas. Utilizing driving data from 25 subjects of 72 simulated road models, driving performance is assessed using the Friedman rank test and multivariate variance analysis. The results highlight the significant influence of both connection distance and signage information load on driving behavior. In tunnel–interchange scenarios, the reduction in velocity increased by 62.61%, and speed variability surged by 61.11%, indicating potential adverse effects on driving stability due to the environmental transitions. Decreased connection distances are associated with reduced lane-changing durations, larger steering angles, and increased failure rates. Furthermore, every two units of increase in signage information leads to a 13.16% rise in maximum deceleration and a 5% increase in time headway. Notably, the signage information volume shows a significant interaction with connection distance ($F > 1.60$, $p < 0.045$) for most car-following indicators. Hence, the study recommends a maximum connection distance of 700 m and signage information not exceeding nine units for optimal safety and stability.

Keywords: tunnel–interchange sections; signage information volume; car following; lane changing; driving stability; road safety

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1. Introduction

Tunnel–interchange connection sections, increasingly prevalent due to geographical constraints, present significant challenges to driving safety and stability. These sections, characterized by their small spacing and rapid environmental changes, often lead to complex traffic flow patterns and frequent vehicle interweaving. This unique environment critically affects two key driving behaviors: car-following (CF) and lane-changing (LC) [1]. Influenced by road infrastructure, the driving environment, and driver characteristics, these behaviors govern vehicles' longitudinal and lateral movements, thereby impacting traffic flow efficiency and safety [2–4]. Drivers traveling on these connection sections must swiftly adapt to shifts in environmental scenarios and detect LC opportunities within limited time frames [5,6], which may alter drivers' decision-making processes and driving responses [7,8]. In addition, the difficulty of setting directions also increases the difficulty of visual recognition in the area [9,10]. Nevertheless, due to the multitude of involved variables and the complexity of conducting empirical experiments, the driving behavior characteristics on these sections remain largely unconfirmed.

Understanding the combined effects of tunnel and interchange divergences on driving behavior is therefore crucial. While numerous studies have investigated driving characteristics in either scenario, their cumulative impact remains less explored. In tunnel sections, the drastic change in illuminance is a key factor affecting drivers' perception of distance and speed [11–13]. Empirical data indicate that drivers respond more effectively when the lighting contrast between the inside and outside of the tunnel is minimal and the tunnel length is short. Otherwise, it may lead to increased speed fluctuations and affect the reaction time [14]. Other factors such as visibility distance, visual bias, and tunnel length may also alter drivers' perception, decision-making, and speed fluctuations [15–18].

Drivers aiming to exit the main line have to shift from the inner lane to the outer lane, resulting in frequent and concentrated forced diverging behaviors. This purposeful LC process is so-called mandatory lane changing (MLC) [19,20]. Multifarious factors influence MLC behavior in divergent areas. For example, research by Jetto, et al. [21] indicates that increased traffic density and a higher probability of braking substantially decrease the LC durations and accepted gap of drivers. Fatema and Hassan [22] posit that the closer a vehicle is to the end of the auxiliary lane, the more likely the driver is to diverge. Moreover, factors like roadway design [23,24], traffic control facilities [25], traffic flow [26], and interaction with surrounding vehicles [27] significantly dictate driving characteristics in divergence areas.

Additionally, drivers in diverging areas tend to focus their visual attention on obtaining directional information, often at the expense of monitoring traffic conditions ahead. This shift in focus is a notable contributor to traffic accidents [28]. In situations with an abundance of directional signs, the overload of information can increase drivers' cognitive load, possibly leading to errors [29]. An excessive amount of signage has been associated with driver distraction, lane deviations, and speed variations [30]. While well-designed traffic facilities can improve drivers' perception abilities, the placement of signs in connection sections is distinctly different from typical roadways due to the spatial constraints in tunnels [31]. Hence, the impact of connection section sign information on driving behavior warrants further exploration.

Previous research has made notable progress in exploring how visual contrasts, sign information, and divergent environments affect driver behavior. However, the added psychological strain faced by drivers near tunnel and interchange exits could impair their ability to process information and make decisions [6,13]. This issue is compounded in tunnels where lane changes are prohibited, forcing drivers to quickly interpret signage and identify opportunities for diverging lane changes under limited time and spatial conditions. These factors highlight the importance of re-examining and validating the existing findings in these specific roadway segments.

Regarding research methods, driving simulation tests are a primary research method for studying driving behavior under complex scenarios [32]. The driving simulation platform allows for the adjustment of test variables and the comprehensive comparison and evaluation of different environment combinations and design schemes [33,34]. Detailed and synchronous driving behavior data obtained from simulations provide a foundation for the in-depth analysis of behavioral indicators under various environmental stimuli [35]. In combination with statistical tests, significant differences in driving behavior under complex scenarios can be further clarified.

Based on the analysis above, this study aims to investigate the driving behaviors in diverging areas of tunnel–interchange connection sections, taking into account vital environmental variables such as connection distance, the volume of signage information, traffic conditions, and tunnel length. Utilizing a high-precision driving simulation platform, this research accurately replicates tunnel–interchange scenarios, providing detailed behavioral data for comprehensive analysis. The findings can help identify factors that significantly influence driving behavior in these roadway sections, understand the main and interaction effects between environmental variables and different driving indicators, and uncover the behavioral mechanisms influenced by these combined factors. The insights garnered from this research hold considerable implications for safety measures in small spacing sections of tunnels–interchanges, particularly the optimization of sign design.

2. Materials and Methods

A thorough and effective experimental dataset is essential for the evaluation of driving performance. In this study, driving simulation methods were used to evaluate the influence of the roadway environment on driving behavior. The connection sections of the tunnel and interchange were selected as the simulation scenarios to collect the CF and LC characteristics in diversion areas. These are compared with the general diversion sections (GDS), which are standard diversion sections without tunnels.

2.1. Simulation Platform and Participants

The experiments utilized a six-degrees-of-freedom (6-dof) vehicle motion simulation platform, complete with UC-win/Road 13.0 software (as shown in Figure 1). This platform includes a vehicle cockpit, steering wheel, brake and accelerator pedals, and automatic transmission, creating a realistic driving experience through visual, auditory, and kinematic feedback. The visual system incorporates three high-definition screens, offering a 130° horizontal and 40° vertical field of view. The auditory system simulates road and vehicle exhaust sounds, while the motion system delivers spatial 6-dof movement, allowing drivers to feel acceleration, turning, and sideslip and mimicking the sensation of vehicle vibration and road bumps.

Figure 1. Six-degrees-of-freedom vehicle motion simulation platform.

Participants were selected based on the following criteria:

(1) Good physical health, ensuring their ability to participate fully in the study;
(2) Vision of 20/25 or better, corrected or uncorrected, with no eye diseases. This ensures all participants meet the necessary visual acuity requirements for driving;
(3) Ownership of a valid Chinese driver's license for a minimum of 3 years, demonstrating a certain level of driving experience and skill.

Furthermore, to minimize the influence of individual traits such as driver age and experience on the results, this study selected young drivers of similar ages. Following these screening criteria, a total of twenty-five drivers, comprising 14 males and 11 females, participated in the simulation. Their ages ranged from 25 to 33 years old (M = 27.38, SD = 1.78), with driving experience varying from 3 to 7 years (M = 4.97, SD = 1.01). The subjects were neither colorblind nor color-weak, and they had no physiological or psychological diseases. All drivers had not experienced similar simulation experiments and did not know the purpose of the experiment.

2.2. Simulation Scenario Design

The simulation scenarios and facilities are designed with reference to the field cases of 11 expressways in the Shaanxi, Jiangsu, Yunnan, and Fujian provinces of China (Table 1).

To analyze driver behavior in tunnel–interchange connection sections under various factors, this study relies on field investigation data (refer to Table 1) to design simulated road models. The simulation scenarios are controlled by four key variables: Connection Distance (CD), Information Volume (IV) of signage, Traffic Conditions (TC), and Tunnel Length (TL). The simulation road layout and facility designs are detailed in Figure 2.

Table 1. Field survey of tunnel–interchange connecting sections in China.

Province	Position	Limit Speed (km/h)	Tunnel Length (m)	Connection Distance (m)	Traffic Volume (pcu/h)	Information Volume of Signs (units)
Jiangsu	S73-G228	70	949	507	420–1120	8
Jiangsu	S73-G310	70	3105	89	400–1020	6
Fujian	S81-S1531	80	1210	104	520–1090	10
Fujian	S81-S1531	80	1210	464	570–1130	9
Fujian	G104-S1531	80	5102	234	360–720	7
Yunnan	G78-G85	100	1108	112	540–1240	11
Yunnan	G56-S33	80	1426	298	480–1207	13
Yunnan	S22-G5611	100	3100	310	386–870	6
Shaanxi	S30-G65	80	2789	306	400–860	11
Shaanxi	S65-G30	80	1300	667	405–934	12
Shaanxi	G5-S21	80	7300	791	420–875	5

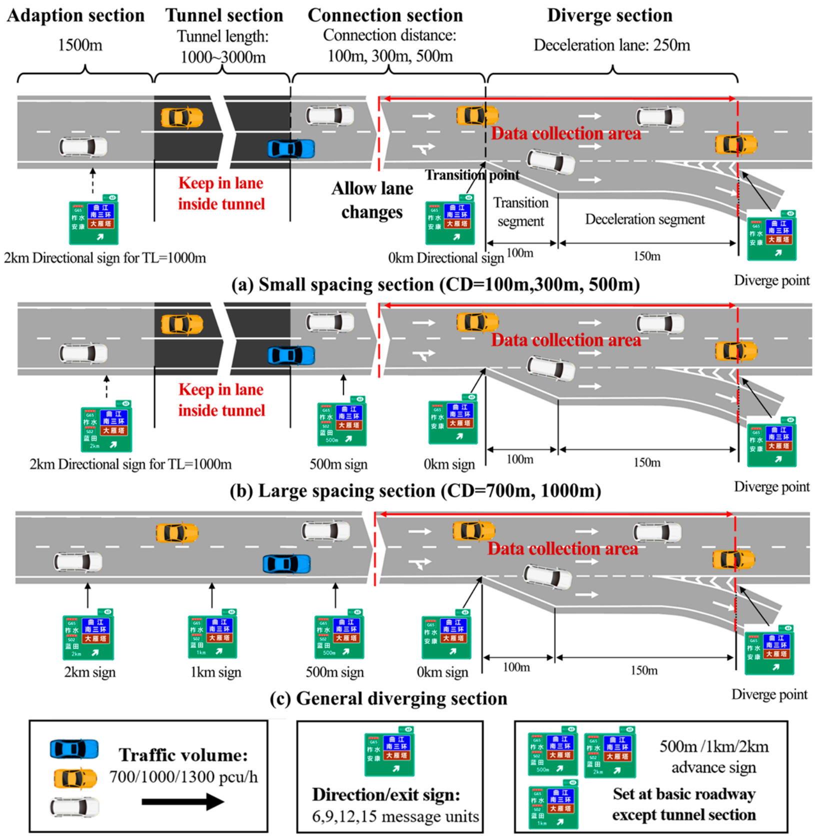

Figure 2. Roadway design and sign setting under the simulated scenario. The signs displayed feature Chinese characters for specific geographical locations (Zhashui, Ankang, Qujiang, etc.) pertinent to the study's context in China and presented in their native script for accuracy.

