The Effect of Road Tunnel Environment on Driving Lane-changing Behavior

Fei SHAO1*, Le ZHU1, Qian XU1*, Qing ZHENG2

1College of Field Engineering, The Army Engineering University of PLA, Nanjing, Jiangsu 210007, China
2PLA Rocket Force NCO College, Weifang, Shandong 261000, China

* Corresponding author E-mail: shaofei@seu.edu.cn, 1058427910@qq.com

Abstract: Underground road systems become popular in many cities as they allow to overcome urban space constraints. Even though it is prohibited to change lanes in tunnels in China, many drivers ignore this rule. In order to research that how road tunnel environments affect vehicle interactions and drivers’ lane-changing behavior, 296 lane-changing samples on open roads and 199 in urban tunnels are obtained through a field experiment and analyzed using SPSS 20.1. The time course of lane-changing cases is explored in terms of drivers’ control, eye movements and psychological behavior in urban tunnels and on open roads. Lane-changing time frequencies are distributed according to the Gaussian distribution, where the average lane-changing time in a tunnel is shorter than that on an open road. The significantly longer fixation duration at rear view mirrors in urban tunnels and significantly larger speed variations, as well as the assessments of the RRCV and heart rates, reveal that lane-changing in tunnel environments is more dangerous from the behavioral perspective.

1. Introduction

There has been a growing conflict between the rapid expansion of cities and their limited land resources. Accordingly, the development of underground spaces has become a popular option in cities to overcome this problem. Especially, underground road systems [1], which help to reduce traffic volumes on important city streets and protect the surface environment from noise and emissions, have become more popular and extensive. Existing literatures suggest that accident rates in road tunnels are lower than those on open roads, but consequences are often more severe [2,3,4,5]. The reason is mainly that road tunnels are associated with a unique form of driving behavior compared to open roads [6]. Driving inside a tunnel in normal situations may cause anxiety because tunnels are always dark, narrow and monotonous [7]. Some drivers may also be frightened of hitting other vehicles or tunnel walls, or even be afraid of fire situations or a tunnel collapse. Except for drivers’ anxiety, traffic rules violations are also a main reason of crashes or traffic jams in tunnels. Even though lane-changing is banned in urban tunnels, many drivers ignore this rule and change lanes to overtake vehicles. Cooper et al. stated that overtaking can have large influence on traffic flows and efficiency[8]. Besides, lane changing is a confused control problem that involves both monitoring to maintain situation awareness and higher-level decision making to determine when to execute [9].

Lane-changing models proved to be an effective way to study lane-changing behavior. In the literature [10], several lane-changing models have been developed, and they always extend single-lane car following models to multilane lane-changeable models by introducing specific lane-changing rules.
The cellular automaton (CA) model is a typical model that simulates traffic flows on a two-lane roadway and investigates parameters related to exchange of cars. A symmetric model was proposed by Chowdhury et al. [11]. In this model, drivers’ behavior was considered. Li et al. [12] combined the symmetric model and two-lane cellular automaton model to investigate aggressive lane-changing behavior of fast vehicles and the effect of different lane-changing probabilities. In order to track the lane-changing feature precisely, Laval and Daganzo [13] proposed a model that combines the features of the macroscopic KW model with the accuracy of microscopic models. Esmaeil Balal and his coauthors presented a Fuzzy Inference System (FIS) to model a driver’s binary decision to or not to execute a discretionary lane changing move on freeways [14].

Simulation is another way to investigate the lane-changing process. Lv et al. [15,16] simulate the lane-changing behavior on roads with different speed limits and traffic conditions with the merging effect before a city road bottleneck. In addition, a lot of simulation software is now used in research on driving behavior including lane-changing.

Although most of the models and simulations mentioned above reflect the characteristics of traffic flows, many of them do not clearly describe the driving behavior during lane-changing and the process is regarded as an instantaneous movement in most models [17], especially in urban tunnel environments. Although Xiang Li [18] investigated the effects of lane-changing on the traffic efficiency, traffic safety and fuel consumption, he did not mentioned the microscope driving behavior. Driving behavior is the manifestation of drivers’ perspectives and perceptions of the surrounding environment according to the environment-behavior theory. Yeung et al. [19] show that drivers perceive open and tunnel expressways differently. However, very limited research is devoted to the analysis of drivers’ behavior in tunnels. Considering the differences in perceptions and attitudes towards road tunnels, the specific objective of this research is to evaluate whether drivers’ lane-changing behavior is different in road tunnel environments.

