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Research Article

Vibration Effect Produced by Raised Pavement Markers on the Exit Ramp of an Expressway

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Driving over raised pavement markers (RPMs) spaced at different spacing, the human body will experience different vibrations. To explore whether RPMs situated at the exit ramp of an expressway induce a good vibration warning effect, this paper determines the spacing of RPMs situated along a deceleration lane and curved ramp. Models of roads, vehicles, and RPMs are first established in the ADAMS software, after which an integrated human-chair model constructed in SolidWorks is imported into ADAMS, and then the complete model is formed so that vibration simulations of different types of vehicle at different spacing and speeds can be carried out. The results show that the vibration warning effects of the spacing proposed by the existing Chinese specifications and this paper are basically between level III and level IV, the driver's subjective feeling is between less comfortable and uncomfortable, and both induce a good vibration warning effect. For a linear deceleration lane, when considering traffic safety, a spacing of 3 m is recommended; when considering the economy, a spacing of 6 m is recommended. For a curved deceleration lane and curved ramp, according to the actual curve radius, the spacing of RPMs can refer to the spacing recommended in the paper. In addition, the vibration warning effect for cars and semi-trailer trucks initially increases with an increase in the speed; then, after reaching a certain peak speed, the effect decreases with an increase in the speed, and finally, it tends to become gentle at speeds exceeding 100 km/h. The vibration warning effect for a semi-trailer truck is better than that for a car under the same spacing and speed.

1. Introduction

Raised pavement markers (RPMs) are often served as centerlines, lane lines, and edge lines on road, and they also play an important role in various pavement markers. Accordingly, RPMs are often used on the exit ramps of expressways. In this condition, RPMs not only function as a visual marker but also have the vibration warning effect when vehicles drive over the RPM.

As an important component of the expressway system, exit ramps constitute the only means to transition from an expressway to local roads. Nevertheless, the traffic environment on an exit ramp is more complex than that of the mainline and the entry ramp. Therefore, the exit ramp has become a traffic bottleneck and an accident-prone point for expressways. Accident statistics in the United States indicate that more than 30% of expressway accidents occur on or near an expressway exit, and more than half of them are related to exit ramps [1]. Research has shown that the security situation of the exit ramp of expressway is severe. The RPM has a function of visual guidance, which plays a certain role in the traffic safety. So RPMs are often used at the exit ramp of the expressway. In 2004, a report suggested that the safety benefits of RPMs decrease with an increasing of road curvature. When the curvature exceeds 3.5°, RPMs begin to have a negative effect. The report also defined the AMF, which represents the ratio of the expected number of crashes with RPMs to the expected number of crashes without RPMs, whose result has shown that when the AMF is greater than 1, the RPM has a positive effect on road safety, whereas the RPM has a negative effect on road safety if the AMF is less than 1 [2].

Another factor that affects the safety benefits of the RPM is the spacing. The spacing of RPMs is the main factor that influences the effectiveness of RPMs [3]. Different spacing will affect the function of visual guidance for the

RPM. Specifications in different countries also give suggested spacing for RPMs based on the function of visual guidance. In China, the recommended range of the spacing of RPMs for different situations is provided in the relevant specifications. When RPMs are used in conjunction with markers, the spacing between two RPMs is 6 ~ 15 m; when RPMs are used alone to mark the boundary of a lane, the spacing between RPMs is 1 m ~ 1.2 m; when RPMs are used in conjunction with markers at both entrance and exit ramps, the spacing should be according to the actual situation; and when RPMs are used as the deceleration marker, the spacing between RPMs is 30 cm ~ 50 cm [4]. In the United States, the recommended spacing for RPMs is as follows: the normal spacing is N (12.3 m). However, on an expressway, the spacing should be 2N-3N. When the RPM acts as a single solid line, the spacing should be less than N/4, and as a virtual solid line, the spacing should be less than N/8 [5]. The Canadian Department of Transportation requires that the spacing between RPMs is 26.0 m when they are used in conjunction with road markers; similarly, the spacing between RPMs on curved sections is also specified [6]. New Zealand regulated the spacing for RPMs according to different road marking as follows: when RPMs are used on centerlines, lane lines, and no-overtaking lines, the spacing is 10 m. When RPMs are used on edge lines, the spacing is 20 m [7]. Australia regulated that the spacing for RPMs should be 24 m when there is no lighting on the road and the spacing for RPMs should be 12 m in other cases [8]. Many scholars have conducted further research on the spacing for the RPM on the basis of norms. For instance, Presaud B. and Bahar G. [9] analyzed the impacts of different spacing for RPM on traffic safety, and Guo-hua Liang [10] calculated the spacing for RPMs at different radii of a horizontal curved section by establishing a nighttime driver's visual field model.