2.2.1. Sign Design

The IV of directional signs significantly impacts driver information processing in interchange sections. The traditional method to calculate information quantity, proposed by Shannon, involves assessing the number and types of bytes in the information [36]. However, due to the differences in character units and word formation between English and Chinese, this approach may not be entirely suitable for determining the IV of Chinese signs. Some researchers opt to use Chinese character blocks, such as road names, as the calculation standard for sign information load, while others base their calculations on the content conveyed by the sign [37,38]. This study combines these methods, considering the types of information transmitted by guide signs (including location, direction, etc.) as individual information units and establishing specific rules for calculating information on highway guide signs.

Previous research indicates that when information units exceed seven, it can impact driver cognition [30]. Thus, this study employs guide signs with 5, 7, 9, 11, and 13 information units in the simulation. The layout, font size, and positioning of these signs comply with G5 expressway standards in Shaanxi Province. To prevent driving adaptation, exit names are altered across different simulation scenarios. The detailed sign design is shown in Figure 3.

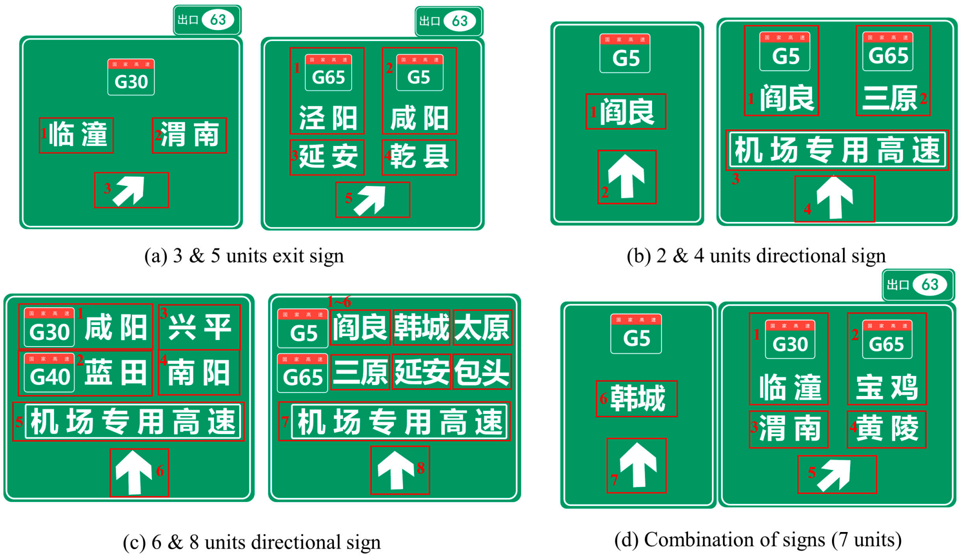

Figure 3. Examples of sign design. The signs displayed feature Chinese characters representing specific geographical locations (Yanliang, Lintong, Sanyuan, Hancheng, etc.), which are pertinent to the study's context in China and presented in their native script for accuracy.

2.2.2. Scenario Design

In addition to the four main control variables, the scenario design depicted in Figure 2 maintains consistency in all other road and environmental variables. Table 2 presents the design information for these scenarios. The basic road information is based on Table 1 and follows the recommended values for a design speed of 100 km/h according to Chinese design standards, including the lengths of deceleration lanes and shoulder widths.

Table 2. Information of scenario design.

(a) Independent variables			
Variables	**Attributes**	**Variables**	**Attributes**
CD (m)	100, 300, 500, 700, 1000	IV (units)	5, 7, 9, 11, 13
TL (m)	1000, 200, 3000	TC (pcu/h)	700, 1000, 1300
(b) Basic roadway information			
Variables	**Attributes**	**Variables**	**Attributes**
Design speed (km/h)	100	Limit speed (km/h)	Mainline 80; ramp: 60
shoulder width (m)	3.0	Lane number	Mainline 2; ramp: 1
Deceleration lane length (m)	150	Transition section Length (m)	100
Lane width (m)	3.75		

Specifically, the test scenarios feature a standard single-direction, two-lane road with a speed limit of 80 km/h. LC are prohibited in the tunnel, marked by the white solid line. All road sections in the diversion area employ parallel deceleration lanes that link with the ramp. The total length of the deceleration lane is 250 m, comprising a 100 m transition section and a 150 m deceleration section. Given the spatial constraints within tunnels, the setting of guide signs is often restricted to 1~2 locations in the connection sections.

As depicted in Figure 2, the road models are categorized into three types based on CD: small spacing sections (CD no more than 500 m), large spacing sections (CD of 700 m and 1000 m), and the GDS serving as the control group. These categories will be referred to by their abbreviations in the subsequent text. A total of 75 test sections were designed based on various combinations of TLs, CDs, and IVs. Upon coupling with three types of TCs, this yielded distinct traffic scenarios.

2.3. Experimental Procedure

The driving simulations were carried out in two daily sessions, from 8:00 to 11:30 and 14:00 to 17:30, with three rotating participants per session to ensure optimal individual driving conditions. Participants were advised to comply with signs, lane markings, and traffic regulations and to avoid any non-driving-related activities. The study utilized a within-subjects experimental design to ensure that each participant experienced different conditions and combinations of variables and scenarios. This approach ensured the comparability of data and minimized the potential impact of individual differences on the results, thereby enhancing the internal validity of the research.

The specific steps of the experiment were as follows:

(1) Participants' familiarization: participants were introduced to the driving tasks and the simulator's functionalities via a practice drive in a non-experimental environment.
(2) Scenario selection and simulation environment setup: the research team randomly selected test road sections and configured the traffic environment. The test vehicle was positioned in the left lane, and participants were informed of the destination.
(3) Experiment commencement and data collection: the formal experiment began, and the related data were recorded.
(4) Post-test breaks: following the completion of each testing round, participants were allowed to take short breaks.

This procedure was replicated across various experimental scenarios. After approximately 20–30 min or five scenarios, participants took a break while the next participant was tested, which also reduced the drivers' adaption for the specific scenarios. Each participant completed tests across all 75 sections, with TC (traffic volume) being randomly but uniformly assigned. Driving data were collected for the 1000 m range before each diverging point. A total of 1800 tunnel–interchange driving samples were collected. Among these, 1712 samples involved successful diverging, while the remaining 88 samples, which involved crashes or failure to enter the ramp, were categorized as failure samples. These will be subject to separate analysis in Section 3.4.

2.4. Selection of Driving Behavior Indicators

To comprehensively portray driving behavior in tunnel–interchange environments, several indicators related to CF and LC behaviors were selected. Definitions and clarifications for each indicator are delineated within this section.

2.4.1. CF Characteristics

The assessment of a driver's CF behavior is effectively conducted using speed and headway metrics, which together offer a detailed evaluation of longitudinal driving comfort and CF stability.

Speed metrics, specifically average velocity (V_{mean}), speed standard deviation (V_{std}), the reduction of velocity (RV), and maximum deceleration (DCC_{max}), are key to assessing driving safety and braking responsiveness [39]. V_{mean} and V_{std} (km/h) are calculated using speed data within a 600 m section preceding the diverging point. RV (km/h) represents the largest absolute difference between peaks and troughs on the speed curve, while DCC_{max} (m/s^2) signifies the journey's highest deceleration.

It should be noted that the V85 speed metric, typically used to measure the maximum speed not exceeded by 85% of vehicles at specific roadway cross-sections, was not employed in this study. Instead, this analysis specifically investigated the trends in vehicle speed distribution at various locations within connection sections. For a more detailed analysis of driver behavior, speed profiles were extracted and the position corresponding to the maximum deceleration was identified for micro-speed characteristic analysis.

Parallel to speed metrics, headway metrics elucidate the spatiotemporal dynamics of CF behavior [40]. Drivers aim to maintain an optimal distance headway (DH) and a suitable time headway (TH), reflecting the physical and temporal distances between consecutive vehicles. This study analyzes the average DH and TH throughout the journey, providing insights into longitudinal interactions and the impact of various factors on CF behavior.

2.4.2. LC Characteristics

In tunnel–interchange connection sections, vehicles execute two types of LC maneuvers after exiting a tunnel: MLC and Diverging Lane Change (DLC). These lateral motion maneuvers are crucial in shaping driving decisions and stability. To characterize LC behavior in these sections, various metrics are utilized, including the LC position relative to the diverging point (P_{MLC} for MLC, P_{DLC} for DLC), LC duration (MLCD, DLCD), LC length (MLCL, DLCL), LC angle (MLCA, DLCA), and the accepted gap.

The initiation and completion of LC are determined by shifts in lateral vehicle speed, with 0.1 m/s as the threshold [41]. LC duration (LCD) and length (LCL) are calculated using the time and distance differences between these two points. LC angle (LCA) is derived as the mean steering wheel angle during the LC. Particularly, P_{MLC} and P_{DLC} are assessed based on the vehicle's lateral position at the lane crossing.

The accepted gap, a unique metric in lane-changing behavior, measures the distance between the front and rear vehicles in the target lane at the onset of the LC. Given that DLCs often occur with a single front vehicle in the deceleration lane, our focus is mainly on the accepted gap during MLCs. Furthermore, the Ashworth method [42] estimates the critical accepted gap under various traffic and road conditions, representing the minimum gap that drivers can accept, which reflects the driving demand for LC space under different scenarios. This method is based on the assumption that both the critical gap and the accepted vehicle gap adhere to a normal distribution across different traffic volumes. The critical accepted gap is thereby calculated using the following formula:

$$\mathrm{Gap_c} = \overline{\mathrm{Gap_a}} - \mathrm{q}\sigma_a^2$$

where $\mathrm{Gap_c}$ denotes the critical accepted gap (s); $\overline{\mathrm{Gap_a}}$ denotes the mean accepted gap (s); q refers to the traffic flow rate (veh/s); and σ_a^2 is the variance of the accepted gap.

