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Identification and Comparative Safety Analysis of Overtaking Patterns on Two-Lane Highways: A Simulator Study with Novice Drivers

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Keywords: Novice drivers, Two-lane highway, Overtaking patterns, Comparative safety evaluation.

ABSTRACT

Overtaking on two-lane highways is one of the riskiest driving maneuvers. However, safety analysis technologies for overtaking patterns and trajectories require development. In this simulator study, 328 overtaking trajectories were collected from 52 novice drivers to analyze difference in overtaking safety performances on two-lane highways under different traffic conditions. Two analyses were conducted: Analysis I focused on structural trajectory differences and classified the trajectory sample into two patterns — "ladder" (LAT) and "triangle" (TRT). In Analysis II, a comparative safety evaluation method was established based on data envelopment analysis to compare overtaking pattern safety; a factor analysis of the safety performance was undertaken by means of ordinary regression models. We found that TRT had a lower spatial consumption and smoother trajectory than LAT, but drivers overtaking using TRT were exposed to higher risk than LAT. Certain environmental and human factors had an influence on the safety levels of the patterns: both deteriorated when drivers were surrounded by vehicles driving at higher speeds, and improved with longer passing sight distances. However, safety levels when overtaking trucks were significantly worse than overtaking cars in the LAT pattern — the opposite was found for TRT. Female drivers' safety performance was superior in the LAT pattern; no significant gender difference were found with TRT. A longer following distance was found to ameliorate the safety of the TRT pattern, with no effect on LAT. These findings aid understanding of overtaking maneuvers on two-lane highways, and provide recommendations for advanced assistance driving and automatic driving systems.

Keywords: two-lane highway, overtaking maneuver, safety, behavioral safety analysis and factor analysis

INTRODUCTION

Although great efforts have been made to improve road safety worldwide in recent years, the number of fatalities is still very high in many countries (*1*). Taking China as an example, 62,767 deaths, 256,101 injuries, and 13.46 billion (U) in property loss resulted from traffic crashes in 2020, of which 86.8% were caused by motorized vehicles (*2*). The death rate per million people is 16.6 in China (*1*). For some time, the complexity of the road environment (i.e., road geometry and traffic flow) and heterogeneous driver behavior have been the two main causes of road crashes considered (*3*). According to different quality of service requirements, the road system in China is divided into four grades: the low grade highways (i.e., 2nd, 3rd, and 4th grades) account for 89.6% of the total mileage, and the high-grade highways (i.e., expressways and 1st grade) with multilane roads represent the minority (*4*). At the same time, there is an average annual growth of nearly 25 million novice drivers and 30 million new cars being registered (*5*). The continuous growth of the population of novice drivers has put more pressure on road safety. Two-lane highways are widespread worldwide, and overtaking crashes on such roads can result in the most serious consequences (*6, 7*). In China, the highest mortality rate for traffic crashes is on 2nd grade highways with two-lane roads: about 2 to 3 times that of other road categories. Novice drivers are more likely to commit traffic violations, and their vehicle crash rate is twice that of their older and more experienced counterparts (*8–10*). Therefore, a better understanding of novice drivers' behavior on two-lane highways would help to improve road safety.

Previous research on overtaking has resulted in two main contributions. One stream of research has focused on the structural properties of overtaking maneuvers, resulting in various overtaking classifications. Early work was mainly descriptive in nature and laid the foundations for the classification of overtaking maneuvers as a function of properties such as duration, distance, and speed in relation to the overtaken vehicle (*11–13*). For instance, Prisk examined single passing maneuvers, and classified these into four types: delayed start, hurried return, delayed start and hurried return, and free moving with no opposing traffic (*13*). Based on this work, multistage analyses of overtaking maneuvers became popular (*14, 15*). For example, Jenkins and Rilett modeled overtaking as a five-stage phenomenon in which the overtaking vehicle (1) initiates the maneuver and begins to enter the opposing lane, (2) is inside the opposing lane, (3) moves abreast of the impeding vehicle, (4) initiates entrance into the origin lane, and (5) is fully situated back in the origin lane (*14*). Through comparison of acceleration in the five stages, flying- and accelerating overtaking strategies were identified. Later work simplified the five stages with a three-stage model consisting of lane-change, overtake, and merge, becoming the most commonly used model to study overtaking maneuvers (*16–20*). Vlahogianni further reduced overtaking maneuvers, resulting in only two stages: the acceleration phase and the back-to-lane phase (*21*). More recent work on undivided roads in India found that overtaking maneuvers can structurally differ depending on the traffic conditions (*22, 23*). These studies provided the first tentative indications that the execution of overtaking maneuvers varies as a function of road- and traffic conditions, rather than overtaking being a maneuver that is structurally executed in a consistent manner across situations. However, further validation of this is required.

A second research avenue was less focused on descriptive classifications and more oriented toward (1) observation of critical safety performance indicators during overtaking (e.g., overtaking gap acceptance, vehicle speed, time and distance traveled in the opposite lane); (2) identification of factors determining the safety performance of overtaking maneuvers; and (3) prediction of safety performance indicators as a function of road geometry, traffic conditions, and driver characteristics. Different research methods and data collection techniques were used for that purpose, including videography (*22, 24*), driving simulation (*14, 21, 25–27*), and the use of instrumented vehicles equipped with different types of sensors (*23, 28*). Videography made it possible to obtain, screen, and analyze massive quantities of noisy driving data in fixed points. Llorca and Gracia observed overtaking maneuvers on existing highways by means of six video cameras installed on fixed points next to sections where overtaking was allowed (*24*). The authors found that the type and speed of the impeding vehicle were the factors that most strongly influenced the time and distance traveled in the opposite lane. Rahul et al. used an instrumented vehicle that was equipped with LiDAR and video cameras (*23*). Overtaking data on divided four- and undivided two-lane roads in India were collected, and a new variable, ''excess distance'' (i.e., the extra distance covered by an overtaking vehicle compared with the overtaken vehicle), was introduced in the analysis of observed overtaking events. The results indicated that the presence of oncoming vehicles and the type of overtaken vehicle had a large and statistically significant impact on overtaking. Farah et al. used a driving simulator to study overtaking (*25*). The authors developed a prediction model that showed that vehicle speed, following distance, road geometry, and driver characteristics (i.e., gender and age) significantly affected gap acceptance in overtaking. Llorca and Farah compared two data samples, that is, one collected via driving simulation and another by means of an instrumented vehicle to validate the results obtained from the simulator (*26*). They found that the overtaking time, distance, and gap acceptance observed in the simulator were similar to those observed with the instrumented vehicle. Figueira and Larocca also compared data from a simulator study with data collected in a naturalistic setting, but focused on eye movements and glance behavior during overtaking (*27*). The drivers' eye behavior patterns during the driving simulation were similar to those observed in real overtaking situations.