In addition to affecting the function of visual guidance for the RPM, the spacing is also one of the main factors affecting the vibration effect of the RPM. The vibration warning function of the RPM can provide a good warning for the driver who deviates from the normal lane to alert them to adjust the driving direction in time and avoid accidents. At present, there are few researches on the vibration warning effect of the RPM. Only Deng [11] studied the vibration effect of the RPM on the straight road in her master's thesis. Moreover, in her research, Deng also used the vibration of the vehicle seat to replace the vibration perceived by human subjectively and did not establish a man-chair-vehicle integration model. Although there are few literatures on the vibration of the RPM, the research on the vibration effect of rumble strips and pavement bumps is relatively mature. Although the physical size and layout of the RPM are different from those of vibration deceleration facilities and vibration bands, some conclusions about the vibration performance of vibration deceleration strips, vibration deceleration markings, and roadside rumble strips are worth investigating. Charltion [12] conducted a study on vibration deceleration markings and found that such markings can alert the driver to reduce the vehicle speed and improve the driving safety. Hou [13] reported the influence of vibrations on speed by analyzing measured data of large and small cars driving over expressway vibration deceleration strips. Chen [14] used the Automatic Dynamic Analysis of Mechanical Systems (ADAMS) simulation software to carry out a simulation of the comfort of a truck driver driving over deceleration strips and created a suitable deceleration strip for roads. Yan et al. [15] simulated and analyzed the vibration warning effects of the design of vibration belt. Then they obtained a relationship between changes in the main design elements of the vibrating belt and the change in the warning effect. Liu et al. [16] analyzed the warning effects of roadside vibration belts with different design sizes by performing field tests on 5 types of cutting-type roadside vibration bands. Nevertheless, the vibration performance needs to be evaluated by examining the driver's comfort during a vibration simulation.

Accordingly, scholars have proposed some indicators and methods for evaluating the driver's comfort. Zheng [17] put forward the comprehensive index to evaluate the smoothness of automobile-automobile vibration comfort. Kim Tae-hyeong et al. [18] proposed a 4-degree-of-freedom (4-DOF) human vertical vibration model based on the seat-head (STH) transfer function and the mechanical impedance of drive points (DPM). Furthermore, Kumbhar Prasad et al. [19] studied the use of multivariate biodynamic models to evaluate human responses to different types of seats.

Due to the exit ramp being difficult to identify and the road alignment on an exit ramp changing quickly, and the high speed of the vehicle, many vehicles will inevitably drive over RPMs located along the edges of the lanes on exit ramps. In this case, the vibration warning function of the RPM can effectively remind the driver that the vehicle has deviated from the normal lane. However, previous studies on RPMs are mainly based on the suggested spacing by the function of visual guidance, and few studies have considered the effect of vibration warning. And when the spacing of RPMs is different, whether drivers feel the vibration is different or not, there is no quantitative conclusion on the level of the vibration warning effect corresponding to the different vibration. In addition, previous studies on vibration simulation are all based on the evaluation of vehicle vibration, without considering the true bearer of vibration -- the subjective feelings of human, which is obviously unreasonable.

Therefore, this paper first determines the spacing of RPMs in each section of expressway exit ramp, and the evaluation standard was established with reference to the Method of Running Test-Automotive Ride Comfort (GB/T4970-2009). Models of roads, vehicles, and RPMs were established based on ADAMS software, and a 9-DOF human-chair model was established in combination with SolidWorks. The vibration warning effect of RPMs was then analyzed under different combinations of spacing, speeds, and vehicle types.

2. Methods

2.1. Determine the Object of the Study. An expressway exit ramp consists of a deceleration lane, an easement curve, and a curved ramp. Among them, the deceleration lane is divided into direct-type and parallel-type lanes [20]. Compared with parallel deceleration lanes, direct deceleration lanes have an unclear starting point and a short length, and thus, drivers

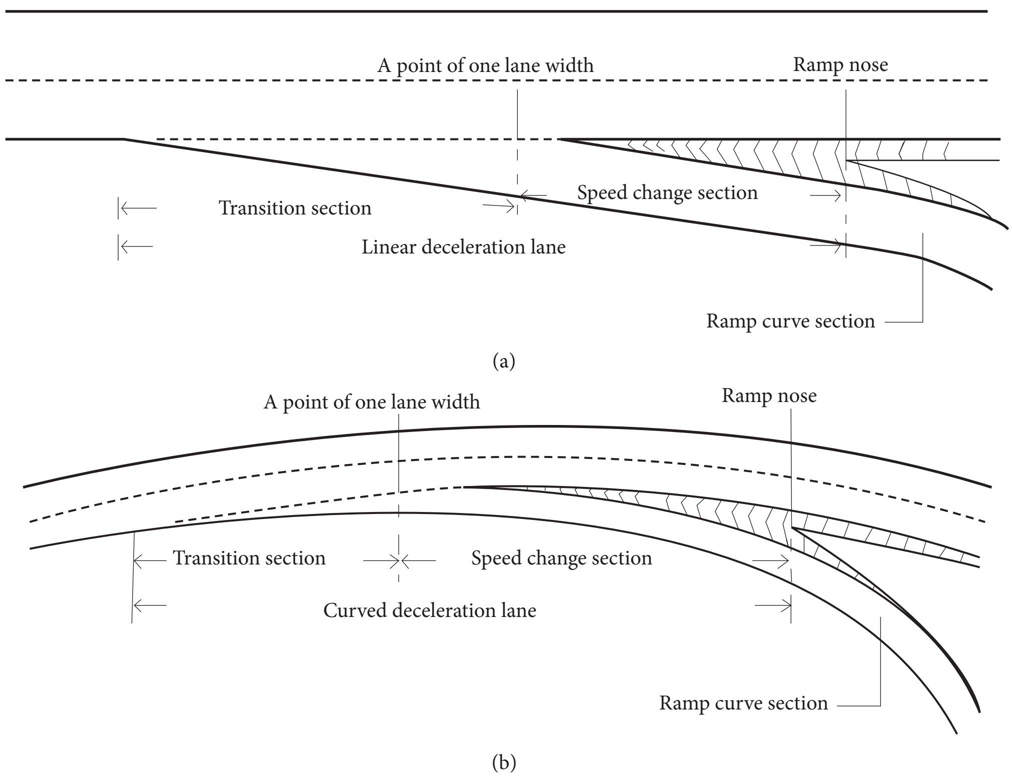

Figure 1: Schematic diagram of the study area of the RPM at the exit of the expressway: (a) freeway exit ramp (straight mainline); (b) freeway exit ramp (curved mainline).

lack sufficient time to achieve steady deceleration. Therefore, this paper mainly takes the direct deceleration lane as the research object and selects a single lane for research. For this purpose, RPMs are arranged outside of the lane edge line, and they are situated 10 cm away from the lane edge line.

