Research Article

Acceleration and Deceleration Parameter Calibration of Tunnel Entrance Based on the Naturalistic Driving Test of Passenger Car

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Received 4 February 2021; Revised 18 May 2021; Accepted 17 July 2021; Published 24 July 2021

Academic Editor: Sanjay Nimbalkar

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The precise calibration of acceleration and deceleration parameters is crucial for improving the accuracy of operating speed prediction and analysis tools at tunnel entrances. Therefore, acceleration and deceleration data of passenger car captured from 20 drivers at 30 tunnel entrances were collected from 200 m outside to 200 m inside the tunnel portal and averaged across four study zones. The results show that, first, the distribution of deceleration rates based on speed differs from that of acceleration rates based on speed in all zones. Second, significant differences in the probability density distribution of deceleration were found between each zone ($p < 0.001$), but differences in acceleration could not be found between any zones ($p > 0.05$). Third, the feature values (breakpoints) of the acceleration/deceleration cumulative frequency curves were located near the 95th percentile, differing from the traditional 85th percentile found with the extant model. The feature values of acceleration in the four zones coincided at 0.5 m/s^2 and those of deceleration were $0.93, 0.85, 0.70$, and 0.47 m/s^2 under zones 1–4, respectively. This study provides accurate feature values of acceleration and deceleration for modelling an updated tunnel entrance operating speed prediction model.

1. Introduction

Operating speed consistency analysis remains an important method for freeway safety evaluation. The core of this method is a common operating speed prediction model that is used to obtain continuous operating speed profiles worldwide. This method examines the differences between vehicle operating speeds and road design speeds per adjacent road segments. Present, operating speed prediction models provide an ubiquitous worldwide quantitative evaluation index. Operating speed prediction is of great significance to accident risk analysis. Thus, improving model accuracy is an enduring focus of research in the field of freeway safety design and auditing.

Since operating speeds were first scientifically estimated [1] and evaluation standards of speed consistency were put forward [2], several operating speed prediction models have been designed and deployed. Most versions of the common

model have two common characteristics. They are applied to specific road segment types (e.g. tangents [3], horizontal curves [4–6], curved slope segments [7, 8], and interchange ramps [9]), and the road segments almost always depend on single or multiple geometric elements. Hence, these elements (e.g. radius, curve change ratio, curve length, and tangent length) are the key variables [10–12]. Speed prediction models differ slightly per country and region, and the selection and combination of these geometric variables differ based on terrain and traffic characteristics [13–15].

The reliance on geometric elements stems from their relationship to operating speeds and accident occurrence. Hence, the characteristics of acceleration and deceleration values are most pertinent [16]. For example, the radius of a horizontal curve affects both the distribution and amplitude of deceleration and acceleration depending on speed [17]. In turn, the operating speed of the horizontal curve segment can be predicted based on the radius [18]. Deceleration and

acceleration values were generally assumed in previous studies to be a certain value or in each range. For example, Lamm and Choueiri [2] estimated the deceleration and acceleration rates to be 0.8 m/s^2 and Calvi et al. [19] estimated them to be 0.85 m/s^2 . Alternatively, the rates on freeways in China are assumed to range from 0.15 to 0.50 m/s^2 [13].

However, the common operating speed prediction models are not very effective at tunnel entrances because the major influencing variables of operating speeds at tunnel entrances are the environmental transitions and not the geometric transitions and the pavement [20–23]. In China, operating speeds at tunnel entrances are predicted by directly discounting the prediction of the front-facing geometric road segment. However, this method fails to identify accident risks [13]. Some freeway accident investigations in China have shown that rear-end accidents, which can be attributed to large speed mutations and insufficient deceleration distances, occur frequently near tunnel entrances [24–27]. This may imply that the current assumptions of deceleration and acceleration do not match the actual situations at tunnel entrances. Therefore, a highly accurate operating speed prediction model of tunnel entrances is needed, and the calibration of deceleration and acceleration measurements at those locations is a prerequisite.

This study aims to calibrate deceleration and acceleration measurements at tunnel entrances, and there are two main issues that need to be solved. First, we must discover whether the assumptions of the existing model differ from the actual situations at the tunnel entrances. Second, we must explore the value range of deceleration and acceleration at those locations. Therefore, this study reports on a naturalistic driving study conducted to obtain drivers' real driving behaviours collected using a speed detector and video recordings. Indicators of 20 drivers at 30 tunnel entrances along the no. G55 mountainous freeway in Guangdong province were statistically analysed.