In summary, previous work on overtaking has substantially improved our understanding of this particular maneuver. Several descriptive classifications have been proposed, and a variety of research methods and data collection techniques have been used to observe critical safety performance indicators during overtaking, to identify factors determining the safety performance of overtaking maneuvers, and to predict safety performance indicators as a function of road geometry, traffic conditions, and driver characteristics. Notwithstanding, some important issues remain unexplored or need further validation. For instance, between-subject and cross-situational variance in overtaking maneuvers have been documented in previous work, but corroboration of findings is required. Additionally, most available work has focused on a selection of separate local safety performance indicators, rather than adopting a more integrated multiple risk sources approach to studying risk. Therefore, the objective of this study was to develop and implement (in a moving-base high-fidelity driving simulator) a method of evaluating safety in overtaking maneuvers on two-lane highways. The focus was on young adult novice drivers as younger and more inexperienced drivers have been found to overtake more frequently and in riskier ways compared with other age groups (*29*). Specifically, the following three research questions (RQs) were proposed

RQ1: How are overtaking maneuvers on two-lane highways executed by young adult novice drivers, and what resulting spatial trajectories are followed?

RQ2: Does the safety performance of novice drivers executing overtaking maneuvers on two-lane highways differ as a function of structural differences in the trajectories?

RQ3: What factors determine the safety performance level of novice drivers executing overtaking maneuvers on two-lane highways?

The remainder of this paper is structured as follows: the METHODS section covers the methodological details of the data collection via the simulator experiment, and presents the safety evaluation method based on a comparative analysis. The RESULTS section is dedicated to data analysis procedures and results. The most important findings are discussed in the DISSCUSSION AND CONCLUSION section.

METHODS

Experimental design

This study adopted a repeated measures within-subject design in which each participant was exposed to a total of eight overtaking situations. To avoid learning effects, 10 parallel scenarios that randomized the order of the eight overtaking situations were produced. Each participant was assigned to one of the 10 scenarios and was required to complete all eight of the situations in the scenario. Each of the overtaking situations was designed in relation to three factors (see Table 1 for an overview of these factors and their respective discretization). These were (1) speed of the impeding vehicle (IMV: two conditions), (2) type of impeding vehicle (IMT: two conditions), and (3) speed of the opposite vehicle (OPV: two conditions). Passing sight distance (PSD) was set at fixed levels in a previous study (*27*), which was limited to exploring the effects of PSD on the safety performance of overtaking. Therefore, we adopted a compound design (see Figure 1) for each situation, in which one IMV in the origin lane faced four OPVs in the opposite lane with a gradually increasing intervehicular distance. The OPV drove past the ego vehicle if participants believed that the current PSD was too short to overtake and continued following in that case. On the other hand, participants executed overtaking with a PSD they deemed reasonable so that a continuous- rather than a fixed-level PSD data set was collected.

TABLE 1 Factors used to design overtaking situations: definitions and discretization

Factors	Meaning	Discretization	
		Rule	value
IMV	The speed of impeding vehicle	Two speed levels that could block the traffic flow on the two-lane highway	Slower: 30km/h Faster: 50km/h
IMT	The type of impeding vehicle	Two common types of vehicles on the two-lane highway	Passenger car (PC) Truck (TR)
OPV	The speed of opposite vehicle	Two common speed levels on the two-lane highway	Slower: 40km/h Faster: 60km/h

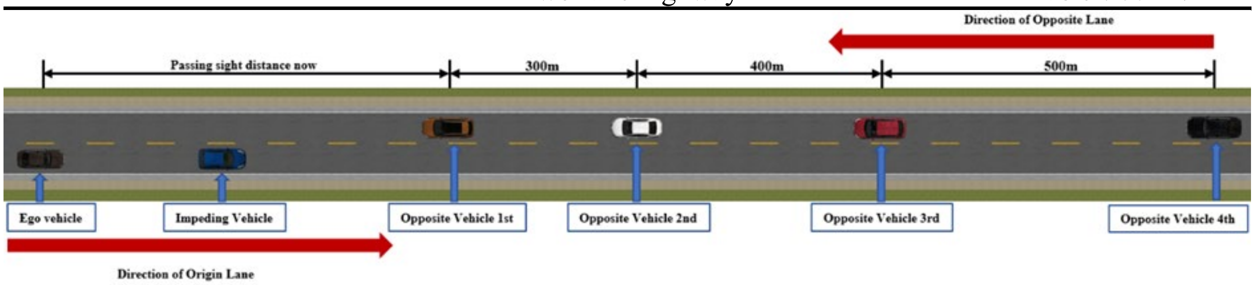


Figure 1 Illustrative spatial sketch of the overtaking situation as included in the driving scenario

The scenario to which participants were exposed mimicked a typical Chinese two-lane highway. A lane width of 3.50m was adopted and shoulders were present. No intersections were included, but tangent sections 2 km in length were combined with left- and right-turning curves. The curve radius was 300m and no vertical crests were included to guarantee an accurate overview. The total length of the scenario was approximately 20 km, with eight tangent sections (S1 to S8), three right-turning curves (C1, C4, and C5), and four left-turning curves (C2, C3, C6, and C7) (see Figure 2).

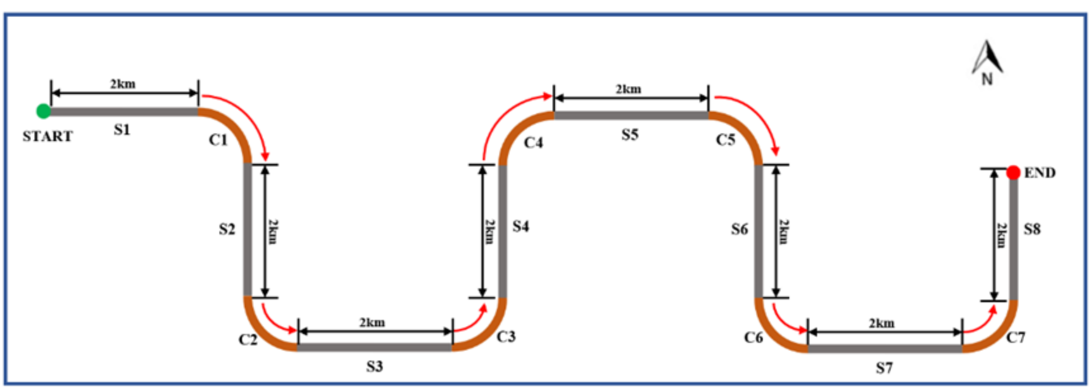


Figure 2. Schematic overview of the driving scenario

Participants and apparatus

Students from the Southeast University campus, Nanjing, were approached via a social media campaign, resulting in a total of 52 participants (33 males and 19 females). Five persons were withdrawn from the sample as they demonstrated slight 3D vertigo during the simulation, resulting in a final sample of 47 participants (28 males and 19 females). Before the experiment, each participant was required to complete the demographic and driving experience self-report survey. The age range was between 20 and 30 years (mean=23.3, SD=2.017), and driving experience ranged from 1 to 7 years (mean= 2.81, SD=1.77). The total driving mileage of each participant is less than 10000 km. The study was conducted on the simulator at the School of Transportation, Southeast University (see Figure 3), which runs the SCANeR driving simulation software developed by INNO, France. Data were recorded at a 100Hz sampling rate. Among the variables of interest were the x- and y-axis positions, speed, acceleration, and steering wheel angle. From these, different performance indicators were calculated, such as overtaking time, distance, and speed.