2. Method

This study collected lane-changing data using real vehicle driving experiments in Shui Xi Men tunnel sections which sited in Nanjing China and on the adjacent urban open roads. The experiment included 24 male experienced drivers between the age of 26 and 34 who have more than 4 years driving experience. To avoid peak times, the experiments were conducted from 9:00am to 11:00am and from 14:00pm to 16:00pm with about 700pcu/h flows in sunny weather conditions. The tested urban open road section had two lanes with a barrier off the side of the road, while the tested unidirectional urban tunnel road also had two lanes with half meter hard shoulder off each side of the road. The posted speed limit was 60km/h for both road sections. All participants were informed to drive as usual, and no subtasks, such as speaking phone, reading messages or talking with passages, were permitted to reduce the impact on drivers. Driving data includes the driving speed, lane position, eye movements, electrocardiograph (ECG), as well as brake and turn signals collected by the D-Lab driving analysis system and Mobile OpenCAN system. The tested vehicles were drove at a required speed along 10 km open road and 4 km urban tunnel road in each experiment, and the drivers were requested to change lanes randomly.

Test procedures were recorded by a scenario camera. Each experiment started with ten minutes of practice driving on open road or in tunnel, then from the open road to the tunnel section, and then back to the open road. Lane-changing tasks were selected and defined in post-processing. We define lane-changing from the time when a driver first looks at an exterior rear view mirror to the moment when the vehicle straightens in the target lane. In this study, 296 lane changes on open road (10.34 per driver, variance 2.46) and 199 lane changes in urban tunnels (7.52 per driver, variance 1.78) were obtained, and there were neither extraneous sceneries nor intersections during the selected lane-changing process.

The D-Lab driving analysis system provides a continual tabular data stream used for analysis. In order to research microscope lane-changing behavior, three kinds of data were extracted synchronously at the sample rate of 10 Hz and combined to data profiles: (1) vehicle data, including
the driver’s vehicle speed, steering angle, and braking (0 represents off, 1 represents on); (2) eye movement data, where the field of driver’s vision was divided into five areas of interest (AOI) as it is shown in Fig.1, the number of glances and their durations in per AOI; and (3) physiological data including the heart rate (HR) and heart rate variation coefficients (RRCV) representing drivers’ emotions or stress when performing a lane change. Since the two lanes used in our experiments had the same posted speed limit and structure, the right-to-left and left-to-right lane changes were symmetrical, so we did no distinguish between them. Accordingly, the right-to-left lane-changing data was merged into the left-to-right lane-changing data.

![Fig.1 Areas Of Interest (AOI) division](image)

3. Results

3.1 Lane-changing time

Each lane change includes three stages: “before”, “during” and “after”. In this study, as Fig.2 shows, according to the steering angle, the before stage is defined from the time of first looking at the rear view mirror to the time when the steering angle starts to change, and the after stage is defined from the time when the vehicle’s lane position is 0 until the steering wheel is straightened.

Define the time-course of a lane change as $T_{\text{before}} = t_1 - t_0$, $T_{\text{during}} = t_2 - t_1$, $T_{\text{after}} = t_3 - t_2$, so the lane-changing time is:
Analyzing the total time $T_{ch}$ that a driver spends on open and tunnel roads, the shortest time $T_{ch\text{open}}$ is 5.4s and the longest time is 18.2s for open road sections, and the shortest and longest time for tunnel sections $T_{ch\text{tunnel}}$ is 5.0s and 24.8s, respectively. The time-course frequency histogram is shown in Fig.3.

Both lane change time frequencies for open roads and tunnels conform to the Gaussian distribution. But there is a trailing in the tunnel’s left for partial minimum existence. And the lane change average time for tunnel sections is lower than for open roads. This is mainly due to more complex traffic conditions on open roads, and vehicles in tunnels always behave more regularly.