The vibration warning effect of RPMs along an exit ramp is closely related to the spacing of RPMs. If the spacing is too sparse, the vibration effect will be insufficiently strong, while if the spacing is too dense, it will not only cause damage to vehicles but also call for a higher cost. Therefore, the spacing of the RPM at the curved ramp and the deceleration lane should be determined before analyzing the vibration warning effect of RPMs. For the deceleration lane, China's relevant regulations stipulate that the linear shape of the deceleration lane should be consistent with the mainline shape of the expressway. Furthermore, when the mainline is a circular curve, the deceleration lane should adopt a curved shape with a curvature that is either similar or identical to that of the mainline [21]. Therefore, if the mainline is a straight line, the study area is shown in Figure 1(a); if the mainline is a curve, the study area is shown in Figure 1(b).

The relevant regulations in China do not specify the spacing of the RPM on the curved ramp. By establishing a model of the driver's visual field, Lin calculated the spacing of RPMs on a circular curve and the specific spacing is shown in Table 1 [22]. In addition, when RPMs are placed inside and outside of the circular curve lane edge line, they should be on a radial line [22]. So when the spacing on the inside of the circular curve lane edge line is determined, the corresponding spacing on the outside of the circular curve lane edge line is also determined. Therefore, this paper takes the spacing of the RPM on the inside of the circular curve lane edge line as the research object.

Based on statistical survey data from the first Highway Survey and Design Research Institute of China, the most frequently used radii of curved ramp on the expressway exit ramp in China are 60 m ~ 80 m, 150 m ~ 210 m, and 280 m ~ 1000 m. This article selects three radii, namely, 70 m, 180 m, and a critical radius of 700 m from the most frequently used curved ramp radii as simulation parameters. In combination with Table 1 and considering the feasibility of the simulation, the corresponding spacings of the RPM are 4 m, 6 m, and 15 m. And the spacing of the RPM on an easing curve is identical to that on the connected circular curve [22].

When the mainline of the expressway is a straight line, the linear shape of the deceleration lane is also a straight line. At this point, according to the example in relevant Chinese specifications [4] and considering the actual construction conditions and the limitations on the simulation conditions, this paper takes 3 m, 4 m, 5 m, and 6 m as the spacing for the RPM of the linear deceleration lane.

In contrast, when the mainline of the expressway is a circular curve, the deceleration lane should have a curvature that is similar or identical to that of the mainline. In China, design speeds of 60 km/h, 80 km/h, 100 km/h, and 120 km/h are considered for the mainline of an expressway. According to Table 1, the minimum radius of the corresponding circular curve is 200 m, 400 m, and 700 m, for which the radius of

Table 1: Spacing for the radius of a circular curve.

Design speed [km·h^{-1}]	20~30	30~40	40~60	60~80	80~100	100~120
General value of minimum radius of circular curve [m]	30~65	65~100	100~200	200~400	400~700	>700
Spacing [m]	2.25~3	3.5~4.5	4.5~7	7~11	11~15	15

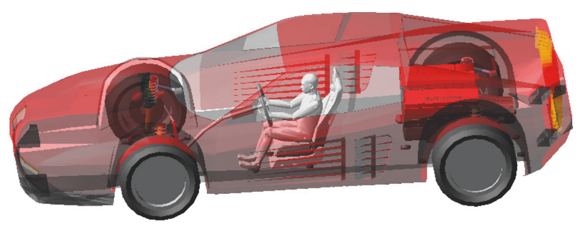

Figure 2: The man-chair-vehicle integration model (Take Santana 2000 as an example).

curvature of the deceleration lane should also be 200 m, 400 m, and 700 m, respectively, and the spacing of the RPM should be 7 m, 11 m, and 15 m.

2.2. Establishing the Simulation Model. When a car drives over an RPM, the process through which the driver experiences vibrations is very complicated. When the car seat is shaken by the body of the vehicle, the car seat will absorb a component of the vibration and transmit the remainder to the driver. Past studies have employed the vibration of the vehicle body instead of the vibration experienced by the driver which is obviously unreasonable. Accordingly, to reflect the actual situation and explore the vibrations on the human body, it is essential to construct a dynamic human-chair-vehicle model. The human model was carried out in SolidWorks according to the dimensions of the various parts of the human body and the ranges of joint angles of the sitting posture [23, 24]. Then, with reference to the human sitting posture model, the tilt angle of the seat back is adjusted to $105^{\circ} \sim 115^{\circ}$, the seat height is 640 mm, and the seat mass is 20 kg. The same seat model is used for both large and small cars. Regarding the connection between the human body and the seat, there are three areas to consider: seat-backrest, seat support surface, and foot [25]. Finally, the connection of the human-chair model is based on the 9-DOF human-chair model [26].

The vehicle models of cars and semi-trailer trucks are created in ADAMS and the constructed human-chair model is imported through ADAMS/VIEW. Then, the man-chair-vehicle integration model is obtained. The car is selected from Santana 2000. In addition to the seats, other parameters of the car and semi-trailer truck are based on the software default values. The complete model is shown in Figure 2.