2. Methods

2.1. Test Road. To avoid the interference of various ancillary elements, such as alignment condition, road pavement condition, and road width, and to obtain sufficient samples, naturalistic driving tests were conducted on a road section of a mountain freeway (no. G55 in western Guangdong province) comprising 15 tunnels $\times$ 2 directions (160 km). As illustrated in Figure 1, the test road runs between the major interchange at Huaijinan and the one at Sihui. Tunnel lengths range between 215 and 1660 m ($M = 642$, $SD = 377$). The design speed of the test area is 100 km/h , and there are three lanes per direction.

To reduce the interference of traffic volume on the results of this study, the testing was conducted between 7 and 11 am because the traffic headway during this period is generally greater than 6 s, which can be treated as a free-flow condition.

2.2. Apparatus. Data collection of real-time vehicle parameters from a controller area network supported by on-board diagnostic (OBD) sensors is common to naturalistic

driving studies. Such experiments well support the analysis of online driving behaviour variables with high realism. Thus, the present study used a high-precision apparatus (Figure 2) that included an OBD sensor, a smartphone, and a video recorder to collect data parameters of acceleration and deceleration.

The OBD sensors and smartphone connections relied on bluetooth connections, from which acceleration and deceleration data were exported at a sample frequency of 2 Hz. Speed data were synchronously recorded alongside acceleration/deceleration data at the same frequency, and the real-time driving position was recorded using the video recorder. Then, the position curves were obtained by calculating the product of speed over time, and the positions of acceleration and deceleration were determined by synchronizing the video recorder and the OBD sensor data.

2.3. Participants. Drivers were recruited from the South China University of Technology and road-testing management companies using online advertising and e-mail. Twenty drivers (26–40 years old ($M = 32.7$, $SD = 3.2$)) were selected. They each had held valid driving licenses between 2 and 12 years ($M = 6.5$, $SD = 3.5$). Hence, they could legally drive a passenger car with fewer than seven seats on a freeway. Their annual accumulated freeway mileage per year ranged from 2,100 to 12,000 km ($M = 5800$, $SD = 3250$). Written consent was obtained, and this study conformed to ethical guidelines.

2.4. Data Preparation. Each driver was instructed to drive one round trip along the test road using normal driving styles. Thus, 30 group data were acquired per tunnel and driver (600 total data items). After eliminating anomalies (e.g. equipment failures, spurious values, and time misalignments), 546 groups were used for analysis.

In the present study, a tunnel entrance was defined as the road segment beginning at 200 m in front of the tunnel portal to 200 m past the portal on the inside. As given in the previous research studies [16, 17, 26, 27], this area was divided into four zones of 100 m each. Acceleration and deceleration data were analysed separately per zone, resulting in 501, 393, 1268, and 1771 data items for zones 1–4, respectively. For deceleration, 3167, 3347, 2269, and 1628 respective data items were acquired.

3. Results and Discussion

3.1. Speed-Related Variations of the Distribution Characteristics of Acceleration and Deceleration. It is clear by definition that speed is the key constituent of acceleration and deceleration measures. Thus, in the tunnel entrance road segments, drivers adjusted their speeds to adapt to the environmental changes from an open road to a semiclosed tube. The fundamental motivation of this type of speed adjustment differs from that of adjustments along open roads, owing to the distinctive road geometries involved. In this study, the relationships of acceleration/deceleration to driving speed in each zone were analysed to verify whether

FIGURE 1: Test road along the no. G55 freeway, Guangdong, China.

FIGURE 2: Data sample and apparatus of the naturalistic driving test.

the effects were consistent with those found in previous open road studies.

Figure 3 illustrates how the distribution of acceleration and deceleration varies based on driving speed. Figures 3(a)–3(d) represent the distribution of acceleration and deceleration in zones 1–4 (averaged across all tunnels), respectively. The positive values in this figure represent acceleration, and the negative values represent deceleration; the red line represents the boundary of the distribution triangle.

In each zone, the distributions of deceleration and acceleration differed with driving speed. Specifically, in zones 1–3, the range of the distribution triangle of deceleration was significantly larger, and the shapes were different from those

of acceleration. In these zones, the distribution triangle of deceleration was nearly isometric and that of acceleration sloped with a high axis located at the side of low driving speed. In zone 4, the distribution triangle of deceleration was antisymmetrical to that of acceleration. This result demonstrates that the acceleration and deceleration distributions vs. driving speed were not similar in any zone. Therefore, acceleration and deceleration should be calibrated separately for the road segments of tunnel entrances, which diverge from the existing assumptions made by specifications in China.

Second, the distribution triangles of acceleration in each zone can be considered the same because their shapes and ranges are very similar. This implies that the

FIGURE 3: Distributions of acceleration and deceleration with the driving speed. (a) Zone 1. (b) Zone 2. (c) Zone 3. (d) Zone 4.

FIGURE 4: Continued.