2.5. Statistical Tests

To investigate the behavioral differences under varying CD, IV, TC, and TL and to comprehend their interaction effects, this study employs three distinct statistical tests:

(1) Friedman test: Employed as a non-parametric method, the Friedman test [43] is utilized to detect significant differences across related groups. It is particularly useful in assessing the impact of independent variables on CF and LC characteristics.
(2) Multivariate Analysis of Variance (MANOVA): Applied when dependent variables display consistent variance, MANOVA [44] detects significant differences among these variables and explores their interactions and combined effects on behavioral indicators.
(3) Dunn's test: Utilized for pairwise comparisons, this test assesses significant variations among dependent variables in different environmental scenarios, effectively highlighting specific differences arising from diverse environmental combinations.

These statistical approaches provide a comprehensive framework to thoroughly evaluate the effects of diverse independent variables on CF and LC behaviors, establishing a solid basis for in-depth analysis.

3. Results and Analysis

3.1. General Analysis

Table 3 offers a comparison of driving indicators between GDS and tunnel–interchange scenarios, which underscores noticeable distinctions in driving parameters between these environments. Particularly in smaller spacing scenarios, a notable trend emerges: a reduction in average speed and an escalation in speed variability. This trend accompanies a decrease in both the duration and length of lane-changing maneuvers. Significantly, the study observes a 62.61% increase in RV (S.E. = 0.217, $p = 0.011$), an 18.60% rise in DCC $_{max}$ (S.E. = 0.021, $p < 0.001$), and a 61.11% escalation in V $_{std}$ (S.E. = 0.26, $p < 0.001$) within tunnel–interchange samples. The distributions of V $_{mean}$, TH, MLCD, and MLCL closely resemble the traffic observational data extracted from the previous study [10,25]. These preliminary analyses point to potential detrimental impacts on driving stability and safety due to environmental transitions specific to tunnel–interchange contexts.

Table 3. Descriptive statistics.

Scenario	Variables	Mean	Std.	Variables	Mean	Std.
TIS *	V $_{mean}$ (km/h)	84.98	5.44	MLCD (s)	4.40	1.54
GDS		89.26	4.37		5.81	1.57
TIS	V $_{std}$ (km/h)	5.05	1.03	MLCL (m)	92.34	26.71
GDS		4.03	0.97		124.82	33.11
TIS	DCC $_{max}$ (m/s^2)	−1.02	0.27	MLCA (°)	16.72	4.51
GDS		−0.86	0.21		13.25	3.65
TIS	RV (km/h)	5.35	2.95	DLCD (s)	4.30	1.54
GDS		3.29	1.93		4.89	1.57
TIS	DH (m)	61.48	9.90	DLCL (m)	92.34	26.71
GDS		52.61	7.40		95.88	27.79
TIS	TH (s)	2.78	0.40	DLCA (°)	14.12	4.51
GDS		2.52	0.33		14.45	4.25
TIS	Gap (s)	3.85	0.89			
GDS		4.36	0.87			

* TIS refers to tunnel–interchange section scenarios; GDS refers to general diversion scenarios.

Delving into the influence of environmental factors, Table 4 elucidates the correlations among various indicators. CD stands out with strong correlations across most driving metrics, particularly evident in MLCD and MLCA, where coefficients surpass 0.60. This implies a pronounced sensitivity of lane-changing behavior to spatial alterations in tunnel–interchange environments. IV, exhibiting moderate correlations with key speed and CF indicators, suggests signage information's substantial influence on driver speed selection. In addition, drivers' gap selection during LC displays the highest correlation with TC, with a coefficient exceeding 0.6. Contrarily, TL does not exhibit significant correlations with other indicators, aligning with findings from prior research [25]. The following analyses will be carried out focusing on combinations of independent and dependent variables with correlation coefficients higher than 0.25 (the bold terms).

Table 4. Correlation analysis.

	CD	IV	TC	TL	Variable	CD	IV	TC	TL
V $_{mean}$	**0.48** *	**−0.30**	−0.18	−0.13	MLCD	**0.65**	−0.10	−0.24	−0.09
RV	**−0.28**	**0.31**	0.10	0.09	MLCL	**0.43**	−0.15	−0.17	−0.04
DCC $_{max}$	**0.29**	**−0.38**	0.16	−0.09	MLCA	**−0.62**	0.11	0.21	−0.07
DH $_{min}$	**−0.31**	**0.30**	**−0.46**	−0.08	DLCD	0.22	−0.07	0.16	−0.03
TH $_{min}$	**−0.45**	**0.39**	**−0.52**	−0.06	DLCL	0.15	−0.13	0.14	−0.05
P_{MLC}	**0.57**	0.05	−0.09	0.03	DLCA	−0.15	0.10	0.05	−0.04
P_{DLC}	**0.54**	0.02	−0.03	0.04	Gap	**0.37**	−0.15	**−0.48**	−0.03

* Bold terms indicate that the correlation coefficient is greater than 0.25.

3.2. Speed and Car following Characteristics

In order to verify the impact of environmental variables on CF indicators, both main and interaction effects under various conditions of CD, IV, and TC have been examined in Table 5 using the Friedman and MANOVA tests. Further, Table 6 utilizes Dunn's test to confirm the intergroup differences under the interactive effects of IV and CD. The subsequent sections will dissect the distribution patterns of CF indicators influenced by significant environmental factors, providing an in-depth exploration of their impacts.

Table 5. Friedman and MANOVA test for speed and CF indicators.

	Friedman Test						MANOVA	
	CD		IV		TV		CD + IV	
	Chi^2	*p*-Value	Chi^2	*p*-Value	Chi^2	*p*-Value	F	*p*-Value
RV	16.3	0.003	14.78	0.002	3.3	0.193	1.86	0.020
AV SP	9.76	0.045	9.58	0.022	3.18	0.203	1.75	0.033
DH	9.94	0.041	12.28	0.006	10.3	0.006	1.60	0.045
TH	18.52	0.001	9.76	0.021	8.44	0.215	1.66	0.034
DCC_{max}	16.12	0.003	8.64	0.034	6.38	0.141	2.87	0.001

Table 6. Intergroup differences in CF indicators under interaction effect of IV and CD.

CD (m)	IV1 (units)	IV2	RV (km/h) Diff.	*p*	V_{mean} (km/h) Diff.	*p*	DCC_{max} (m/s^2) Diff.	*p*	DH_{min} (m) Diff.	*p*	TH_{min} (s) Diff.	*p*
100	5	7	**−2.61** *	0.001	1.33	0.066	**0.119**	0.001	−0.75	0.522	−0.065	0.273
	7	9	**−1.37**	0.001	0.97	0.182	**0.135**	0.001	**−4.66**	0.001	−0.099	0.096
	9	11	**−1.24**	0.001	**1.76**	0.015	**0.214**	0.001	−2.05	0.079	**−0.120**	0.039
	11	13	**−1.06**	0.001	0.52	0.472	**0.069**	0.048	**−3.94**	0.001	**−0.197**	0.001
300	5	7	**−1.28**	0.001	0.81	0.262	**0.160**	0.001	−0.09	0.940	−0.031	0.604
	7	9	**−1.24**	0.001	0.78	0.281	**0.115**	0.001	**−2.29**	0.049	−0.080	0.178
	9	11	**−2.21**	0.001	**1.70**	0.019	**0.142**	0.001	**−5.18**	0.001	**−0.168**	0.005
	11	13	**−1.81**	0.001	0.73	0.311	**0.098**	0.005	**−4.18**	0.001	**−0.188**	0.001
500	5	7	−0.44	0.103	0.09	0.710	**0.142**	0.001	0.26	0.824	0.002	0.970
	7	9	**−1.55**	0.001	**1.44**	0.047	**0.080**	0.022	−1.35	0.248	−0.064	0.284
	9	11	**−2.37**	0.001	**1.69**	0.019	**0.101**	0.004	**−5.31**	0.001	**−0.128**	0.031
	11	13	**−1.99**	0.001	1.38	0.058	**0.125**	0.001	−2.14	0.067	−0.055	0.356
>700	5	7	−0.33	0.236	0.19	0.431	0.041	0.244	−0.61	0.599	−0.077	0.196
	7	9	−0.51	0.062	0.81	0.262	0.054	0.118	−1.32	0.212	−0.019	0.751
	9	11	**−2.13**	0.001	0.97	0.182	**0.124**	0.001	**−4.29**	0.001	**−0.146**	0.014
	11	13	**−1.74**	0.001	1.15	0.110	**0.093**	0.007	−1.76	0.318	0.017	0.774

* The bold terms indicate that the difference between the groups is significant at the 95% level.

3.2.1. Speed Distribution

Vehicle speed fluctuations provide valuable insight into driving safety, as erratic speed patterns can significantly increase the likelihood of accidents [45,46]. According to the detailed speed profiles, tunnel–interchange sections can be differentiated into distinct areas based on vehicle speed attributes: steady car-following area, speed variation area, and diversion exit area, as depicted in Figure 4. A notable observation across most driving samples is that peak speed fluctuations typically occur within 350 m before the transition point, which coincides with the interval of maximum speed reduction. After implementing noise reduction with a three-point moving average window and enhancing curve smoothness using third-order B-spline methods, Figure 5 demonstrates the speed profiles in this zone under different CD and IV conditions.

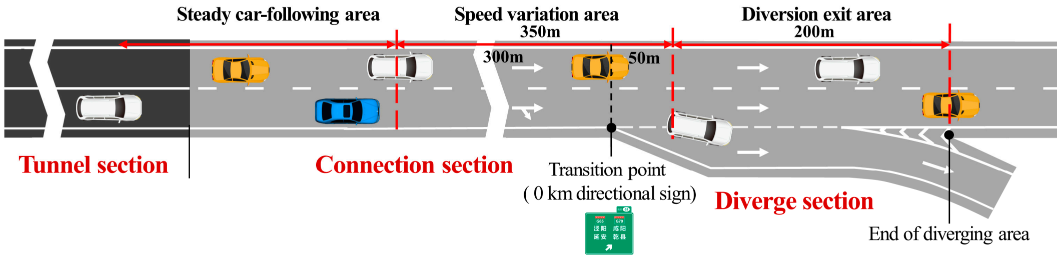

Figure 4. Zonal classification of diverging area based on the vehicle speed attributes. The sign displayed feature Chinese characters for specific geographical locations (Jingyang, Xianyang, yanan, etc.) pertinent to the study's context in China and presented in their native script for accuracy.