3.2 Speed and braking behavior
Since the time of lane-changing is different for tunnels and open roads, we computed a scaled time unit for per stages of each lane-change segment as 1/30 of the total lane change time, and then re-sampled data during lane changes by averaging within these time units. The aggregate speeds $V_{85}$ and brake ratios in all experiments are shown in Fig.4 and Fig.5.
During the before stage, the aggregate speed $V_{85}$ declines, and brakes show a high proportion. This can be explained as often a relatively slow vehicle in front becomes an obstacle and the driver has to decelerate and prepare to change the lane. Until time $t_1$, at the second stage, when lane-changing onsets, $V_{85}$ increases, and the brake ratio decreases. The lane change maneuver is often aimed to get a faster speed, so, after $t_2$, at the after stage, when the vehicle reaches the target lane, drivers do accelerate immediately, and the brake ratio reduces to zero.

It is clear that $V_{85}$ and the brake ratio present the same trend from $t_0$ to $t_3$ regardless of whether in a tunnel or on an open road. However, taking into consideration the range of $V_{85}$, we define the speed volatility coefficient $D$ as follows:

$$D = \frac{V_{85,i} - V_{85,0}}{V_{85,0}}$$

where $V_{85,i}$ represents $V_{85}$ of the $i^{th}$ segment, and $V_{85,0}$ represents $V_{85}$ at time $t_0$. The results of ANOVA analysis show that $p<0.01$ ($F(1, 59) = 165.3$), implying that $V_{85}$ volatility is significantly larger in tunnel sections than on open roads. In addition, the brake ratio is always higher and lasts longer in tunnel sections as shown in Fig.5.

3.3 Eye movements
The three lane change stages were divided into 10 segments, and the gaze ratio data was re-sampled during lane changes by averaging within the time units. Fig.6 and Fig.7 show the eye movement data for each AOI as the gaze ratios for open roads and tunnel sections, which are the ratios of time spent looking at the rear view mirror, start lane or target lane.
Before a lane change, drivers spend almost 80% of time looking to the rear view mirror, which can be attributed to ensuring a safe lane change opportunity. At time $t_1$, the steering wheel is rotated in the target lane direction, and drivers shift more attention to the target and start lanes, as this can help drivers to avoid potential crashes with front vehicles while visually scanning their environment. When the vehicle enters the target lane, drivers look almost 80% of time at the new lane and 20% of time on the side lane.

In the first two stages, drivers perform differently when looking at the rear view mirror on open road and urban tunnel sections. So we just consider the procedure from $t_0$ to $t_2$, and calculate the ratio of the fixation duration in each AOI as in Eq. (3). The aggregate results are shown in Table 1.

$$R_m = \frac{t_m}{t_2 - t_0} \times 100\%$$  \hspace{1cm} (3)

where $R_m$ is the rear view mirror AOI attention ratio, and $t_m$ is the glance duration at the rear view mirror AOI.

| Open roads | Tunnel sections | $F$     | $P$   |
|------------|-----------------|---------|-------|
| $R_m$      | Average         | 0.85    | 0.76  |
|            | Std. error      | 0.09    | 0.15  | 8.047  | 0.011  |

The ANOVA analysis results show a significance difference between $R_m$ for the two experiment environments. It is concluded that drivers spend more time looking at the rear view mirror in tunnel sections than on open roads before the vehicle leaves the current lane. The illumination of a tunnel can substantially change the impression on drivers, where it is difficult to judge the situation around, especially the speeds of vehicles moving in the target lane after the lane-changing vehicle. Therefore, drivers are more careful to ensure a safe lane change (as we will see in the physiological data).