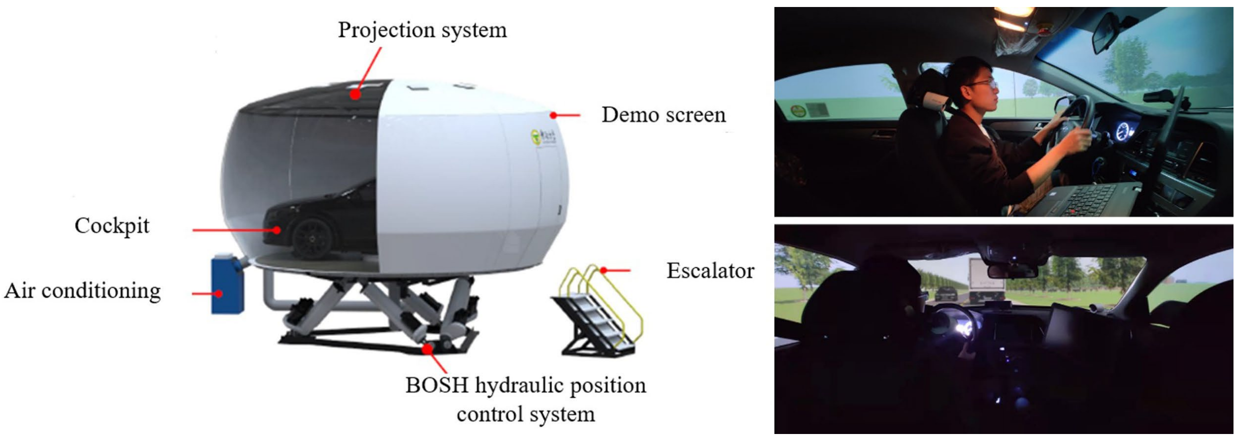


Figure 3 Simulator set-up

Framework for data analysis

Analysis I: Structural Trajectory of Overtaking Maneuvers

The data analysis was subdivided into two parts. Analysis I focused on how overtaking maneuvers were executed by the participants (cf. RQ1). In detail, as a first step, the vehicle heading angle was used to examine the spatial trajectory followed by the participants while executing the overtaking maneuvers. In line with previous work, overtaking maneuvers were considered to consist of three main stages: lane-change, overtake, and back-to-lane (see Figure 4). Four points of interest had to be determined, that is, lane-change start, the transition from lane-change to overtake, the transition from overtake to back-to-lane, and back-to-lane end.

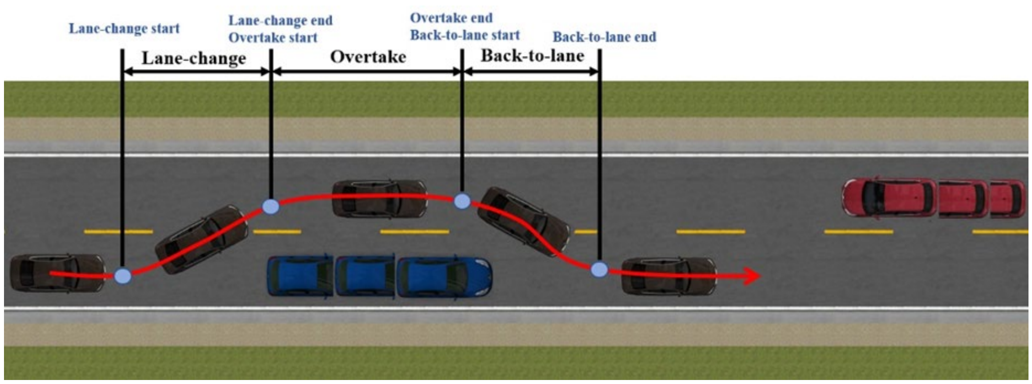


Figure 4. Three main stages of an overtaking maneuver

As a second step, following Dario et al. (*30*), the time-course graphs of steering wheel angle and Y position were plotted together with error bars to investigate whether there were any structural differences in the way of overtaking maneuvers were executed. As a third step, a repeated measures multivariate analysis of covariance (MANCOVA) was employed to investigate whether overtaking time, distance, and the mean value as well as the variance of speed were statistically significantly different as a function of the structural differences in the execution of overtaking maneuvers. The null hypothesis, H_0, for H_1 states that the overtaking patterns of young novice drivers are consistent, and there is no significant difference in spatial characteristics between the patterns. The alternative hypothesis (Ha) states that different overtaking patterns can be found, and there is a significant difference in the spatial characteristics between the patterns (cf. RQ1). The H1 test was formulated as follows, i and j referring to a specific overtaking pattern, and Sc_i the spatial characteristic of pattern i:

$$H_0: Sc_i = Sc_j$$
$$H_a: Sc_i \neq Sc_j$$

Analysis II: Comparative Safety Performance Assessment of Overtaking Maneuvers and Related Determinants

Analysis II focused on the level of safety performance of overtaking maneuvers, and whether the safety performance differed as a function of the structural differences in the execution of overtaking maneuvers (cf. RQ2). The second H_0 states that there is no significant difference in safety performance between the patterns. The Ha states that there is a significant difference in safety performance between the patterns (cf. RQ2). The H_2 test was formulated as follows: i and j refer to the different overtaking patterns, and Sl_i the safety level of pattern i:

$$H_0: Sl_i = Sl_j$$
$$H_a: Sl_i \neq Sl_j$$

In addition, which factors determine the level of safety performance of overtaking maneuvers (cf. RQ3) were also explored. We proposed the third hypothesis (H3) with H0 as follows: the effects of human and environmental factors on the safety performances of different patterns are consistent. Ha states that the effects of human and environmental factors on the safety performances of different patterns are inconsistent (cf. RQ3). The H_3 test was formulated as follows: i and j refer to the different overtaking patterns, and Ef_i denotes the effects of human (e.g., gender, PSD, and following distance) and environmental (e.g., speeds of the IMV and OPV, and IMT) factors on pattern i:

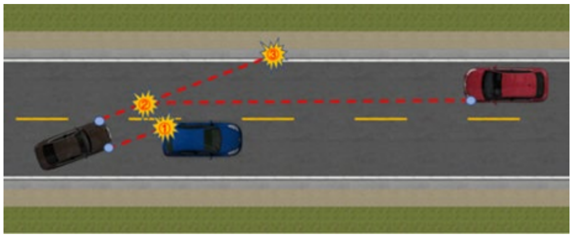
$$H_0: Ef_i = Ef_j$$
$$H_a: Ef_i \neq Ef_j$$

The rationale for the safety assessment of overtaking performance was derived from previous studies, albeit those that examined safety performance indicators in isolation rather than considering them in combination. Figueira and Larocca showed that rear-end and frontal collisions are among the most common crashes on two-lane highways (*27*). Ma and Hui argue that oblique collisions with the IMV and lane exceedance during the lane-change stage are two additional safety risks when overtaking (*31*). Therefore, these four crash risks were included in this study to determine the safety performance of overtaking maneuvers.

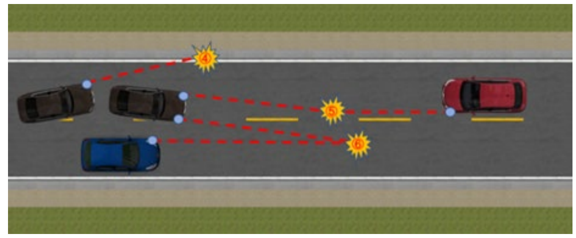
For the mathematical calculation of safety, data envelopment analysis (DEA) was used, specifically Charnes, Cooper, and Rhodes' (CCR) model. This was to allow the creation of one comprehensive score for safety performance (*32*). To determine whether the safety performance indicators differed as a function of the structural differences in the execution of overtaking maneuvers, a repeated measures MANCOVA was conducted. Moreover, multiple linear regression (MLR) analysis was used to identify factors determining the level of safety performance of overtaking maneuvers. Before presenting the results of Analyses I and II, the next section covers the composition of the comprehensive score of safety performance for overtaking maneuvers.