FIGURE 4: Distribution characteristics of acceleration and deceleration in different zones. (a) Proportions of acceleration and deceleration in the four zones. (b) Probability density distributions of acceleration and deceleration in the four zones.

distribution of acceleration vs. driving speed was not affected by zone division. However, the distribution triangles of deceleration in each zone were dissimilar in aspects of both shape and range. Furthermore, the

distribution triangle of deceleration in zone 4 was obviously different. This illustrates that the distribution of deceleration vs. the driving speed was affected by zone division.

TABLE 1: Kruskal–Wallis H test results of the probability density distribution of acceleration and deceleration.

Zones	Acceleration (m/s ²)		Deceleration (m/s ²)		$P_{a,a}^1$				$P_{d,d}^2$				$P_{a,d}^3$
	Mean	SD	Mean	SD	Zone 1	Zone 2	Zone 3	Zone 4	Zone 1	Zone 2	Zone 3	Zone 4	
Zone 1	0.28	0.15	−0.41	0.25	1	0.66	0.65	0.48	1	0.001	<0.001	<0.001	<0.001
Zone 2	0.26	0.14	−0.43	0.26		1	0.35	0.24		1	<0.001	<0.001	<0.001
Zone 3	0.29	0.17	−0.33	0.2			1	0.75			1	<0.001	<0.001
Zone 4	0.3	0.17	−0.26	0.14				1				1	<0.001

¹ $P_{a,a}$ is the significance test indicator of the probability density distribution of acceleration between zones. ² $P_{d,d}$ is the significance test indicator of the probability density distribution of deceleration between zones. ³ $P_{a,d}$ is the significance test indicator of the probability density distribution of acceleration and deceleration.

3.2. Distribution Characteristics of Acceleration/Deceleration in Different Zones. In previous operating speed prediction models, most acceleration and deceleration values are assumed to either be a constant or within a given range, depending on the models' horizontal curve segment, tangent segment, and slope segment specifications. However, the various assumptions made by the different models have one thing in common: the distribution characteristics of acceleration and deceleration in the road segments are assumed to be the same. Therefore, in view of the peculiarity of tunnel entrances, it is necessary to analyse each zone separately as we have done.

Figure 4(a) shows the proportions of the number of accelerations and decelerations in the four zones. With the zone changes, proportions of variability regarding acceleration and deceleration were observed. From zones 1–4, the proportion of deceleration increased first and decreased later, whereas with acceleration, the situation was the opposite. Specifically, the proportions of deceleration were 0.86, 0.89, 0.64, and 0.46 for zones 1–4, respectively, whereas the proportions of acceleration were 0.14, 0.11, 0.36, and 0.54, respectively. This indicates that the probabilities of acceleration and deceleration are not the same in all the zones. The data indicate that drivers had a high probability of deceleration just before the tunnel portal, but it decreased after entering the tunnel. The probabilities of acceleration and deceleration were balanced in zone 4, which may explain the relevant result observed by Bella et al. (2007), who found that the speed difference prior to entering the tunnel portal (zones 1 and 2) was significantly larger than that after entering (zones 3 and 4).

Figure 4(b) shows the probability density distributions of acceleration and deceleration with absolute value less than 1 m/s² in the four zones. The bars reflect the frequencies of acceleration or deceleration over a range of 0.1 m/s². Moreover, Table 1 presents the results of the Kruskal–Wallis (K-W) H test for the probability density distributions of acceleration and deceleration in the four zones. The results of the K-W test indicate that the significance test indicator of the probability density distribution of acceleration between zones ($P_{a,a}$) was larger than 0.05, demonstrating that the distributions in the four zones were subject to the same form. This may be due to the unchangeable vehicle engine torques and the stable designs of continuously variable transmission. Second, the probability density distribution of deceleration in the four zones were not subject to the same form because the probability density distribution of

acceleration between zones ($P_{d,d}$) was lower than 0.05. This implies that there were significant differences in the drivers' deceleration behaviours in the different zones. Finally, in each zone, there were significant differences between the probability density distributions of acceleration and deceleration ($P_{a,d} < 0.001$). These results further illustrate that acceleration and deceleration should be calibrated separately in the different zones.

3.3. Feature Value Calibration of Acceleration/Deceleration in Different Zones. Following the observations, we conducted an in-depth analysis of the feature values and calibrated them to the different zones of this study. Figure 4 shows that the acceleration and deceleration values in each zone exceeded the commonly accepted range of values (0.15–0.50 m/s²) for both acceleration and deceleration recommended by the Specifications for Highway Safety Audit of China. Hence, the upper limit values were calibrated by analysing the breakpoints of their cumulative frequency curves because those points are recognized feature values in existing operating speed prediction models. Until now, the 85th percentile point of the cumulative frequency curve has been assumed to be the standard breakpoint, and extant operating speed prediction models are calibrated based on this.