The Road Builder module in ADAMS is easy to operate and contains many parameters with which to define the road. Accordingly, this paper constructs a 3D road model of the deceleration lane and curved ramp by the given node coordinates. When the mainline is a straight line, the deceleration lane is built along a straight line with a length of 200 m. When the mainline is curved, the deceleration lane is established along a circular curve, and the radii of the deceleration lane are 200 m, 400 m, and 700 m, while the radii of the curved ramp are 70 m, 180 m, and 700 m as the simulation road radius. The following three parameters also use the default values: the width of the road is 3.75 m, the slope of the longitudinal slope is 0, and the friction coefficient is 0.9. The length, width, and height of the RPM studied in this paper are set as 10 cm, 10 cm, and 2.5 cm, respectively [4]. RPMs are modeled by a convex block obstacle in ADAMS/CAR, and the width, length, and height of RPMs are set using the independent obstacle setting of the Road Builder module. After the models of RPMs are completed, place them on outside of the lane edge line, and they are situated 10 cm away from the lane edge line. The specific modeling process is shown in Figure 3.

2.3. Simulation Parameters. After running the model, we make a preliminary simulation to determine the experimental factors. Because the changes of various structural parameters of vehicles have complex effects on vibration, we do not consider the influence of the variation of vehicle parameters on the experiment in the preliminary simulation experiment. Only two factors, the vehicle type and the vehicle speed, are selected as variables. The preliminary simulation also shows that, in addition to the spacing of RPMs, the vehicle type and the vehicle speed have a great influence on the vibration warning effect. And when the simulation time is 15 s, the vehicle can drive over RPMs many times, which is sufficient for collecting experimental data. Therefore, the processing parameters, such as the spacing of the RPM, vehicle type, vehicle speed, and simulation time, are selected as the simulation parameters. The simulation speeds on the deceleration lane are 55 km/h, 60 km/h, 65 km/h, and 70 km/h [22]. The simulation speeds on the curved ramp section are 40 km/h, 50 km/h, and 60 km/h [20]. The simulation time is 15 s. The specific simulation scheme parameters are shown in Table 2.

After entering the relevant simulation parameters into the software and running the model, Adams/Car will output the three-axis acceleration curves of the x-axis, y-axis, and z-axis of the seat cushion, seat back, and foot.

2.4. Evaluation Index of the Simulated Vibration Warning Effect. When the vehicle drive over RPMs, vibration is generated, and then the driver gets a warning through the touch. The vibration warning effect is related to the vibration acceleration generated by different vehicles driving over the RPM. Therefore, the vibration warning effect can be evaluated by the vibration acceleration. International standard entitled

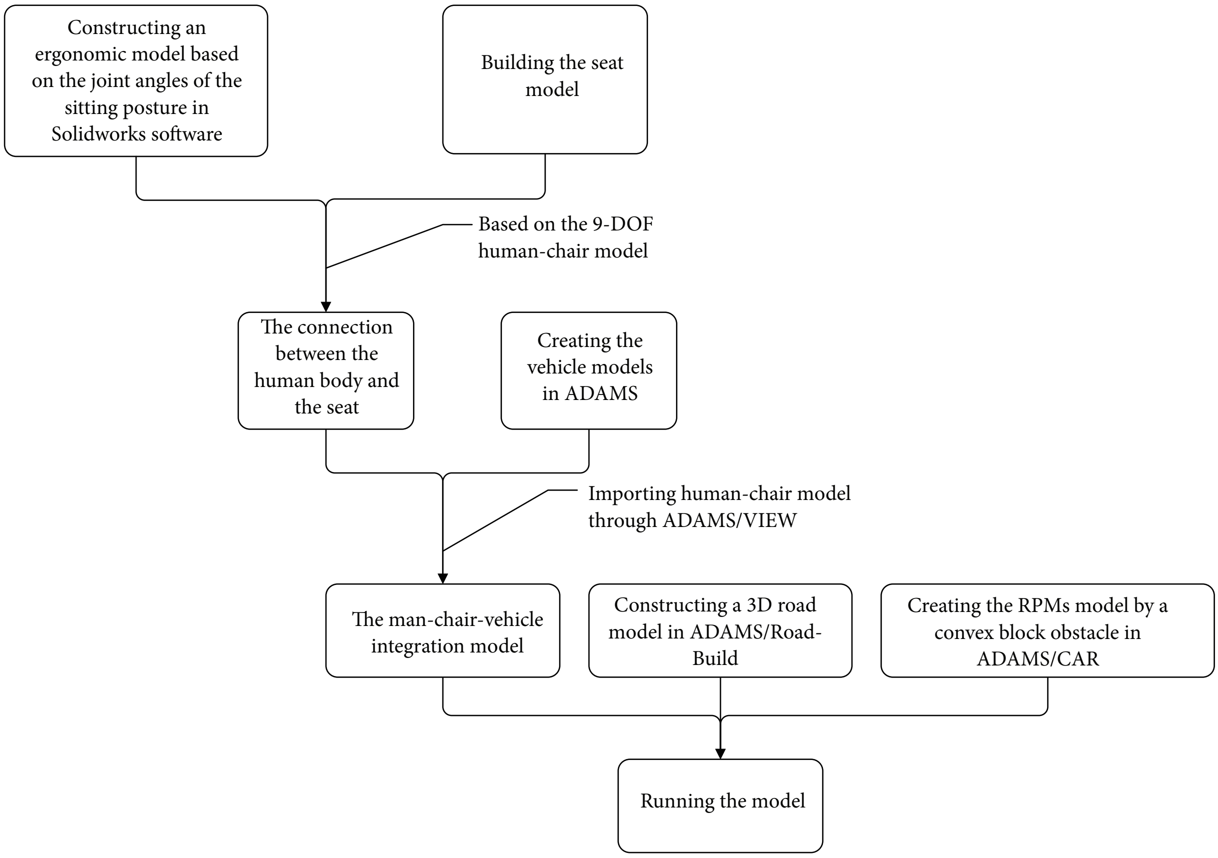

Figure 3: Flowchart of building simulation model.