Numerical Modeling of a Comprehensive Score of Safety Performance for Overtaking Maneuvers

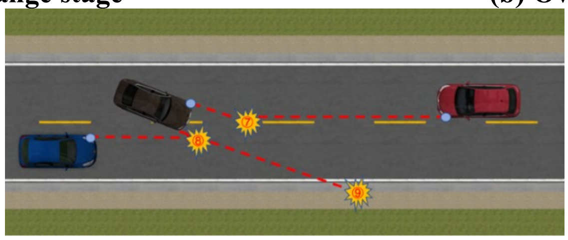
As explained, DEA, specifically the CCR model, was used for the calculation of a comprehensive safety score to assess overtaking maneuvers. Four crash types (i.e., rear-end, frontal, oblique, and off-road) were considered in the evaluation. In Figure 5, the points where one of these crash types could occur are marked in yellow for each of the three stages of an overtaking maneuver. It is worth mentioning that the outer contour points of the vehicle, instead of the centroid, were used to determine the exact potential crash spots. In this study, the size of the car model was 4.9 × 1.8m and the truck model was 9.6 × 2.4 m.



(a) Lane-change stage



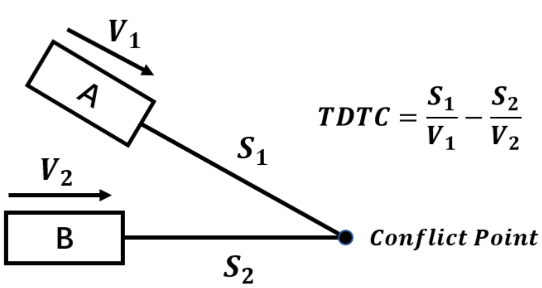
(b) Overtake stage



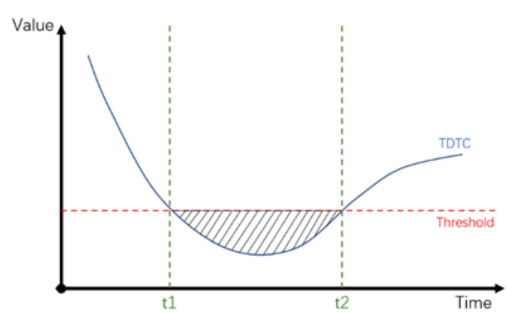
(c) Back-to-lane stage

Figure 5. Potential conflict points in each stage of an overtaking maneuver

Some of the most widely used surrogate safety indicators for crash risk assessment are Time-to-collision (TTC), Time exposed TTC (TET), and Time integrated TTC (TIT) (*34, 35*). Yet, these TTC indicators are more suitable for vehicle conflicts in the same lane, such as in car following situations (*36, 37*). For the conflict of lane-change, the calculation of TTC is made after decomposing the X / Y coordinate, which led to excessive calculation. Hence, the instantaneous Time Difference to Collision (TDTC) was used to determine the risk for each time point of the overtaking trajectory (see **Figure 6 (a)**). It actually represents the time difference between two vehicles passing through the conflict point at each time point (*38*). Based on time integrated TDTC (TITC), the risk score from each potential conflict point can be obtained (see **Figure 6 (b)**). As for the selection of the TDTC threshold, not enough crash data was available to determine the risk level, so we refer to the Post encroachment time (PET) threshold value used in previous studies since the TDTC can be considered as a derivative of PET. Zheng et al. illustrated that the PET threshold decreases with the increase of road design speed (*38*). In a pedestrian and left-turning conflict study, 3 to 6 s was the threshold used (*39*), and 1 to 1.5 s in a study of crash risk on expressways (*40*). The design speed of two-lane highways is commonly at 60 to 80 km/h, which is between that of the urban road intersection and expressway. Therefore, according to the results of the sensitivity analysis, we took 2 s to be the TDTC threshold in this study, to calculate the TITC value. **Figure 7** depicts the nine potential risk measurements in the three stages of overtaking, and Table 2 gives a more detailed overview of how risk scores for each of the nine different conflict points were calculated.



(a)



(b)

Figure 6. Time integrated time difference to collision (TDTC): (a) Instantaneous TDTC value, (b) Time integrated TDTC.

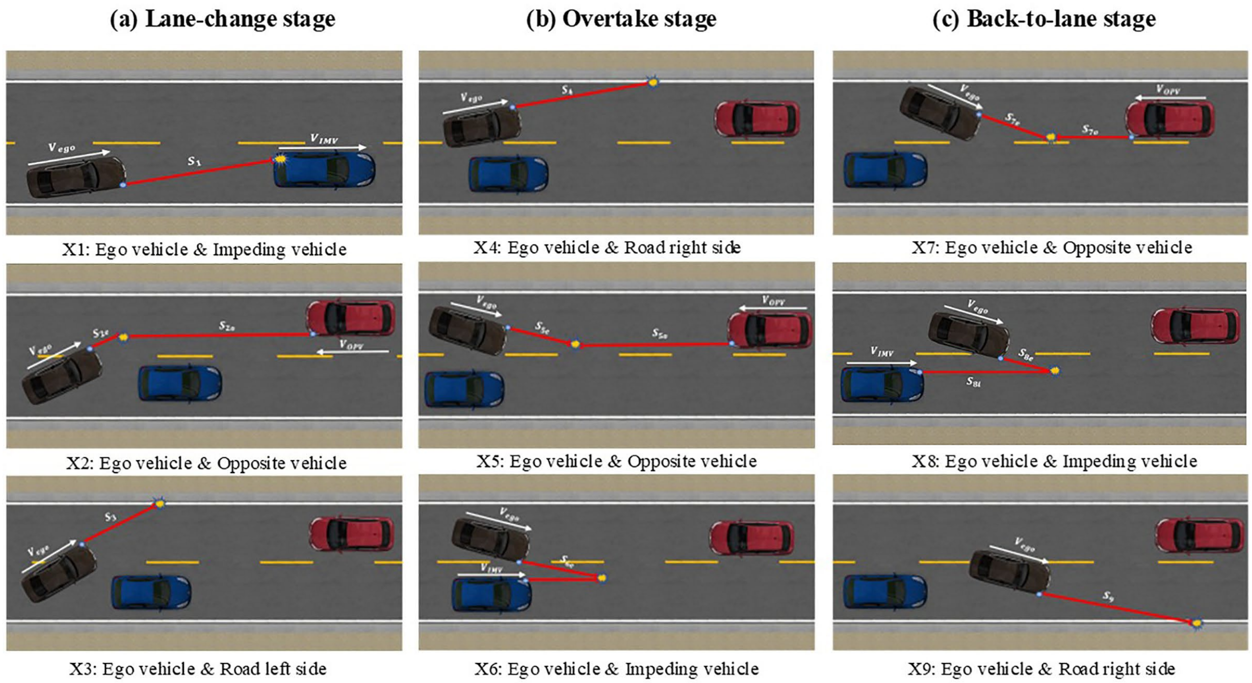


Figure 7. Nine conflict points: (a) lane-change stage, (b) overtake stage, and (c) back-to-lane stage.