Figure 5 shows the cumulative frequency curves of the acceleration and deceleration for each zone. Notably, the breakpoints were neither observed at the 85th percentile of the cumulative frequency curves of acceleration nor at the deceleration. They were instead found at the 95th percentile, highlighting a notable model discrepancy. This suggests that modifications are necessary for tunnel entrances.

The 95th percentile breakpoint rates of acceleration were nearly the same (0.5 m/s²) in the different zones (0.50, 0.50, 0.50, and 0.47 m/s² for zones 1–4, respectively). Thus, they were not larger than 0.5 m/s². Hence, realistic expectations of acceleration at tunnel entrances fall within the suggestion range assumed by the Specifications for Highway Safety Audit of China.

However, these rates varied in the different zones (0.93, 0.85, 0.70, and 0.47 m/s² for zones 1–4, respectively). Only in zone 4, the 95th percentile rate of deceleration falls within the suggested range, whereas that of deceleration in the other zones was greater than the upper limit of the suggestion range. The largest 95th percentile

FIGURE 5: Cumulative frequency curves of acceleration and deceleration for each zone. (a) Acceleration. (b) Deceleration.

rate of deceleration was found in zone 2 (0.93 m/s^2), which exceeded the upper limit (0.5 m/s^2) of the suggested range by 86%. This implies that the suggested range of acceleration and deceleration at tunnel entrances should be considered separately.

The calibration determined the 95th percentile rate of acceleration ($0 \sim 0.5 \text{ m/s}^2$ in all zones) can be used for modifying operating speed prediction models. Thus, if the worst condition in the tunnel entrance zones is considered, the largest 95th percentile rate of deceleration (0.93 m/s^2 in Zone 2) can be used to establish boundary conditions of deceleration for operating speed prediction. Furthermore, in the simulation cabin, Lamm and Choueiri [2] estimated the deceleration and acceleration rates to be 0.8 m/s^2 and Calvi et al. [19] estimated them to be 0.85 m/s^2 . Thus, the rates in simulation cabin are obviously different from the 95th percentile breakpoint rates of the naturalistic driving test. The 95th percentile breakpoint rates of acceleration and deceleration may provide reference for simulation parameter correction.

4. Conclusion

This study found that the differences of acceleration and deceleration distributions at tunnel entrances are extremely important to calibrating and improving the common operating speed prediction model currently in use. To obtain the actual acceleration and deceleration characteristics of vehicles, naturalistic driving tests and continuous online data observations were carried out on a freeway segment spanning 30 tunnels. The distribution characteristics in four specified zones at each tunnel entrance were observed, and the feature values were analysed. The main conclusions of the research are as follows:

- (1) In the four sections of each tunnel entrance, the distributions of deceleration differed from those of acceleration, which contradicts the assumptions of

common operating speed prediction models. Moreover, the distribution of acceleration and deceleration according to driving speed may be affected by zone divisions. Therefore, acceleration and deceleration should be calibrated separately in the different zones of tunnel entrances.

- (2) From the area outside the tunnel (zone 1) to that completely inside the tunnel (zone 4), the proportion of deceleration increased first and decreased afterward. Specifically, the proportions were 0.86, 0.89, 0.64, and 0.46 in zones 1–4, respectively, whereas the proportion of acceleration was reversed. Furthermore, there were no significant differences in the probability density distribution of acceleration in any zone. However, there were significant differences of the probability density distribution of deceleration in all zones. Furthermore, the probability density distributions of acceleration and deceleration were different in all zones. Thus, value calibration of acceleration and deceleration should be performed separately.
- (3) For both acceleration and deceleration, the breakpoints were not found at the 85th percentile of the cumulative frequency curves, as expected from past utilisation of the common model. Instead, they were predominately found near the 95th percentile. The breakpoint values of acceleration were close to 0.5 m/s^2 in the different zones, whereas the breakpoint values of deceleration varied (i.e., 0.93 , 0.85 , 0.70 , and 0.47 m/s^2 under zones 1–4, respectively). The largest breakpoint value of deceleration (0.93 m/s^2) was found in zone 2: a fact that can be used as a modified parameter for operating speed prediction models at tunnel entrances.

In the present study, owing to the technical limitations of the transmission and collection of continuous online data from trucks, data of acceleration/deceleration were collected

using passenger cars only. Therefore, future works should calibrate acceleration and deceleration parameters of heavy trucks at tunnel entrances.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This study was funded by the National Natural Science Foundation of China (51778242, 51978283, and 51808370).

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