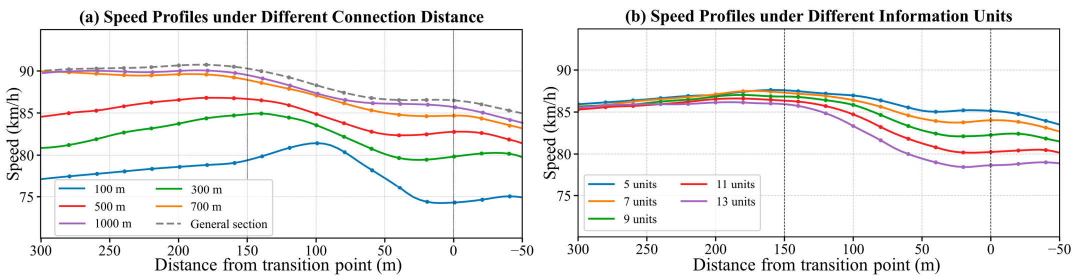

Figure 5. Speed profiles under different CDs and IVs.

Figure 5a demonstrates the significant impact of CD on speed control within the diversion area. Shorter CDs are associated with a decrease in average speed and an uptick in speed fluctuations. Specifically, larger spacing sections (≥700 m) show a speed distribution akin to the GDS group, maintaining a stable range of 85~95 km/h, with an average deviation of around 2.33 km/h. In contrast, smaller spacing sections (≤500 m) lead to a reduction in average speed by approximately 10.16%, alongside an increase in standard deviation to 4.58 km/h, thereby adopting a distinct "accelerate-decelerate-steady" pattern. The data also suggest an earlier onset of deceleration in tighter spaces, transitioning from 200 m to 100 m before the signage.

In relation to signage information density, Figure 5b shows that denser signage information increased speed fluctuation and velocity reduction. This trend is particularly evident as drivers encounter more signage information, necessitating a reduction in speed to process the additional data. The average deceleration range widens from 2.58 km/h for 5 units of information to 7.53 km/h for 13 units, with a marked difference emerging beyond 7 units.

Providing a holistic view, Figure 6 compares driving speeds under various CD and IV combinations. It is evident that in shorter spaces, drivers respond with greater deceleration to the same informational stimuli compared to more spacious sections, likely due to constrained decision-making time. According to Table 6, all IV groups show significant speed reduction differences in 100 m and 300 m sections. However, this distinction fades in 500 m sections between five and seven information units and becomes prominent again only when the spacing extends beyond 700 m and information units increase past nine. This pattern underscores the need for strategic signage placement and design adjustments based on the specific characteristics of each tunnel–interchange connection section.

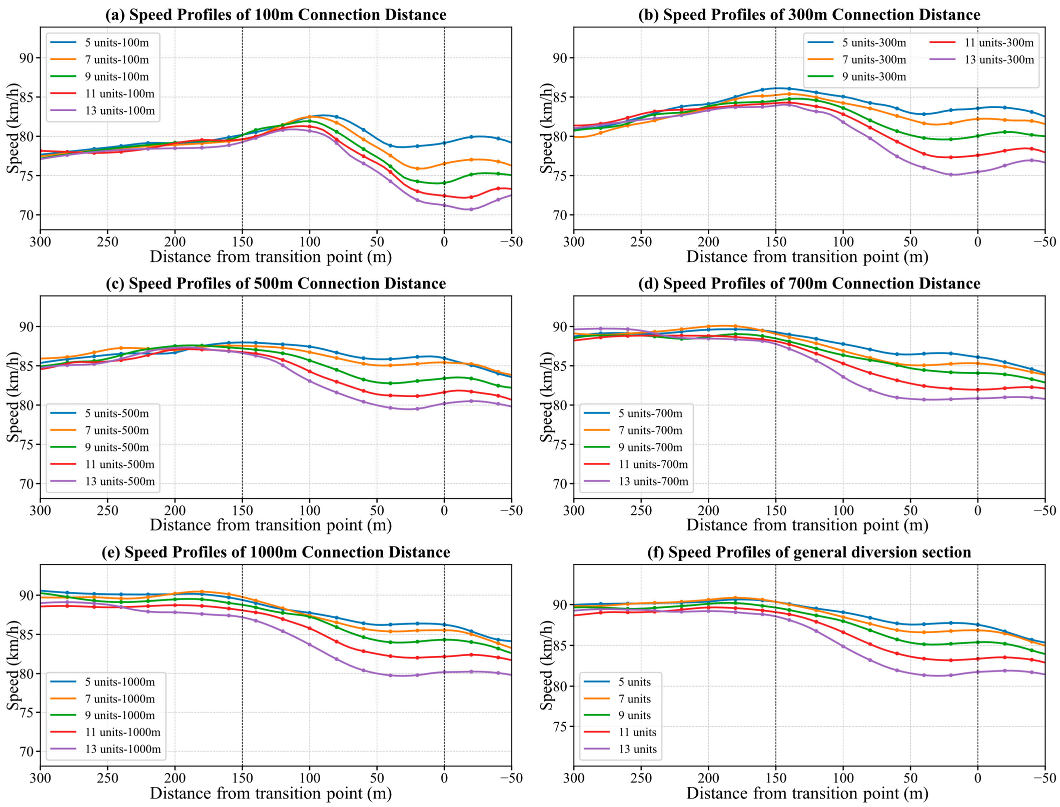

Figure 6. Speed profiles under the combination of CD and IV.

3.2.2. Maximum Deceleration

DCC $_{max}$, a measure of braking response during vehicle operation, serves as a common indicator for assessing longitudinal driving safety and comfort [47,48]. Table 5 reveals significant main effects ($p < 0.034$) and interaction effects ($p = 0.001$) between CD and IV with respect to DCC $_{max}$. This relationship is further visualized in Figure 7, which depicts the distribution of DCC $_{max}$ across different combinations of CD and IV. The legend in Figure 7c categorizes information volumes as low (5 and 7 units), medium (9 units), and high (11 and 13 units), respectively.

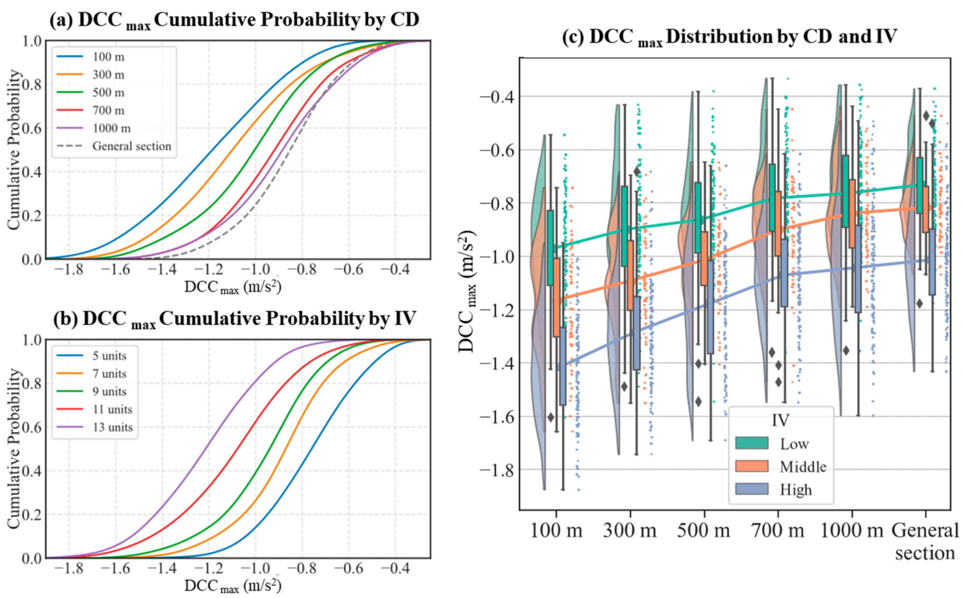

Figure 7. DCC $_{max}$ distribution under different CDs and IVs.

The results indicate that reduced spacing and elevated IV significantly amplify the deceleration level within diversion sections, with DCC $_{max}$ ranging between −1.65 and −0.80 m/s². It appears that IV carries a more profound influence on braking responses. Given a consistent spacing, DCC $_{max}$ displays a linear relationship with IV. Each additional two units after an IV of seven units results in approximately a 13.16% increase in DCC $_{max}$, implying that drivers tend to drive more cautiously under high information loads.

On the other hand, reduced CD also escalates drivers' deceleration levels. As the spacing shrinks below a CD of 700 m—identified as a turning point in the DCC $_{max}$ distribution—the rate of deceleration intensifies. Specifically, for every 200 m reduction in CD, DCC $_{max}$ experiences an average surge of 14.02%. However, this trend is not pronounced in larger spacing and GDS groups ($p > 0.085$).

According to Table 6, the interaction effects between CD and IV significantly shape the distribution of DCC $_{max}$. Under varying levels of IV, the difference in DCC $_{max}$ between the 100 m section and GDS sections ranges from 0.213 to 0.425 m/s2. This indicates that drivers maintain relatively stable deceleration rates over different distances when signage information is low. However, with an increase in sign information, the deceleration in smaller spacing sections markedly exceeds that in the GDS scenarios.

Figure 8 further shows the relative relationship between the location of maximum deceleration and DCC $_{max}$, with the x-axis distance reference aligned with Figure 6. The intensity of scatter colors reveals the distribution density of samples, with darker hues denoting more concentrated maximum deceleration behavior within a particular interval. The results indicate that, when the CD is no less than 500 m, as seen in Figure 8c,d, the locations of maximum braking are widely distributed, yet primarily situated within 300 m of the transition point. When the CD falls below 300 m, the maximum deceleration position rapidly clusters within 100 m before the sign and the DCC $_{max}$ intensifies. This abrupt deceleration behavior could undermine driving comfort and potentially trigger backward transmission of traffic disturbance waves.