Table 2. Calculation of Risk Scores for the Nine Conflict Points

$$TDTC(x_1) = \frac{S_1}{V_{ego}} - \frac{0}{V_{IMV}} \qquad TDTC(x_4) = \frac{S_4}{V_{ego}} \qquad TDTC(x_7) = \frac{S_{7e}}{V_{ego}} - \frac{S_{7o}}{V_{opv}}$$

$$TDTC(x_2) = \frac{S_{2e}}{V_{ego}} - \frac{S_{2o}}{V_{IMV}} \qquad TDTC(x_5) = \frac{S_{5e}}{V_{ego}} - \frac{S_{5o}}{V_{opv}} \qquad TDTC(x_8) = \frac{S_{8e}}{V_{ego}} - \frac{S_{8i}}{V_{imv}}$$

$$TDTC(x_3) = \frac{S_3}{V_{ego}} \qquad TDTC(x_6) = \frac{S_{6e}}{V_{ego}} - \frac{S_{6i}}{V_{imv}} \qquad TDTC(x_9) = \frac{S_9}{V_{ego}}$$

$$TITC(X_i) = Time\ integrated\ TDTC(x_i) = \int_{t_1}^{t_2} x_i\, dt, i = 1,2, \ldots, 9$$

Note: TDTC = time difference to collision; t_1, t_2 represent the start and end points of a time interval in which the instantaneous TDTC value is lower than the threshold (cf. Figure 6).

Figure 7. Nine conflict points: (a) lane-change stage, (b) overtake stage, and (c) back-to-lane stage.

The final step was to compose a comprehensive risk value, that is, a value that would allow the estimation of the safety performance of overtaking maneuvers by accounting for the risk associated with the potential conflict points. The TITC was a definite integral based on time series (i.e., delta t) so that the risk value would be higher if the overtaking time was longer. Hence, it was affected by the length of time. Therefore, in this study, the comprehensive risk value aggregated from the nine TITCs per time unit was taken as the final value for the assessment. The CCR model was used for that and is presented by Equations 1 to 4. The objective function of the model is to minimize the comprehensive risk value of each overtaking maneuver. The model is subject to the following constraints: 1) the risk values of all maneuvers should not be lower than the benchmark value of 1, and the case with a value of 1 corresponds to the safest maneuver in this sample; and 2) the value of all weight variables should be equal to or greater than 0. The comprehensive risk value for each maneuver was calculated by Equations 1 to 4. The lower the value, the better the safety.

$$Y_{ik} = \frac{X_{ik}}{T_k} \qquad (1)$$

where

X_{ik} refers to the TITC of the potential conflict point i of the driver k,

T_k refers to the time duration of overtaking maneuver k,

Y_{ik} refers to the value of TITC per time unit of the conflict point i of the maneuver k.

$$\min Risk_o^U = \sum_{i=1}^{m} v_i \times Y_{io} \quad (2)$$

$$s.t. \begin{cases} \sum_{i=1}^{m} v_i \times Y_{ik} \geq 1, \ k = 1,2,3, \dots n \\ v = (v_1, v_2, \dots v_i, \dots, v_m)^T \geq 0 \end{cases} \quad (3)$$

Where m and n refer to the number of potential conflict points and overtaking maneuvers, respectively; and v_i refers to the weight of the score of the conflict point, i.

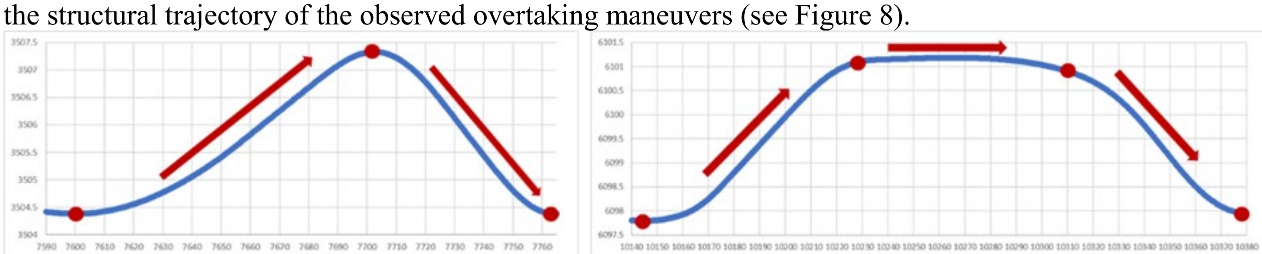
$$Risk\ value_o = Risk_o^{U*} \quad (4)$$

Where $Risk_k^U$ refers to the comprehensive value of maneuver k.

RESULTS

Analysis I: Structural Trajectory of Overtaking Maneuvers

A total of 328 overtaking maneuvers were executed in this study. As already explained, overtaking maneuvers were assumed to consist of three consecutive stages: lane-change, overtake, and back-to-lane. To empirically validate this assumption, scatter plots of x- and y-axis coordinates were created to replicate the structural trajectory of the observed overtaking maneuvers (see Figure 8).



(a) 'Triangle' type **(b) 'Ladder' type**

Figure 8. Scatter plots of x- and y-axis coordinates of overtaking trajectories: (a) 'Traiangle' type, (b) 'Ladder' type.

We then investigated the distribution of constant duration of the heading angle after the lane change stage (see Figure 9), and found that 0.5 s significantly divided the 328 trajectories into two categories. Therefore, two overtaking trajectories, the ''triangle'' type (TRT) and the ''ladder'' type (LAT), were identified based on the classification of heading angle after the lane-change stage. If the heading angle remained constant along the lane direction for less than 0.5 s after the lane-change stage, the trajectory was regarded as TRT, otherwise it was regarded as LAT. Therefore, 143 observed maneuvers were classified as TRT and 185 as LAT. To further explore differences between TRT and LAT, the data sample was split into two subsamples according to the trajectory followed. As in Dario and Liu (*30*), time-course graphs of steering wheel angle and y-position were plotted together with the error bars (see Figure 10). To that purpose, aggregated data were used, that is, mean value sequences were obtained through segmentation of trajectory data into standardized units of time. Specifically, data for steering wheel angle and y-position were first turned into 50 standardized unit sequences with the mean value for each unit of sequences calculated to form trend point sequences.

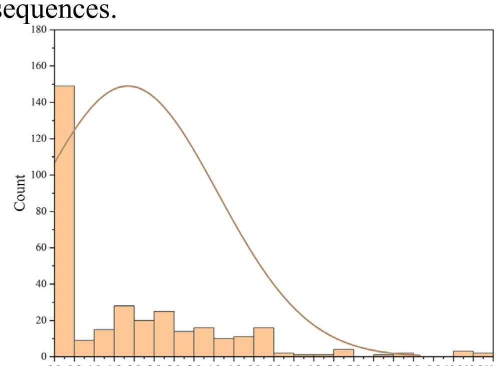


Figure 9 Distribution of constant duration of the heading angle after the lane-change stage.