Table 2: Simulation scheme parameters.

Section		Cars and semi-trailer trucks			
		Spacing [m]	Speed [km·h^{-1}]	Radius [m]	Time [s]
Deceleration lane	Linear	3	55/60/65/70	/	15
		4			
		5			
		6			
	Curved	7	55/60/65/70	200	15
		11		400	
		15		700	
Ramp curve section		4	40/50/60	70	15
		6		180	
		15		700	

Mechanical Vibration and Shock-Evaluation of Human Exposure to Whole-Body Vibration-Part 1: General Requirements (ISO2631-1:1997) describes the vibration model of the human body when the vehicle drives over a road with a rough surface. At the time of evaluation, we should start from the backrest, the support surface of the seat and the foot, and choose the acceleration root mean square (RMS) as the evaluation index for the effect of the vibrations on human comfort and health [25]. According to the above standards, China has formulated the *Method of Running Text-Automotive Ride Comfort (GB/T4970-2009)* [27]. Therefore, referring to the above-mentioned ride comfort evaluation method, this paper selects the combined total weighted acceleration RMS as the evaluation index and establishes an evaluation criterion for the vibration warning effect of the RPM.

In order to obtain the weighted acceleration RMS of the human body accurately and quickly, this paper analyzes the spectrum of the three-axis acceleration curves of the x-axis, y-axis, and z-axis of the seat cushion, backrest, and foot generated by Adams/Car. Then, the obtained acceleration self-power spectral density function curve is, respectively, imported into Glyphworks in Ncode software, and then

Table 3: The relationship between the human subjective feeling and the combined total weighted acceleration RMS.

The combined total weighted acceleration RMS [m/s^2]	Human subjective feeling	The level of the vibration warning effect
<0.315	No discomfort	I
0.315-0.63	A little uncomfortable	II
0.5-1.0	Less comfortable	III
0.8-1.6	Uncomfortable	IV
1.25-2.5	Very uncomfortable	V
>2.0	Extremely uncomfortable	VI

the total weighted acceleration RMS of each point ($\overline{a}_{vj}$) is calculated, as shown in formula (1). Thus the combined total weighted acceleration RMS of the seat cushion, seat back, and foot ($\overline{a}_v$) is calculated, as shown in formula (2). To be more intuitive, this paper marks the evaluation standard of each level from I to VI, as shown in Table 3.

(1) Calculate the total weighted acceleration RMS of each measurement point position:

$$\overline{a}_{vj} = \left(k_x{}^2\overline{a}_{wx}{}^2 + k_y{}^2\overline{a}_{wy}{}^2 + k_z{}^2\overline{a}_{wz}{}^2\right) \tag{1}$$

In the above formula:

$\overline{a}_{vj}$ is total weighted acceleration RMS at j, $j = 1, 2, 3$, they represent the seat, seat back, and foot support surfaces, respectively, (m/s^2);

$\overline{a}_{wx}$ is longitudinal (x-axis) weighted acceleration RMS, (m/s^2);

$\overline{a}_{wy}$ is horizontal (y-axis) weighted acceleration RMS, (m/s^2);

$\overline{a}_{wz}$ is vertical (z-axis) weighted acceleration RMS, (m/s^2);

k_x, k_y, k_z are weighting coefficients for each axis, specific values according to *"Method of Running Text-Automotive Ride Comfort" (GB/T4970-2009)* [27].

(2) The combined total weighted acceleration RMS of the three measuring points is calculated as follows [27]:

$$\overline{a}_v = \left(\sum \overline{a}_{vj}{}^2\right)^{1/2} \tag{2}$$

In the above formula:

$\overline{a}_{vj}$ is the total weighted acceleration RMS at j, where j=1, 2, and 3 represent the seat, seat back, and foot support surfaces, respectively (m/s^2).

2.5. Significant Test of Variables. There are three control variables in this paper: the type of vehicle, spacing, and speed, and the observed variable is the combined total weighted acceleration RMS ($\overline{a_v}$). This is a typical ANOVA problem because it studies the significance of the influence of three discrete variables on $\overline{a_v}$. The basic idea of ANOVA is to decompose the total dispersion and degree of freedom of all observations into several parts according to the design type and research purpose of the data. In addition to the random error, the variation of each part can be explained by the effect of a factor, such that the variation between the mean of each group can be explained by the processing factor. Then by comparing the mean square of different sources of variation and making statistical inference by F-distribution, it is judged whether the factor has influence on the observed variable. However, ANOVA also has its applicable conditions: independent, normal distribution, and homogeneity of variance. The data must satisfy the three conditions before using ANOVA. Through the test, it can be seen that the experimental data of this paper satisfy the three applicable conditions of ANOVA. Therefore, ANOVA was used to analyze the significance of the variables in this paper.