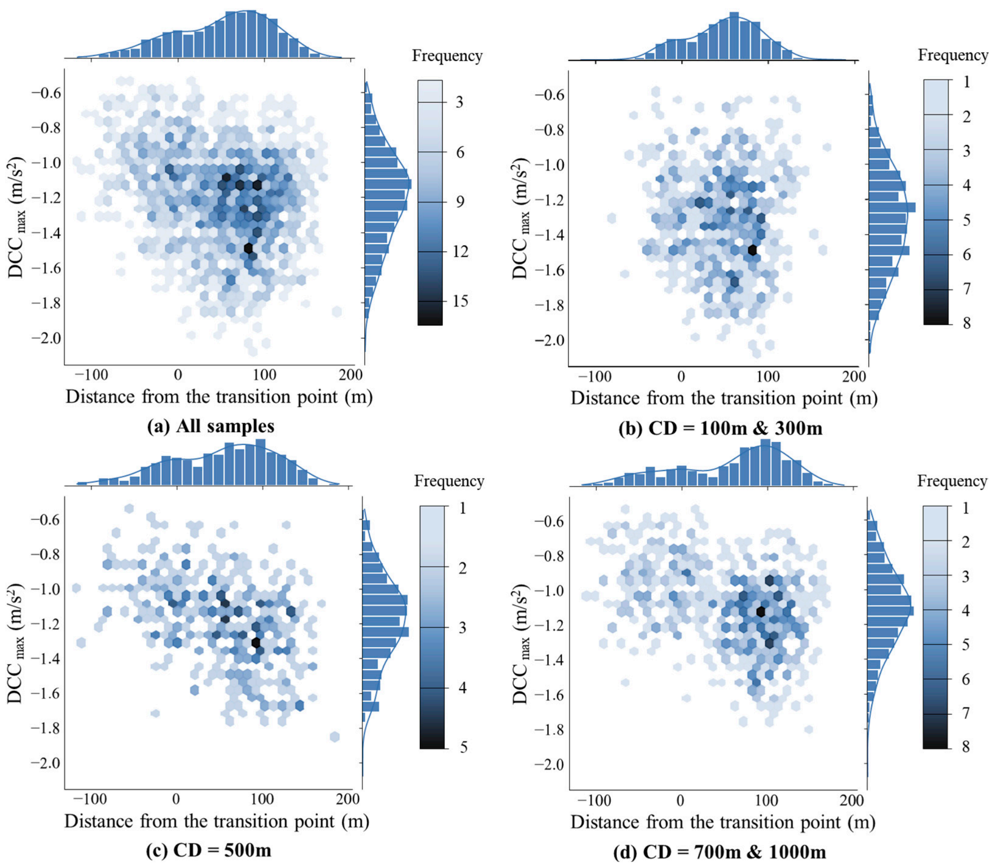

Figure 8. The distribution of maximum deceleration position.

3.2.3. CF Headway

The CF headway is key for understanding vehicle interactions and driver responses on the road. The Friedman test in Table 6 highlights significant differences in average TH and DH under varying CD, IV, and TC ($p < 0.041$). Figures 9–11 offer a comparative analysis of these distributions. Broadly, TH is more sensitive to environmental changes than DH, with adjacent CD groups displaying small differences in DH but larger ones in TH. This indicates that complex environments noticeably lower the average vehicle speed (Figure 6), consequently increasing TH variability.

Traffic volume, denoting the average TH of a traffic flow, is a major determinant of CF behaviors. In the 3rd LOS condition, the average TH for vehicles is 2.22 s, a reduction of 0.63 s and 0.32 s compared to the 1st and 2nd LOS conditions, respectively.

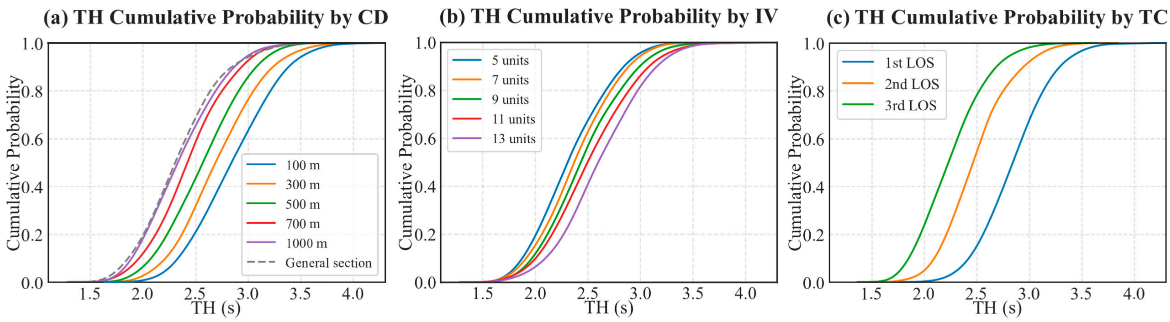

Figure 9. Cumulative probability distribution of TH.

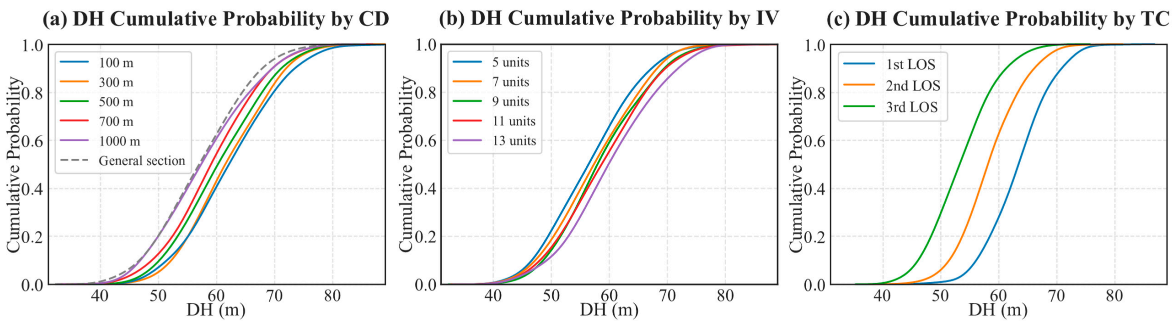

Figure 10. Cumulative probability distribution of DH.

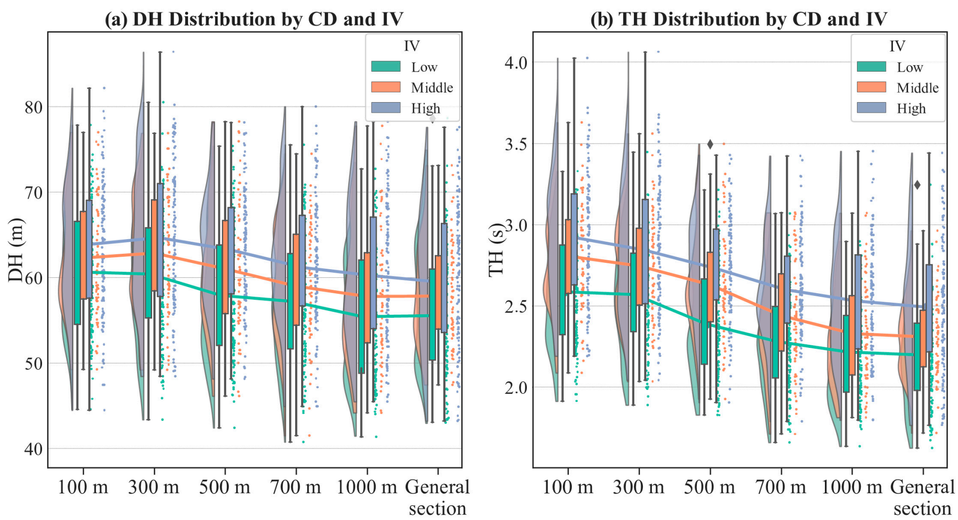

Figure 11. Distribution of TH and DH under different CDs and IVs.

Furthermore, when CD decreases and IV increases, there's an observed rise in both DH and TH. For instance, when compared to the CD of 1000 m, drivers under the CD of 100 m display an increase of 7.71% in DH and 17.96% in TH. This pattern could stem from increased driving uncertainty due to environmental switches in tunnels–interchanges, suggesting drivers adjust their behavior for safety in changing environments.

Besides, IV has a significant impact on DH and TH distribution, with drivers often decelerating near signs to adjust to environmental changes. The study reveals that once the information volume exceeds seven units, each two-unit increase leads to an approximately 1.48% and 4.95% rise in DH and TH, respectively.

The interaction effects in Table 6 demonstrate that in sections with small spacing, IV changes more profoundly affect CF behavior. In comparison to GDS samples, the average intergroup differences in the DH and TH of small spacing rise by 42.8% and 84.2%, respectively. On the other hand, for large spacing sections, a significant difference in TH (S.E. = 0.025, $p < 0.001$) is only observable when the IV exceeds 11 information units. For CDs under 500 m, however, this threshold reduces to nine units.

Maintaining safe following distances is crucial for driving safety. However, longer headways can reduce traffic capacity, particularly under conditions of increasing traffic volume. This can lead to capacity challenges and potentially cause congestion near diversion zones, highlighting a key balance between safety and traffic flow efficiency.

3.3. Lane Changing Characteristics

In order to verify the impact of environmental variables on LC indicators, main and interaction effects have been examined using Friedman and MANOVA tests, as presented in Table 7. Notably, DLC indicators do not exhibit significant differences under varying environmental conditions, a result that aligns with the low correlation (<0.2) found in the correlation analysis (Table 4). Conversely, MLC characteristics demonstrate notable variation under differing CD conditions, and the choice of LC gaps is significantly influenced by traffic volume. Further examination of these differences will be undertaken in this section, focusing on three aspects: LC position, MLC characteristics, and the accepted gap.

Table 7. Friedman and MANOVA test for LC indicators.

Independent Variables	Friedman Test CD		IV		TC		MANOVA CD + TC	
	Chi^2	p	Chi^2	p	Chi^2	p	F	p
MLCD	**22.22**	0.000	8.68	0.070	**7.94**	0.019	/	/
MLCL	**12.18**	0.032	**9.65**	0.047	4.98	0.082	/	/
MLCA	**18.88**	0.002	7.18	0.127	5.76	0.056	1.613	0.097
DLCD	9.97	0.076	3.74	0.442	3.70	0.157	/	/
DLCL	7.29	0.200	6.94	0.139	2.58	0.225	0.895	0.537
DLCA	9.45	0.092	5.27	0.261	4.56	0.102	0.854	0.576
P_{MLC}	**13.82**	0.017	5.26	0.262	5.33	0.070		
P_{DLC}	**11.61**	0.041	1.28	0.864	3.48	0.175	/	/
Gap	**12.39**	0.030	7.51	0.111	**17.20**	0.000	**3.303**	0.001

The bold terms indicate that the difference between the groups is significant at the 95% level.

3.3.1. Distribution of LC Position

Table 8 details the distribution of LC positions relative to the end of the diverging area under various CDs. These positions are categorized into three groups at distances of 460 m and 250 m, corresponding, respectively, to the diverging influence areas as defined by the Highway Capacity Manual (HCM) [49] and the starting of the deceleration lane. Figure 12 reveals a trend where the P_{MLC} typically occurs later in the tunnel–interchange sections, with about 90% of drivers transitioning to the outer lane within these influence areas. Additionally, an increase in IV significantly influences MLC positioning. For instance, increasing IV from 5 to 13 units results in the average LC position being delayed by around 20 m, suggesting that higher IV shifts the LC position closer to the exit area.

Table 8. Distribution of P_{MLC} and P_{DLC}.