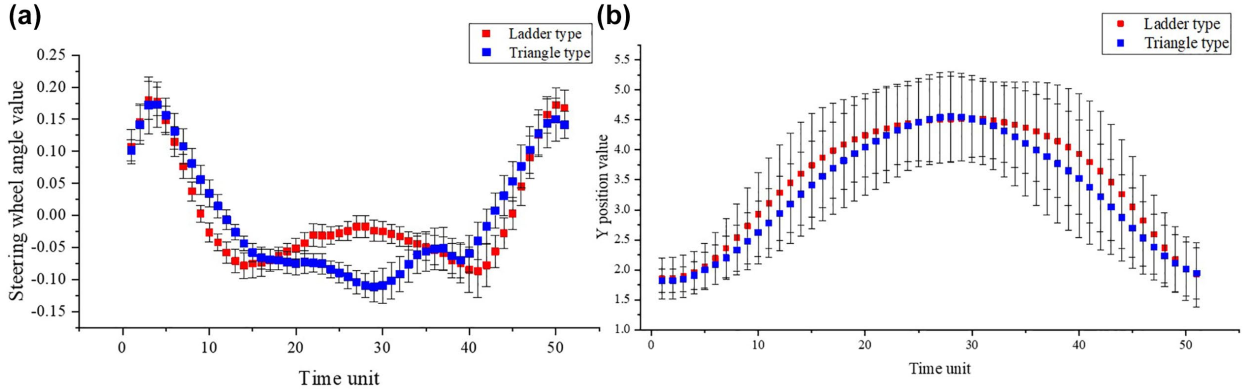


Figure 10. The time-course graphs of steering wheel angle and Y position

To clarify understanding of the steering wheel angle graphs, participants turned to the left when the steering wheel angle was greater than 0, and to the right when the steering wheel angle was less than 0. In the case of LAT, participants firstly turned the steering wheel to the left to enter the opposite lane, and subsequently kept the steering wheel stable for a certain period of time to stay in the opposite lane and overtake the IMV. Afterwards, they returned to their original lane. In the case of TRT, drivers turned the steering wheel to the left to enter the opposite lane, but directly turned the steering wheel to the right to return to the original lane. From the graph representing the y-position (Figure 10b), a clear ‘‘transition’’ section can be observed in the case of LAT, but not for TRT. In addition to steering wheel angle and y-position, time duration, distance, average speed, and speed variance were compared between LAT and TRT. These parameters were the dependent variables in a repeated measures MANCOVA, and speed of the IMV, IMT, speed of the OPV, and PSD were entered as covariates to control for traffic conditions. The results are presented in Table 3; all tests were performed at the 0.05 level of significance.

Based on the data in Table 3, we can reject H_0 for H_1 as it can be observed that, for the complete maneuver, duration and distance were both statistically significantly different with a longer duration and distance for LAT than TRT. This was anticipated since execution of LAT entails completion of a second ‘‘transitioning’’ stage whereas this is not the case for TRT. As for the speed-related variables, average speed was significantly higher for TRT in total. Overall, it seems that LAT was a more conservative way of overtaking compared with TRT. Analysis II proposes a more formal assessment of the safety performances of LAT and TRT.

TABLE 3. Results for repeated measures MANCOVA

Variables	Definition	LAT Num = 185	TRT Num = 143	F	Sig.
T_{total}	Duration of the overtaking maneuver	13.733	10.763	21.638	<.001
D_{total}	Distance of the overtaking maneuver	249.742	201.241	20.452	<.001
AS_{total}	Average speed of the overtaking maneuver	18.968	19.618	4.846	.028
VS_{total}	Speed variance of the overtaking maneuver	22.327	22.568	1.406	.237

Analysis II: Comparative safety performance assessment of overtaking maneuvers and related determinants

As a first step, we obtained the comprehensive safety value of the trajectories of each overtaking pattern based on DEA. $Mean_{LAT} = 1.6426$ and $Mean_{TRT} = 1.8321$ (The mean risk values of two patterns), we have to refuse the null hypothesis H_0 of H2. Speed of the impeding vehicle, type of impeding vehicle, speed of the opposite vehicle, and passing sight distance were entered as covariates to control for traffic conditions. From the results of repeated measures MANCOVA, we found that risk value for the TRT is significantly higher compared to that of LAT (F=5.258 and p=0.022, [significant at 0.05 level]). It indicates that an overtaking behavior as TRT was really a riskier behavior choice compared to LAT.

Secondly, there are still environment and human factors affecting novice drivers' behavior in this experiment. We considered six factors of human aspects and environment, as potential factors in the MLR models. The speed of the impeding vehicle (IMV), the type of the impeding vehicle (IMT) and the opposing vehicle (OPV) are three presupposed traffic environment variables. Gender (GEN), the choices of passing distance (PSD) and following distance (FD) are three human-related factors.

The results of MLR models are listed in **TABLE 3**, all tests were performed at the 0.05 level of significances. We have to refuse the null hypothesis H_0 of H3. In the LAT pattern, three presupposed environment factors all have a significant impact on the "Ladder type" overtaking maneuver. When novice drivers faced a higher speed of other vehicles or overtaking a truck, their risk value increased. In the perspective of human factors, the safety attribute of their overtaking maneuvers would be better when they choose a longer PSD. But different initial positions (FD) do not affect the safety of the LAT. Moreover, the safety of male drivers' LAT overtaking is statistically worse than that of female drivers.

In the TRT pattern, the three presupposed environment factors still have a significant impact on the "Triangle type" overtaking maneuver. But the opposite result occurred with respect to IMT. The risk value of overtaking a truck is lesser than that of overtaking a car. In terms of safety, accepting a longer PSD is always good. Besides that, to keep a longer following distance before overtaking is also effective to reduce risk values. There are no significant differences in safety attribute between males and females to perform TRT.

TABLE 4. Results from the MLR models on the safety performance

	LAT		TRT	
	B (Unstandardized)	**Sig.**	**B (Unstandardized)**	**Sig.**
IMV	.031	<.001	.038	<.001
IMT	.220	.036	-.264	.022
OPV	.022	<.001	.013	.025
GEN	.250	.023	-.012	.920
PSD	-.485	<.001	-.515	<.001
FD	.000	.126	-.001	.012
R^2		0.395		0.372

Note: LAT = ladder type; TRT = triangle type; Sig. = significance; IMV= the speed of impeding vehicle; OPV = the speed of opposite vehicle; IMT= the type of impeding vehicle; GEN=gender; PSD= passing distance; FD= following distance.
*p<.05

DISCUSSION AND CONCLUSION

Compared with other types of accidents, the outcomes caused by overtaking on two-lane highways are among the most serious, as this type of overtaking risks highspeed frontal collisions with vehicles in the opposite lane (*7*). Drivers need be vigilant of the traffic environment to determine appropriate opportunities to drive into and out of the opposite lane. Several factors can increase the overtaking risk during this complex, multistage maneuver, especially for novice drivers. In this study, we investigated the overtaking behavior of young novice drivers on two-lane highways via a driving simulator experiment. Two overtaking patterns—LAT and TRT—were firstly distinguished from the perspective of structural differences in trajectory (cf. RQ1). We found significant differences in spatial characteristics and steering wheel operation after the lane-change. Drivers demonstrating TRT overtaking, that is, smoother turning and faster speeds, would complete the maneuver in a more efficient way (shorter time and distance) than those employing LAT. Pattern differences have rarely been addressed in previous studies, only acceleration differences (i.e., accelerating or flying overtaking patterns [*14*]) and overtaking side (i.e., from the left or right side [*23*]) were considered by safety analysts. However, confusion surrounding different patterns of driving behavior in analyses could mask their difference. Therefore, the cooperative control of throttle and steering wheel following the lane-change was explored in this study, and proved to be a good indication of overtaking pattern discrimination. However, the significant spatial differences between the two patterns should not be ignored as potential predictors of overtaking characteristics.