ANOVA can be divided into one-way analysis of variance and multivariate analysis of variance according to the type of data design. Because there are three factors in this paper, such as the type of vehicle, spacing, and speed, the multivariate analysis of variance is used in this paper and the 95% confidence interval is taken. Multivariate analysis of variance can not only analyze the independent influence of multiple factors on observed variables, but also analyze whether the interaction of multiple control factors can have a significant influence on the distribution of observed variables and finally find the optimal combination for the observed variables.

Now the type of vehicle, spacing, and speed are converted into classified variables. The classification of each variable is shown in Table 4.

Table 4: The classification of each variable.

Variable name		Variable value
Type of vehicle	Car	0
	Semi-trailer truck	1
Spacing	3 m	0
	4 m	1
	5 m	2
	6 m	3
	7 m	4
	11 m	5
	15 m	6
Speed	40 km/h	0
	50 km/h	1
	55 km/h	2
	60 km/h	3
	65 km/h	4
	70 km/h	5

Table 5: Interaction test. The dependent variable: the combined total weighted acceleration RMS.

Source	Type III Sum of *Squares*	df	Mean *Square*	F	Sig. (P)
Corrected model	2.633[a]	67	0.039	3.409	0.062
Intercept	56.520	1	56.520	4903.704	0.000
Type of vehicle	0.415	1	0.415	36.043	0.001
Speed	0.278	5	0.056	4.819	0.041
Spacing	1.227	6	0.204	17.740	0.001
Type of vehicle∗Speed	0.031	5	0.006	0.540	0.742
Type of vehicle∗Spacing	0.205	6	0.034	2.958	0.106
Speed∗Spacing	0.199	22	0.009	0.785	0.691
Type of vehicle∗Speed∗Spacing	0.027	22	0.001	0.105	1.000
Error	0.069	6	0.012	--	--
Total	71.209	74	--	--	--
Corrected total	2.702	73	--	--	--

a. R^2=0.974 (Corrected R^2=0.689).

The converted variable data was imported into SPSS for Multivariate Analysis of Variance. The results are shown in Tables 5 and 6.

It can be seen from Table 5 that the statistic of corrected model (F) is 3.409, P=0.062, and Type of Vehicle∗Speed, Type of Vehicle∗Spacing, Speed∗Spacing and Type of Vehicle∗Speed∗Spacing have no statistical significance, and the values of P are both greater than 0.05. This indicates that the current model of the interactions of several variables is not significant, so that the significance test of the model is not strong enough. However, type of vehicle, speed, and spacing all have statistical significance, and the significances were P=0.001, P=0.041, P=0.001. This shows that the type of vehicle, speed, and spacing all have significant influence on the combined total weighted acceleration RMS. That is, they all have the significant influence on the vibration effect. But when the three factors interact with each other, they have no significant effect on the vibration effect.

As can be seen from Table 6, the statistic of corrected model (F) is 21.185, and the value of P is far less than threshold value 0.05, which indicates that the model has statistical significance. The type of vehicle, speed, and spacing all have statistical significance, and the values of P are both far less than 0.05, which indicates that the type of vehicle, speed, and spacing all have significant influence on the combined total weighted acceleration RMS. That is, they all have the significant influence on the vibration effect.

Tables 5 and 6 show that the three factors of the type of vehicle, speed, and spacing all have significant influence on the combined total weighted acceleration RMS. That is, they all have the significant influence on the vibration effect. Therefore, we will discuss how these three factors affect the effect of vibration warning in combination with the curve trend in Results.

3. Results

When a vehicle is on the road, it sometimes departs to the left of the lane or to the right of the lane. When the above model is running, the vehicle will also randomly deviate to the left or to the right, which will result in two different directions of vibration acceleration. In each case, there will be the combined total weighted acceleration RMS in both directions, namely, the left combined total weighted acceleration RMS and the right combined total weighted acceleration RMS. In this paper, the deviation to the right of the lane is defined as the deviation to the inside of the lane, and the deviation to the left of the lane is defined as the deviation to the outside of the lane. The specific experimental results are shown in Figures 4 and 5.

In the speed range of 55 km/h ~ 70 km/h, whether it is the linear deceleration lane or the curved deceleration lane, the combined total weighted acceleration RMS of the car and the semi-trailer truck deviating toward the inside and outside of the lane decrease with an increase in the spacing under the same simulation speed conditions. That is, the denser the spacing of the RPM, the more uncomfortable the driver's subjective feeling, which means the better the vibration warning effect.

For the linear deceleration lane, when the spacing is either 3 m or 4 m, drivers of the car feel less comfortable or uncomfortable, and the vibration warning effect for the car is between level III and level IV, while drivers of the semi-trailer feel uncomfortable, and the vibration warning effect is mostly level IV. When the spacing is either 5 m or 6 m, most drivers of the car feel less comfortable, and the vibration warning effect is mostly level III, while drivers of semi-trailer still feel uncomfortable, and the vibration warning effect is level IV (Figures 4(a) and 4(b)). Therefore, it can be seen that the subjective feeling of drivers is between less comfortable and uncomfortable, which is a medium level, neither making drivers feel very uncomfortable, nor letting drivers ignore the discomfort. Therefore, for the spacing of the RPM, 3 m is recommended in consideration of safety; in consideration of the economy, the spacing of an RPM of 6 m is recommended.

For the curved deceleration lane, the subjective feelings of the driver of the semi-trailer and the car are between the less comfortable and uncomfortable, and also at a medium level.

Table 6: Main effect test. The dependent variable: the combined total weighted acceleration RMS.