CD	P_{MLC}				P_{DLC}			
	Mean (m)	Distribution			Mean (m)	Distribution		
		>460 m	460~250 m	<250 m		>150 m	100~150 m	<100 m
100 m	208.11	/	16.7%	83.3%	99.2	1.0%	49.3%	49.7%
300 m	273.18	/	72.3%	27.7%	123.8	7.3%	82.0%	10.7%
500 m	307.65	8.3%	83.7%	8.0%	143.1	30.0%	65.0%	5.0%
700 m	343.85	17.3%	79.4%	3.3%	158.0	69.3%	29.3%	1.3%
1000 m	356.00	32.4%	65.1%	2.4%	158.6	70.7%	22.3%	7.0%
Total	297.4	11.6%	63.4%	25.0%	136.5	35.7%	49.6%	14.7%
GDS	437.6	48.3%	50.5%	1.2%	159.1	70.0%	25.3%	4.7%

We further extracted LC trajectories within the diverging influence area and applied smoothing and noise reduction to the curves, as depicted in Figure 13. The y-axis denotes the distance from the vehicle's left side to the road's left line. As CD decreases, there's an increase in MLCs near the directional sign. For a CD of 1000 m, the average P_{MLC} is at 356 m, which shortens to 261 m in smaller spacing scenarios, suggesting that limited spacing affects drivers' sign recognition time and, consequently, their LC decisions.

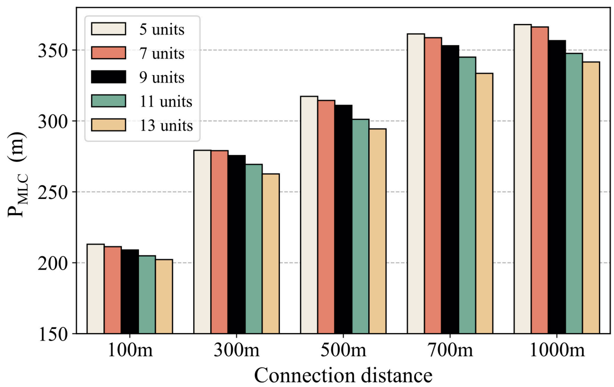

Figure 12. Distribution of P_{MLC} under different CDs and IVs.

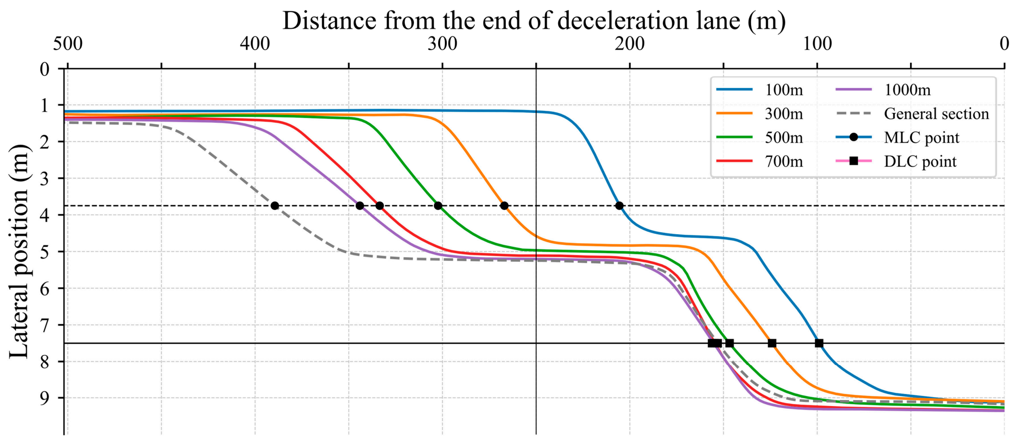

Figure 13. LC trajectories under different CDs.

In terms of P_{DLC} distribution, most vehicles are observed to diverge just after the taper of the deceleration lane, with about 96% diverging in the first half of this lane. However, for CDs of 100 m and 300 m, the point of divergence initiation is notably delayed.

The LC trajectories showcased in Figure 13 indicate a trend of more urgent MLCs in smaller spacing sections, particularly for CDs of 100 m and 300 m. This observation points to heightened risks associated with MLC. Interestingly, the trajectories for Diverging Lane Changes (DLCs) from the mainline to the auxiliary lane display less variation, suggesting a more consistent behavior pattern in DLCs regardless of CD.

3.3.2. MLC Characteristics

Expanding on the impact of CD on MLC, Figure 13 reveals that as CD decreases, drivers engage in quicker lane changes over shorter distances, leading to steeper trajectories. This observation is further detailed in Figure 14, which quantitatively analyzes the variations in LCD, LCA, and LCL, providing deeper insights into the specific ways CD influences MLC behavior in constrained environments.

The results indicate that a shorter CD typically leads to a reduced LCD and an increased LCA in most cases. Specifically, at CDs below 300 m, vehicles face a limited time window for LC, with most LCDs centered around 2.55 s and LCAs exceeding 18°. In contrast, for CDs greater than 700 m, LCAs tend to be within 14° and LCDs extend to about 3.59 s, closely resembling the GDS conditions and exhibiting a wider distribution. This trend points to a significant improvement in MLC stability as CD increases.

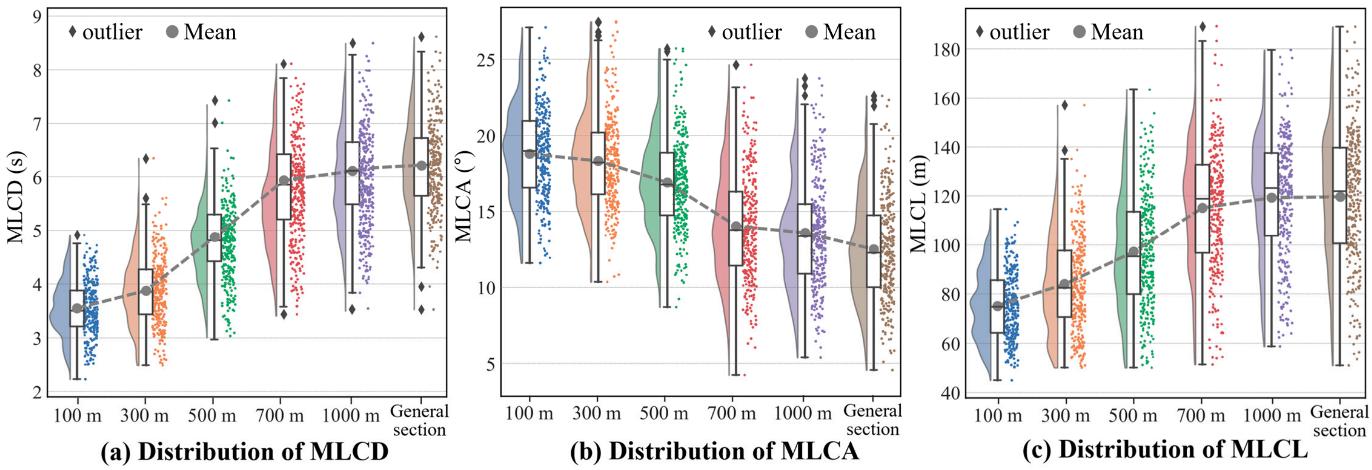

Figure 14. Distribution of MLC characteristics. The colors represent different sample groups.

The distribution of MLCL largely mirrors that of MLCD, albeit with more distinct distribution variations. For large spacing sections, there's noticeable variability in the distance covered during the lane change, with LCL typically ranging between 50 and 180 m. As CD decreases, vehicles must complete the MLC within a restricted distance, leading to a more uniform LCL distribution. For example, at a CD of 100 m, the majority of samples maintain the LCL between 50 and 100 m.

The results highlight that insufficient spacing between tunnels and interchanges limits drivers' LC maneuvers, compelling them to adopt a more aggressive strategy. To delve into these dynamics, Figure 15 presents the joint distribution of three indicators and shows clear relations: as expected, LCL decreases and drivers opt for larger steering angles within shorter LCD, illustrating the adjustments of drivers under various spacing constraints.

Table 9 lists the intergroup differences in MLC features at a 95% significance level. It shows no significant variances in three indicators between large spacing and GDS samples. However, in small spacing sections, these differences become more pronounced. Combined with the results of Figure 15, for optimal LC stability, the CD should ideally not surpass 700 m, slightly above the critical spacing obtained by traffic conflicts [13].

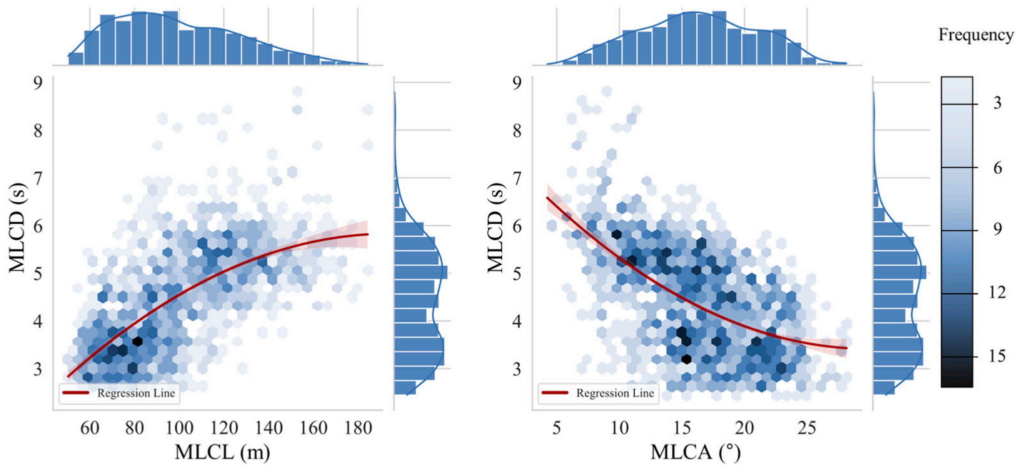

Figure 15. Joint distribution between MLCD, MLCL, and MLCA.

Table 9. Dunn's test for intergroup differences in MLC indicators.

CD		MLCA (°)		MLCD (s)		MLCL (m)	
Group 1	Group 2	Difference	*p*-Value	Difference	*p*-Value	Difference	*p*-Value
1000 m	100 m	**6.26** *	0.000	**−2.56**	0.000	**51.04**	0.000
	300 m	**5.69**	0.000	**−2.23**	0.000	**43.65**	0.000
	500 m	**4.41**	0.000	**−1.23**	0.000	**27.46**	0.000
	700 m	0.68	0.064	−0.15	0.147	4.04	0.079
	GDS	−0.30	0.805	**0.17**	0.047	−1.31	0.570
300 m	100 m	0.58	0.147	**−0.33**	0.000	**7.38**	0.001
	500 m	**−1.27**	0.000	**1.00**	0.000	**−16.19**	0.000
	700 m	**−5.01**	0.000	**2.08**	0.000	**−39.61**	0.000
	1000 m	**−5.69**	0.000	**2.23**	0.000	**−43.65**	0.000
	GDS	**−5.98**	0.000	**2.40**	0.000	**−44.96**	0.000

* The bold terms indicate that the difference between the groups is significant at the 95% level.