In addition to the spatial characterization, evaluation of the safety performance of overtaking trajectories is another contribution of this study. Evaluation of local risk, such as rear-end- and frontal collisions, was the main objective in previous studies, which were limited by risk measurement methods. There is still plenty of room for improvement in the comprehensive risk characterization of overtaking on two-lane highways. Nine potential risk conflicts in different stages were considered, and the indicators of TITC of these risk sources were aggregated into a comprehensive risk score based on DEA. Thus, further investigation of a driver's risk level at each potential conflict point to identify his/her behavioral intervention focus was possible. From comparisons between the two patterns, we found that novice drivers employing TRT overtaking were exposed to statistically significantly higher risk than those using the LAT pattern (cf. RQ2). This was in line with expectations that aggressive driving would be accompanied by higher risk. The cooperative throttle and steering wheel operations of the TRT after the lane-change were the main reasons for this higher risk. The faster average speed is likely to increase the risk of a frontal collision. Furthermore, a smoother trajectory represents a closer return with the IMV from the opposite lane, which could lead to a significant increase in side crashes. Therefore, we believe that a driver's choice of overtaking pattern could be considered an external manifestation of their risk preference. The LAT pattern could be considered a more conservative, textbook way of overtaking; possibly these novice drivers were unable to determine an appropriate opportunity by which to drive into and out of the opposite lane. Conversely, the TRT might be considered more ''aggressive'' and skillful, on account of novice drivers who, in that case, adopted a faster speed and more skillful throttle and steering wheel cooperation. However, this does not mean that novice drivers should follow either a TRT or LAT pattern when overtaking, each pattern has its own strengths and weaknesses. We believe novice drivers should select the overtaking pattern that is right for the specific situation.

Having explored the heterogeneity in the spatial and safety performances of the two patterns, we further explored the human- and traffic environmental factors affecting the risk values of these two overtaking patterns (cf. RQ3). We found that the risk values of both increased when drivers faced IMVs or OPVs driving at higher speeds. This finding is in line with the results of research by Figueira and Larocca (*27*). It is more difficult for novice drivers to decide whether to overtake or not, when the surrounding vehicles are traveling at a higher speed. It would be better for novice drivers to overtake in a LAT pattern in challenging conditions as the risk value increment of the TRT pattern is more sensitive to the speed change of surrounding vehicles; conversely, TRT would be preferable under more straightforward conditions for the same reason. We found that the IMT had a different effect on the safety performances of the two patterns. The LAT results were the results are consistent with the results of previous studies, which indicated that the truck, with high occupation of road source and sight impact on the ego vehicle, significantly increased the risk of overtaking. The opposite result was found in the TRT pattern. One possible reason for this could be that the TRT is a faster and smoother way of completing overtaking: novice drivers might have the confidence to overtake a small car, but be more cautious when overtaking a truck. This indicates that novice drivers who prefer overtaking trucks using a TRT pattern are likely to be more sensitive to traffic-related environmental information provided by an advanced driving system. Human factors were also found to significantly affected the safety performances of the two patterns. In the LAT pattern, the safety performance of male novice drivers was statistically worse than that of female drivers; this result was consistent with the conclusion that male drivers have a stronger risk preference than female drivers (*29*). However, no significant safety differences were found between the male and female groups who overtook using the TRT pattern. It seems that overtaking in this more "skillful" way (i.e., TRT), effectively eliminated any gender-related differences in safety performance. The conservative, textbook method (i.e., LAT), exposed more driving deficiencies in males. The safety performance of both patterns was affected by PSD, which indicates that guiding drivers to overtake with an appropriate PSD would be a good means of improving safety. In addition, FD before overtaking was found to be important for safe overtaking using TRT, but had no effect on LAT. The LAT pattern involves taking an earlier position, further away from the IMV, before driving into the opposite lane, which weakened the effect of the FD value. Conversely, drivers in the TRT case would select a more advanced position, closer to the IMV, which was sensitive to the FD value. Optimization of the FD determinant could be the key improvement for the TRT case.

In summary, by distinguishing between two overtaking patterns (i.e., LAT and TRT), assessing the overall risk of potential conflict points in each pattern, and further comparing influencing factors between these two patterns, this study has provided valuable insights into how young novice drivers execute overtaking maneuvers on two-lane highways, their safety performance level, and the potential determinants of their behavior. Firstly, we have to emphasize that observation of the differences in trajectory, from the perspective of micro-operations, was meaningful. The two overtaking patterns—LAT and TRT—cannot be ignored in behavioral studies, as the differences in safety performance and factor exploration would be affected were the overtaking patterns not clearly distinguished. Secondly, overtaking on two-lane highways is a multistage behavior comprising multiple risk sources. It is therefore essential to assess safety performance from the perspective of overall risk rather than solely local risk, as this could provide assistance for Advanced Driving Assistance System (ADAS) and automatic driving technology to optimize overtaking behavior. Lastly, impact factor heterogeneity of the two patterns merits attention. We believe that the aspects discussed are significant for active intervention in novice drivers' overtaking behavior, such as the design of an advanced driving assistant system that is able to manage each pattern according to its merits. However, despite promising results, this study had some limitations that should be considered in future research. Although the sample of novice drivers was suitable for our study, certain demographic variables need further exploration, such as age and driving experience. A larger data set containing more demographic groups will be the focus of future work. Another limitation was that the structural differences in overtaking trajectories were only observed from qualitative analyses (i.e., speed choice and steering wheel operation after lane-change). A greater range of micro-operations within the different stages of overtaking should be considered, such as returning opportunities from the opposite lane, which could be meaningful for behavior prediction and characteristics analysis. Finally, the comprehensive safety evaluation method is built on a relative risk theory. Therefore, an absolute risk judgment method could be key to enhancing the applicability and practicability of future research.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: R. Zhang, Y. Shen; data collection: R. Zhang, Q. Bao; analysis and interpretation of results: R. Zhang, Q. Bao, K. Brijs, E. Hermans, Y. Shen; draft manuscript preparation: R. Zhang. All authors reviewed the results and approved the final version of the manuscript.

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REFERENCES

1. World Health Organization, WHO Clobal Status Report on Road Safety 2018. https://extranet.who.int/roadsafety/death-on-the-roads/#country_or_area/CHN. Accessed June 30, 2021.

2. National Bureau of Statistics, China, Road Crash Data in 2019. https://data.stats.gov.cn/easyquery.htm?cn=C01&zb=A0S0D01&sj=2020, Accessed June 30, 2021.

3. Özkan, T., and T. Lajunen. *Person and Environment. In Handbook of Traffic Psychology*, 2011, pp. 179-192.

4. Ministry of Transport of the People's Republic of China, China, Statistical Bulletin on the Development of Transportation Industry in 2020. https://xxgk.mot.gov.cn/2020/jigou/zhghs/202105/t20210517_3593412.html. Accessed June 30, 2021.

5. The Ministry of Public Security of the People's Republic of China, China, Data of Newly Registered Motor Vehicles and Newly Licensed. Drivers. https://www.mps.gov.cn/n2254314/n6409334/c7993912/content.html. Accessed June 30, 2021.

6. Thomas R., S. Ruhl., J. Ortlepp., and E. Bakaba. Causes, consequences and countermeasures of overtaking accidents on two-lane rural roads. *Transportation Research Procedia*, 2017. 25: 1994-2006.