Source	Type III Sum of *Squares*	df	Mean *Square*	F	Sig. (P)
Corrected model	2.179[a]	12	0.182	21.185	0.000
Intercept	49.724	1	49.724	5801.422	0.000
Type of vehicle	0.650	1	0.650	75.874	0.000
Speed	0.275	5	0.055	6.406	0.000
Spacing	1.284	6	0.214	24.965	0.000
Error	0.523	61	0.009	--	--
Total	71.209	74	--	--	--
Corrected total	2.702	73	--	--	--

a. R^2=0.806 (Corrected R^2=0.768).

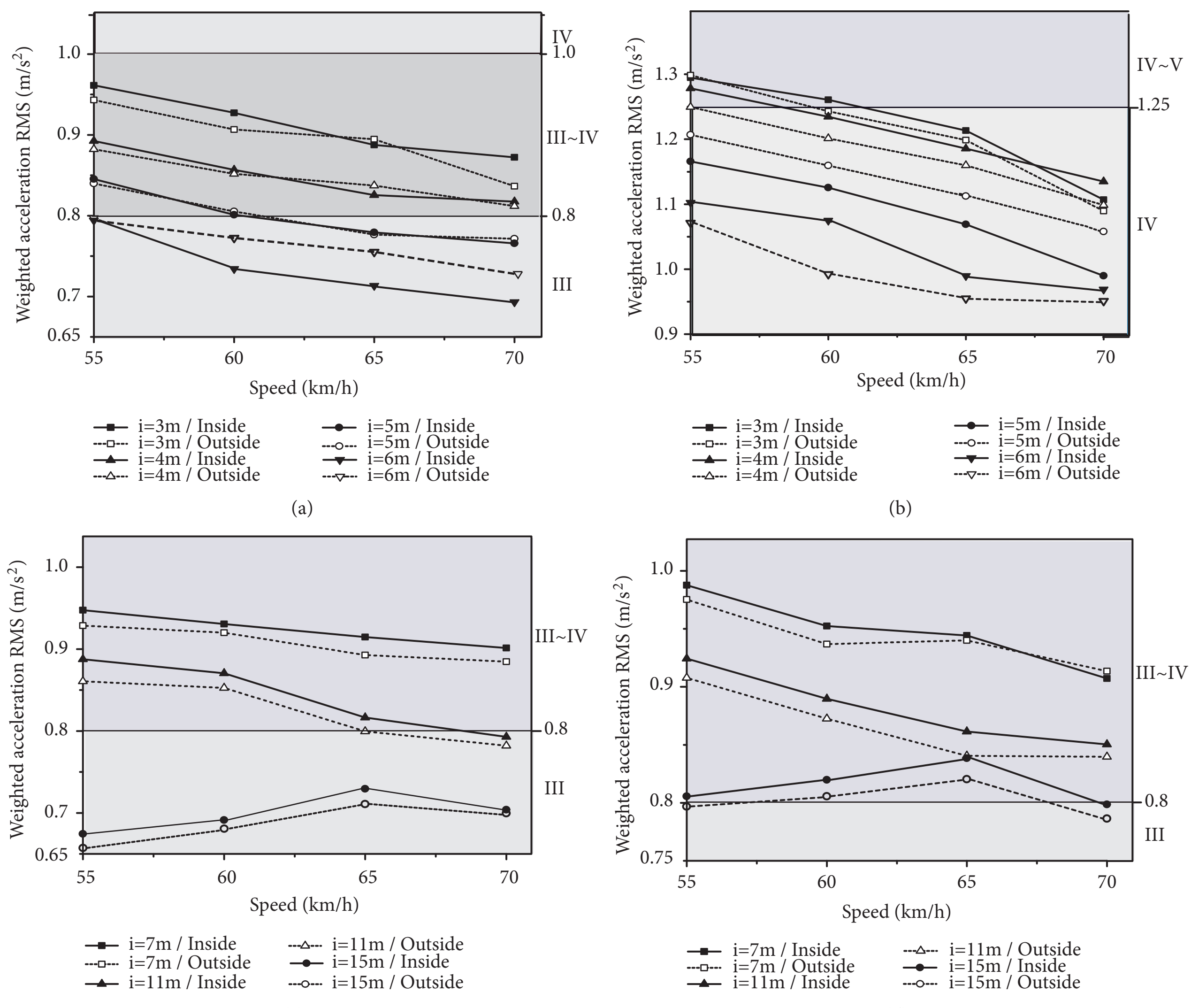

Figure 4: The combined total weighted acceleration RMS for the deceleration lane: (a) the linear deceleration lane (car); (b) the linear deceleration lane (semi-trailer truck); (c) the curved deceleration lane (car); (d) the curved deceleration lane (semi-trailer truck).

Therefore, regardless of the spacing, mainly corresponding to the radius of the curve, the vibration warning effect of the RPM is better. When the spacing of the RPM is 15 m, the combined total weighted acceleration RMS of the car and semi-trailer truck deviating toward the inside and outside of the lane increase with an increase in the speed at first; however, after reaching a peak at the speed of approximately 65 km/h, it shows a downward trend with an increase in the speed (Figures 4(c) and 4(d)). For other spacing of the linear deceleration lane and the curved deceleration lane, the