3.3.3. Accepted Gap

Gap acceptance, a key factor in LC modeling, reflects drivers' safety and smoothness expectations during LC decisions. Statistical tests show a significant influence of CD and TC on gap acceptance, with both main ($p < 0.001$) and interactive effects ($p < 0.001$) observed. Figure 16 displays the distribution of accepted and critical gaps, illustrating the impact of CD and TC interaction on gap selection. As CD decreases, drivers tend to choose smaller gaps for LC, indicative of a proactive LC strategy. For instance, in 100 m CD scenarios, about 30% of vehicles opt for gaps of less than 3 s for LC completion (Figure 16a). Conversely, at a 1000 m CD, such choices are much rarer, seen in under 5% of samples. These patterns highlight a heightened urgency for LC in small spacing sections.

Table 10 further examines the variance in the accepted gaps due to changes in CD across different LOS. At the first service level, the accepted gap in different CDs is similar, with only a 0.26 s difference between the 100 m and 1000 m samples. In contrast, at the 2nd and 3rd LOS, these differences expand to 0.67 s and 0.91 s. As traffic volume escalates, intergroup differences for various CDs widen, particularly elevating LC difficulties in shorter spacing sections under heavy traffic.

Figure 17 further details the joint distribution relationship between the accepted gaps and MLC characteristics. When the gap drops below 3 s, the average LCA increases to 17.6°, and the average LCD drops to about 3.8 s. It can be inferred that drivers on larger spacing sections with low traffic volumes benefit from more time and space to assess and select suitable gaps. Conversely, on shorter spacing sections with high traffic volumes, drivers are compelled to choose smaller gaps and expedite LC completions. This change consequently lowers the actual gap selection to less than 3 s, negatively impacting the vehicle's lateral control.

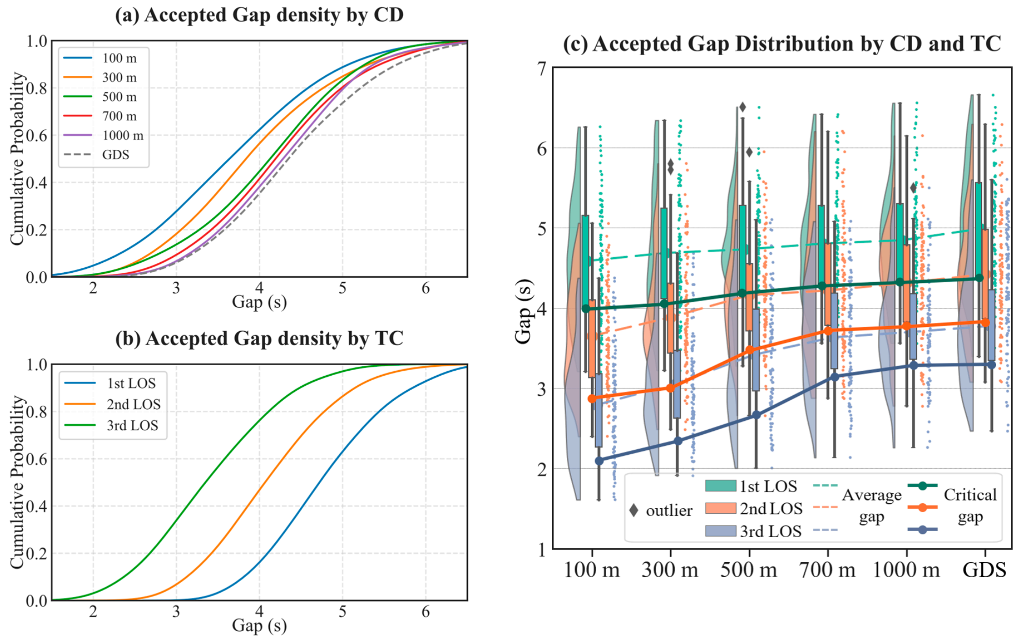

Figure 16. Distribution of accepted gaps.

Table 10. Intergroup differences in accepted gaps under interaction effect of TC and CD.

LOS	Type		Gap (s)		LOS	Type		Gap (s)	
	CD1	CD2	Diff.	*p* Value		CD1	CD2	Diff.	*p* Value
1st level	100 m	300 m	−0.101	0.315	3rd level	100 m	300 m	**−0.264**	0.008
	300 m	500 m	−0.044	0.661		300 m	500 m	**−0.360**	0.001
	500 m	700 m	−0.073	0.467		500 m	700 m	**−0.196**	0.031
	700 m	1000 m	−0.042	0.673		700 m	1000 m	−0.067	0.506
	1000 m	GDS	−0.144	0.100		1000 m	GDS	−0.075	0.453
2nd level	100 m	300 m	**−0.234**	0.020					
	300 m	500 m	**−0.278**	0.006					
	500 m	700 m	**−0.157**	0.048					
	700 m	1000 m	−0.096	0.338					
	1000 m	GDS	−0.107	0.286					

The bold terms indicate that the difference between the groups is significant at the 95% level.

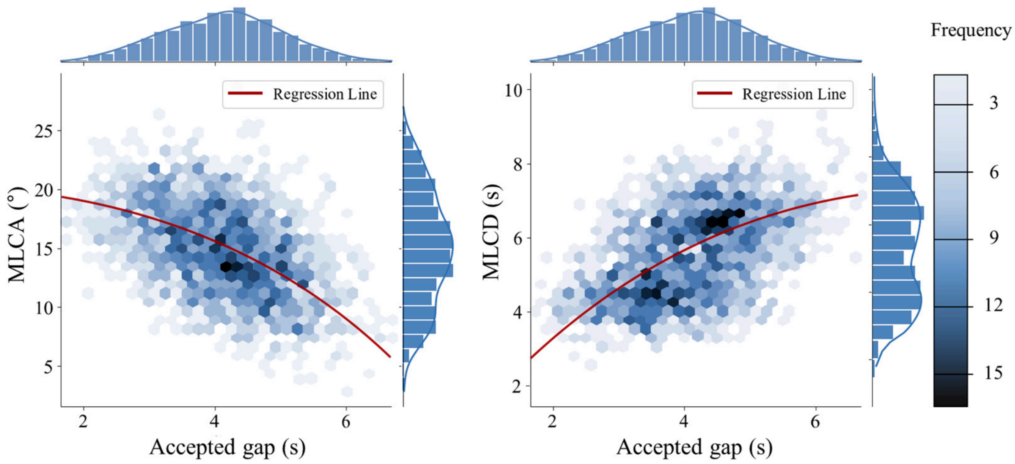

Figure 17. Joint distribution between accepted gap and MLC indicators.

3.4. Analysis of Failure Samples

In addition to the aforementioned correct diverging samples, this study collected 88 failure samples, comprising 61 cases that resulted in crashes and 27 instances of vehicles failing to enter the ramp. Figure 18 showcases the relative proportions of error samples under varied CD and IV conditions, and also includes a statistical examination of the crash reasons and location distribution.

As demonstrated in Figure 18a, both collision frequency and misdirection rates amplify with decreasing CD, corroborating our earlier analysis. Larger spacing provides drivers with ample time to read signs and choose cut-in gaps, which helps improve LC stability and diminish speed fluctuations. However, the benefits of additional safety margins diminish once the CD extends beyond a certain threshold (about 700 m).

Figure 18b displays how increased signage IV corresponds to a rise in collision instances and misdirection rates. The results indicate that when information volume exceeds nine units, there is a marked surge in direction misjudgments. Excessive information can result in cognitive overload and prevent drivers from identifying the expected direction, thus hampering the successful execution of lane changes.

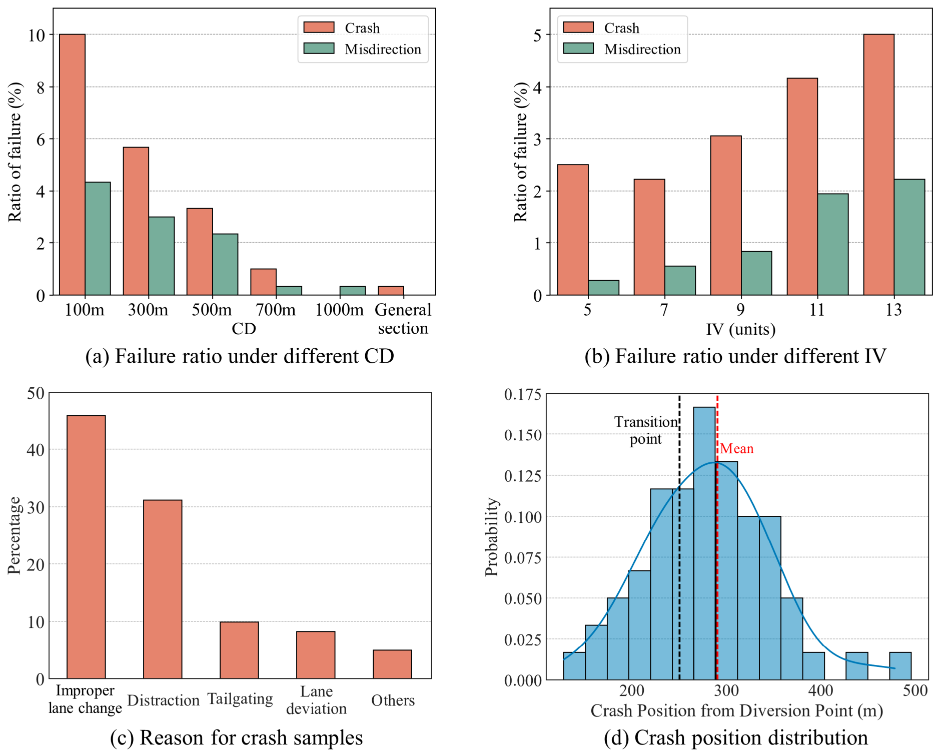

Figure 18. Analysis of failure samples.

Of all crash samples, 45% can be attributed to improper lane changing and 31% to driver distraction. The term "improper lane changing" includes inadequate gap selection and untimely lane changes, both factors escalating traffic conflicts and driving risks. Furthermore, over 77% of crashes occur within 200 m of the transition point (dot line in Figure 18d), correlating with the majority of vehicles' MLC location (Figure 13) and maximum deceleration rate area (Figure 8). It means that drivers have to make correct decisions and accurately operate vehicles within this challenging range, which heightens task difficulty and driving risk [37].