7. David D C., P. J Ward, and J. Jones. Overtaking road-accidents: differences in maneuver as a function of driver age. *Accident Analysis and Prevention*, 1998. 30: 455–467.

8. Fabio L., A.M. Giannini, R. Sgalla, L. Mallia, A. Devoto, and S. Reichmann. Young novice driver subtypes: relationship to driving violations, errors and lapses. *Accident Analysis and Prevention*, 2010. 42: 1689-1696.

9. Gabriela R., D. Poulter, E. Barker, F.P. McKenna, and R. Rowe. Novice drivers' individual trajectories of driver behavior over the first three years of driving, *Accident Analysis and Prevention*, 2015. 82: 61-69.

10. Gresham, B., B. Mcmanus, S. Mrug, K. Visscher, T. Anthony, and D. Stavrinos. Validation of the attention-related driving errors scale in novice adolescent drivers. *Accident Analysis & Prevention*, 2021. 159, 106249.

11. Matson, T. M., T. W. Forbes, and B. D. Greenshields. Overtaking and passing requirements as determined from a moving vehicle. Presented at 18rd Annual Meeting of the Transportation Research Board, Washington, D.C., 1939.

12. Normann, O. K. Progress in study of motor vehicle passing practices. Presented at 19rd Annual Meeting of the Transportation Research Board, Washington, D.C., 1940.

13. Prisk, C. W. Passing practices on rural highways. Presented at 21rd Annual Meeting of the Transportation Research Board, Washington, D.C., 1942.

14. Jenkins JM, Rilett LR. Classifying Passing Maneuvers: A Behavioral Approach. *Transportation Research Record: Journal of the Transportation Research Board*, 2005. 1937:14-21.

15. Rong, J., S. J. Liu, C. Q. Shao, and J. Liu. Application of overtaking model in two-lane highway simulation system. *Journal of Highway and Transportation Research and Development*, 2007. 24, 11.

16. Bai W., and C.J. Li. Overtaking Model Based on Different Limiting Speed. *Journal of Transportation Systems Engineering and Information Technology*, 2013. 13, 2.

17. Chandra, S., and S. Shukla. Overtaking behavior on divided highways under mixed traffic conditions. *Procedia-Social and Behavioral Sciences*, 2012. 43: 313–322.

18. Hassan, S. A., O. C. Puan, N. Mashros, and N. S. A. Sukor. Factors affecting overtaking behaviour on single carriageway road: Case study at Jalan Kluang-Kulai. *Jurnal Teknologi*, 2014. 71: 87–91.

19. Qin, Y. Q., J. Zhang, X. G. Jia, Y. Y. Hui, and C. Y. Cui. Safety evaluation for the overtaking behavior on the two-lane highway based on the structural equation model. *Journal of Safety and Environment*, 2017. 40, 1.

20. Liu, Y, X. Li, G. Wei, H. M. Zhang, and, L. Fan. (2018). Effect of traffic density on drivers' lane change and overtaking maneuvers in freeway situation-a driving simulator–based study. *Traffic Injury Prevention*, 2018. 19: 1-25.

21. Vlahogianni, E. I. Modeling duration of overtaking in two-lane highways. *Transportation Research Part F: Traffic Psychology and Behavior*, 2013. 20: 135–146.

22. Asaithambi, G., and G. Shravani. Overtaking behaviour of vehicles on undivided roads in non-lane based mixed traffic conditions. *Journal of traffic and transportation engineering (English edition)*, 2017. 4: 252–261.

23. Rahul S., V. Vasudevan, and B. Dutta. Analysis of overtaking patterns of indian drivers with data collected using a lidar. *Transportation Research Part F Traffic Psychology and Behaviour*, 2020. 74: 139-150.

24. Llorca, C., and A. García. Evaluation of passing process on two-lane rural highways in Spain with new methodology based on video data. *Transportation Research Record: Journal of the Transportation Research Board*, 2011. 2262: 42–51.

25. Farah, H., S. Bekhor, A. Polus, and T. Toledo. A passing gap acceptance model for two-lane rural highways. *Transportmetrica*, 2009. 5: 159–172.

26. Llorca, C., and H. Farah. Passing Behavior on Two-lane Roads in Real and Simulated Environments. Transportation Research Record: Journal of the Transportation Research Board, 2017. 2556: 29–38.

27. Figueira, A. C., and A. Larocca. Analysis of the Factors Influencing Overtaking in Two-lane Highways: A Driving Simulator Study. Transportation Research Part F: Traffic Psychology and Behaviour, Vol. 69, 2020, pp. 38–48.

28. Llorca, C., A. Garcia, A. T. Moreno, and A. M. Pe´rez-Zuriaga. Influence of Age, Gender and Delay on Overtaking Dynamics. IET Intelligent Transport Systems, Vol. 7, 2013, pp. 174–181.

29. Farah, H. Age and gender differences in overtaking maneuvers on two-lane rural highways. *Transportation Research Record: Journal of the Transportation Research Board*, 2011. https://doi.org/10.3141/2248-04.

30. Dario, D, Salvucci, Andrew, and Liu. (2002). The time course of a lane change: driver control and eye-movement behavior. *Transportation Research Part F Traffic Psychology & Behaviour*, 2002. 5, 123-132.

31. Ma X., and F. Hui. Research of Low-Cost Overtaking Strategy and Auxiliary System based on Cooperative Vehicle Infrastructure, *Chang' an University*, 2017.

32. Cook W. D., and L. M. Seiford, Data envelopment analysis (dea) - thirty years on. *European Journal of Operational Research*, 2009. 192: 1-17

33. Guo Y., T. Sayed, and M. Essa, Real-time conflict-based Bayesian Tobit models for safety evaluation of signalized intersections. *Accident Analysis & Prevention*, 2020.144: 105660.

34. Li M., Z. Li, C. Xu, and T. Liu, Short-term prediction of safety and operation impacts of lane changes in oscillations with empirical vehicle trajectories. *Accident Analysis & Prevention*, 2020. 135.

35. Zhu S.Y., R. X. Jiang., H. Wang, H. Zou, P. Wang, and J. Qiu. Review of research on Traffic Conflict Techniques, *China Journal of Highway and Transport*, 2020. 33: 16-33.

36. Wang C., Y. Xie, H. Huang and P. Liu, A review of surrogate safety measures and their applications in connected and automated vehicles safety modeling. *Accident Analysis & Prevention*, 2021. 157(2): 106157.

37. Wang, Y., and Y. Chen. A method of identifying serious conflicts of motor and non-motor vehicles during passing maneuvers. *Journal of Transport Information and Safety*, 2015. 33: 61-68.

38. Lai, Z., K. Ismail, and X. Meng. Investigating the heterogeneity of postencroachment time thresholds determined by peak over threshold approach. *Transportation Research Record: Journal of the Transportation Research Board*, 2016. 2601: 17-23.

39. Lord D. Analysis of Pedestrian Conflicts with Left-Turning Traffic. *Transportation Research Record: Journal of the Transportation Research Board*, 1996. 1538: 61-67.

40. Ismail K, Sayed T, Saunier N, Lim C. Automated Analysis of Pedestrian–Vehicle Conflicts Using Video Data. *Transportation Research Record: Journal of the Transportation Research Board*, 2009. 2140: 44-54.