3.4 RRCV and Heart Rates
The Heart Rate Variability (HRV) is an important parameter which reflects the strain and balance of the Sympathetic Nervous System (SNS) and Parasympathetic Nervous System (PNS). The heart rate variation coefficient (RRCV) is an indicator which is used to reflect the physiological load, where the higher the load, the lower the RRCV value [20]. Fig.8 shows the RRCV during lane changes. From $t_1$ to $t_2$ is the most intensive period for the RRCV value achieving its lowest values. And drivers would be more tension when drivers perform lane changes in tunnels as the RRCV values are always lower than the values on open roads.
The Poincare section is an efficient method to evaluate the Heart Rate (HR), which draws all adjacent HR values in the 2D coordinates and forms a regular scattered point figure. It can display differences among HR values intuitively, and reflect the nonlinear nature of the HRV. Normally, the Poincare section presents four different shapes: 1) the comet shape, resulting from an increase in the beat-to-beat dispersion as the heart rate slows down; 2) the torpedo shape, resulting from the low R-R interval dispersion over the entire range of heart rates; 3) the fan shape, resulting from the restriction of overall R-R interval ranges with enhanced dispersion, and 4) a complex shape with clusters of points characteristic for stepwise changes in R-R intervals [21]. The Poincare section of the lane-changing procedure is shown in Fig.9.

In Fig.9 a), the scattered points are mostly concentrated near the 45°line, indicating that drivers’ adjacent RR interval is roughly equality. By contrast, the points are scattered around the 45°line and present the fan shape in Fig.9 b), indicating the phenomenon of sinus arrhythmia when changing lanes in tunnel sections. It is generally known that the dense core of a scatter gram indicates a consistent heart rate reflecting the sympathetic nervous activity, and sparse points represent a large heart rate variance reflecting the vagus nerve activity. Comparing Fig.9 a) and b), we can conclude that drivers are more nervous when performing lane-changing in tunnels than on open roads. And the Poincare section results are consistent with the RRCV.

4. Discussions and Summary
The data was collected during mean hours on urban tunnel sections and open roads that shared similar traffic conditions and average speeds. This section discusses the results and highlights significant implications of the findings.

The times of lane changes for the two sites present the Gaussian distribution, and the mean time for urban tunnels is shorter than that for open roads (12.41s < 14.88s). Since Yeung et al. found that drivers desire higher safety margins in road tunnel environments [22], lane changes are smoother in tunnels. Another possible explanation for faster lane-changing behavior in tunnels is the presence of...
traffic cameras. It is forbidden to change lanes in tunnels, and an important characteristic of urban road tunnels is the high density of traffic cameras. In our experiments, participants were told that they should drive as they would normally do in the described situation, so the drivers tried to finish lane changes in tunnels faster due to the awareness of being monitored.

Some authors show the relationship between the vehicle speed and traffic safety, and conclude that accident rates do not necessarily increase with an increase in the average speed, but do increase with an increase in the speed variance [23,24,25,26]. During a lane change, especially in the first two stages, the $V_{85}$ variance in tunnel sections is significantly larger than on open roads and brakes have a slightly longer duration in tunnels, so we can conclude that lane-changing in tunnels is more dangerous on the whole. However, since $V_{85}$ is an aggregate index, we are unable to perform a more systematic analysis to determine the presence of smaller maneuvers, and it is difficult to judge how dangerous it is to perform lane-changing in tunnels. We hope to explore these issues further in future studies.

Rumar (1985) [27] concludes that 95% of driving accidents are attributed to human errors. And driver distractions are thought to be the main reason which occupies around 20–30% of these cases [28]. Liang et al. [29] suggest that 81% of distracted drivers can be identified by disruptions in their eye movements. In addition, many studies show that an effective hazard perception is also performed by an increase in the fixation duration to the detected hazard, which reflects an increased attention capture by this important information as it develops [30,31,32]. In our study, the ANOVA analysis results show a significantly larger fixation duration for the rear view mirror AOI in tunnel environments than on open roads. Therefore, it can be concluded that tunnel environments are more difficult for drivers to perform an effective back surroundings perception providing poor conditions for lane-changing. The results of the RRCV comparison and HR Poincare section comparison are in accordance with these results showing that drivers experienced hard intensions when changing lanes in tunnels.

5. Conclusion
This study assesses car lane-changing behavior observed both on urban open roads and in tunnel sections. Lane-changings behavior in road tunnel environments is found to be more dangerous (longer fixation durations at the rear view mirror, greater speed variations and higher intension) than that in open road environments from the microscopic behavioral perspective. The conclusion is consistent with the traffic rule that it is not allowed to perform lane changes in tunnels. However, lane changes are always performed in tunnels without traffic regulations. And with growing underground systems, we hope to improve tunnel environments from the view of the microscopic driver behavior in future studies.

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