4. Discussion

This research aims to examine the driving behavior characteristics and the determining factors influencing them within tunnel–interchange connection sections. Drawing upon 11 highway project instances, the study creates 72 road models and 216 corresponding driving simulation scenarios. Comprehensive driving data were collected and processed, yielding indicators related to CF and LC maneuvers such as driving speed, headway, the duration and angle of LC, and the accepted gaps. These indicators shed light on the behavioral patterns exhibited by drivers under varying road conditions.

The experimental findings highlight noteworthy primary and interaction effects of CD, IV, and TC on driving performance. Particularly, under fluctuating traffic volumes, CD significantly shapes drivers' decision-making concerning LC gaps. To further clearly quantify these effects, Table 11, informed by Dunn's test results, summarizes the thresholds of CD and IV's impacts on various behavior indicators.

The spacing between the tunnel and interchange, referred to as CD, is a pivotal factor affecting driving behavior. When the CD falls below 700 m, certain behavioral indicators notably differ from those observed in GDS. For instance, drivers demonstrate more urgency in LC behaviors within small spacing scenarios, reflected in LCD of 2 to 5.5 s and accepted gaps ranging from 2.5 to 4 s, which elevates the potential for rear-end risks, indicated by a sharp increase in DCC_{max} and failure rate.

Table 11. Threshold values of environmental variables impacting driving behavior.

Behavior Indicators	Threshold for Single Variable		Threshold of IV under Different CDs (units)					
	CD (m)	IV (units)	100 m	300 m	500 m	700 m	1000 m	GDS
V_{mean}	500	9	7	9	7	11	11	11
RV	700	7	7	7	9	9	11	11
DCC_{max}	700	7	/	/	/	7	9	9
DH_{min}	700	7	7	7	9	9	9	9
TH_{min}	500	9	9	9	9	9	11	11
P_{MLC}	700	7	7	7	7	9	9	9
Failure rate	500	9				/		

Thresholds from Table 11 suggest that the CD of tunnels–interchanges should be at least 700 m to avert negative effects on the majority of drivers' behavioral performance. Intriguingly, this threshold is consistent with findings from ergonomics and traffic conflict studies [2,50], exceeding the diverging influence area length recommended by the HCM [49]. According to Shang's study, the rapid environmental transitions within a limited space and time can exacerbate drivers' anxiety and competitive pressure, detrimentally affecting driving safety [25].

The volume of information presented in traffic signs is typically considered a significant influence on drivers' information processing capabilities. Overloaded information may result in delayed LC and can impact driving speed and tailgating control [51]. As depicted in Figure 6, when the IV exceeds seven units, drivers need to slow down to maintain an adequate sight distance. Furthermore, as CD decreases, the impact of sign information on driving behavior becomes more pronounced. Most drivers cannot ensure adequate time to adapt to the rapid environmental switch in small spacing sections and might get distracted by recognizing directional signs, thereby increasing the failure rates. Conversely, larger CDs allow for more efficient processing of road information, leading to behaviors similar to those in general diverging sections.

The task-capability interface model offers an explanation for this phenomenon [52]. This model proposes that to mitigate task demands, drivers often reduce their speed, freeing up cognitive resources to handle various levels of task requirements. Within the tunnel–interchange scenarios, this implies drivers often moderate their velocity to alleviate task demands, maintaining a certain cognitive capacity to manage multifaceted driving tasks. Consequently, most driving samples tend to slow down and increase the following distance to effectively process navigational information.

While such compensatory behavior ensures driving safety, concentrated deceleration can generate traffic disturbances that propagate backward, contributing to instability.

Similarly, an extended headway can compromise traffic efficiency, especially under high-volume conditions, potentially leading to congestion. Past studies suggest that compared to a tunnel–interchange spacing of 500 m, road capacity decreases by approximately 7.6% to 9.67% when the distance shrinks to 300 m [13].

Thus, for maintaining driving stability and traffic efficiency, it is recommended that the information volume in the diverging area should not exceed nine units. If the CD between the tunnel–interchange falls below 500 m, the information volume should ideally be capped at seven units. In regions with substantial directional information, clear and concise prompts should be utilized to guide drivers effectively toward the correct choices.

In contrast to other indicators, drivers' gap acceptance selection is primarily influenced by TC and exhibits significant interaction with CD. This could be attributed to the inverse relationship between the average headway and traffic volume. Under conditions of low-density traffic (1st LOS), the average TH is relatively large (>4 s), allowing drivers to identify suitable gaps without speed adjustments. However, with escalating volume, the average TH within the 3rd LOS falls to below 3 s. In such circumstances, combined with a short CD (below 500 m), drivers are faced with the challenge of rapidly identifying suitable gaps within a limited LC window and promptly transitioning to the outer lane. The critical accepted gap drops significantly from 4 s to 2.73 s, which is considerably lower than that in general sections.

The distribution of gap acceptance offers additional insights into the distribution of other LC indicators under conditions of reduced spacing. It is worth noting that the traffic conditions examined in this study, based on field surveys, consider a relatively conservative 1st to 3rd LOS. If traffic density continues to increase, gap acceptance behavior could pose an even greater challenge for drivers. However, this hypothesis requires further investigation for validation.

To enhance road safety, considering the role of navigation systems and Cooperative Intelligent Transportation Systems (C-ITS) is crucial. Building an effective in-tunnel navigation system could preemptively inform diverging vehicles of the distance to upcoming exits. Moreover, emerging technologies like C-ITS, which facilitate vehicle-to-everything (V2X) communication, are particularly relevant in tunnel–interchange scenarios. These technologies can improve navigation and enhance the real-time communication of traffic conditions and operational advisories, potentially mitigating some of the challenges identified in our study. For example, V2X could enable more accurate and timely gap acceptance decisions by providing drivers with enhanced situational awareness and predictive data on vehicle movements and speeds.

Future studies should explore how the implementation of C-ITS can positively impact traffic efficiency and safety, particularly in complex driving environments where traditional navigational aids falter. Such research could provide valuable insights into the potential for these technologies to significantly improve driving conditions.

5. Limitations

This study employs driving simulation technology, which is essential for investigating the complex driving environments of tunnel and interchange connecting sections. These scenarios require high levels of experimental control to effectively isolate and analyze specific behaviors and variables. A simulator provides an ideal setting for such precise manipulation and repeatability of conditions, which would be challenging and potentially hazardous to replicate in real-world environments [53]. However, while simulators ensure safety and detailed control, they inherently lack some real-world complexities and may amplify specific driver behaviors, potentially leading to variations in error rates compared to actual scenarios. These controlled conditions are crucial for conducting safe and effective preliminary investigations into core behavioral patterns in these challenging environments.

Furthermore, the selection of participants may impact the applicability of our findings. Our study involved exclusively younger drivers, aged 25–33, limiting the generalizability to more experienced or older drivers. The literature suggests that experienced drivers typically exhibit quicker reaction times and more proactive driving behaviors, influencing their decision-making regarding speed control and following distances [54]. This demographic limitation raises concerns about the representativeness of other drivers.

Additionally, the within-subjects experimental design, where drivers encountered multiple scenarios in randomized orders, could also introduce biases [55]. While randomization helps mitigate some effects, repeated exposure to the simulator may lead to increased familiarity with the experimental setup, potentially altering drivers' behaviors over successive trials and leading to skewed results.

To build on our findings and enhance the generalizability of the results, integrating field experiments into future research could validate our findings and uncover additional influential factors not apparent in simulator settings. Diversifying the demographics of study participants would also help broaden the applicability of our results. Implementing methods to counteract simulator familiarity effects, such as varying the complexity of scenarios, should be considered to mitigate potential biases and ensure the robustness of outcomes.

6. Conclusions

This study conducts a driving simulation test to examine the effects of roadway characteristics, signage information volume, and traffic circumstances on drivers' car-following and lane-changing behaviors in tunnel–interchange connection sections. The study reveals the following key insights:

1. Insufficient connection distances negatively impact driver behavior, leading to lower vehicle speed, increased speed variance, and urgent lane-changing maneuvers. Such strong environmental switching from tunnels to interchanges could undermine driving stability and safety, especially when connection distances are shorter than 500 m.
2. Increased signage information loads significantly influence drivers' speed selection, causing an increase in maximum deceleration and following distance. Notably, the velocity reduction amplitude triples when the signage information volume escalates from five to thirteen units.
3. Significant interaction effects are observed between connection distance and signage information volume on car-following behavior. As the connection distance diminishes from 1000 m to 100 m, the average group differences in time headway induced by increased information volume rise by 84.2%, signifying a heightened influence of signage information on driving behavior.
4. Drivers' accepted gap demonstrates a negative correlation with traffic volume and a positive correlation with connection distance. An increase in traffic volume results in a more significant discrepancy in the critical gap acceptance between small spacing and general diverging sections.
5. Based on the critical threshold of behavior index and failure rate, this study suggests that the critical distance of tunnels–interchanges should be 700 m and the sign information should be limited to nine units. For sections with less than 500 m spacing, traffic information should be kept within seven units, complemented by enhanced traffic control in the diverging area.

To bolster driving stability and safety in such scenarios, it is essential to maintain the tunnel–interchange distance within acceptable limits, define appropriate signage information volume, and adjust connection clearance according to traffic service level. Consideration of drivers' behavioral traits and traffic conditions is vital in road design and traffic management, contributing to improved road efficiency and safety.

This research clarifies the behavioral uncertainty in tunnel–interchange areas and underscores the need for targeted preventive measures from the drivers' perspective. Future work aims to accumulate significant crash samples and traffic conflict data to explore accident mechanisms and latent risks in small spacing sections. Moreover, the growing number of tunnel–interchange project samples paves the way for more extensive on-road driving tests to investigate the impact of dynamic traffic, weather conditions, and other real-world factors on driver workload and behavior.

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Abbreviations

Abbreviation	Full Name
CF	Car-following
LC	Lane-changing
CD	Connection distance
IV	Information volume of signs
V_{mean}	Average velocity
RV	The reduction of velocity
DH	Distance headway
DLC	Diverging Lane Change
PDLC	LC position for DLC
DLCD	LC duration for DLC
DLCL	LC length for DLC
DLCA	LC angle for DLC
GDS	General diversion sections
6-dof	Six-degrees-of-freedom
TC	Traffic conditions
TL	Tunnel length
V_{std}	Speed standard deviation
DCC_{max}	Maximum deceleration
TH	Time headway
PMLC	LC position for MLC
MLCD	LC duration for MLC
MLCL	LC length for MLC
MLCA	LC angle for MLC
TIS	Tunnel–interchange section

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