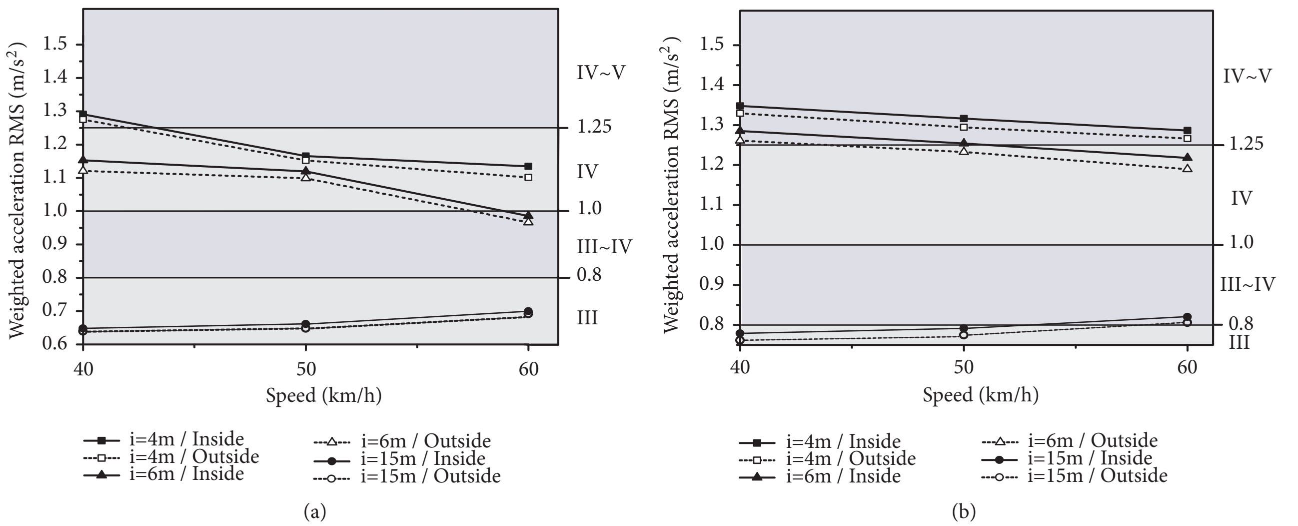

Figure 5: The combined total weighted acceleration RMS for the curved ramp section: (a) the curved ramp section (car); (b) the curved ramp section (semi-trailer truck).

combined total weighted acceleration RMS of the car and semi-trailer truck decrease with an increase in the speed in the speed range of 55 km/h ~ 70 km/h. That is, the higher the speed, the weaker the subjective feeling of the driver, and the weaker the vibration warning effect.

Under the same simulation speed and spacing, the combined total weighted acceleration RMS of the semi-trailer truck deviating toward the inside and outside of the lane are larger than those of the car. That is, drivers of the semi-trailer truck feel more uncomfortable than drivers of the car, meaning that the vibration warning effect for the semi-trailer truck is stronger than that for the car.

For the curved ramp section, it is shown in Figures 5(a) and 5(b).

In the speed range of 40 km/h ~ 60 km/h, with the increase of the spacing, the subjective feeling of the driver is weaker; that is, the vibration warning effect of cars and semi-trailer trucks also decreases as the spacing increases. When the spacing is either 4 m or 6 m, the vibration warning effect for the car is mostly level IV, and most drivers of the car feel uncomfortable; whereas the vibration warning effect for the semi-trailer truck is between level IV and level V, most drivers of the semi-trailer truck feel uncomfortable and a few feel very uncomfortable. Therefore, it also has good vibration warning effect. When the spacing of the RPM is 15 m, the vibration warning effect is the same as the trend for the curved deceleration lane.

4. Discussion

Previous research has shown that the change trend of the combined total weighted acceleration RMS for the linear deceleration lane at speeds of 55 km/h, 60 km/h, 65 km/h, and 70 km/h is approximately constant under different spacing; that is, they decrease with an increase in the speed. Meanwhile, the trends of the curved deceleration lane and the curved ramp are similar to that of the linear deceleration lane. When the spacing is 15 m, the combined total weighted acceleration RMS shows a rising trend first and then decreases. However, the variation in the vehicle speed during the actual driving process is more complicated, and these trends are limited to the speed range discussed in the Results part of this paper. However, it is not clear whether the change trends of speeds below and above the speed range discussed herein will be the same. Therefore, this paper analyzes the vibration warning effect for vehicles driving over RPMs in other speed ranges.

Generally, the starting speed of a vehicle in first gear is approximately 10 km/h; thus, this speed is selected as the minimum simulation speed, and the maximum speed limit on a Chinese expressway of 120 km/h is selected as the maximum simulation speed with 10 km/h as the spacing step. For the deceleration lane, the simulation speeds were selected from the low speed range (10 km/h, 20 km/h, 30 km/h, 40 km/h, and 50 km/h) and the high speed range (80 km/h, 90 km/h, 100 km/h, 110 km/h, and 120 km/h). Similarly, for the curved ramp, the simulation speeds were selected from the low speed range (10 km/h, 20 km/h, and 30 km/h) and the high speed range (70 km/h, 80 km/h, 90 km/h, 100 km/h, 11 0 km/h, and 120 km/h). ADAMS was used to carry out the simulation experiment under the same simulation parameters as described above and summarize the conclusion of this simulation and the conclusion of Results section. The results are shown in Figures 6 and 7.

For a linear deceleration lane, the spacing of an RPM of 3 m is recommended when considering safety, whereas a spacing of 6 m is recommended when considering the economy. Therefore, these two representative spacings of 3 m and 6 m are selected for further discussion.

From Figures 6 and 7, in the speed range of 10 km/h to 120 km/h, most drivers still feel less comfortable or uncomfortable, and only a small number of drivers feel a little uncomfortable or very uncomfortable. And the vibration warning effect is good.

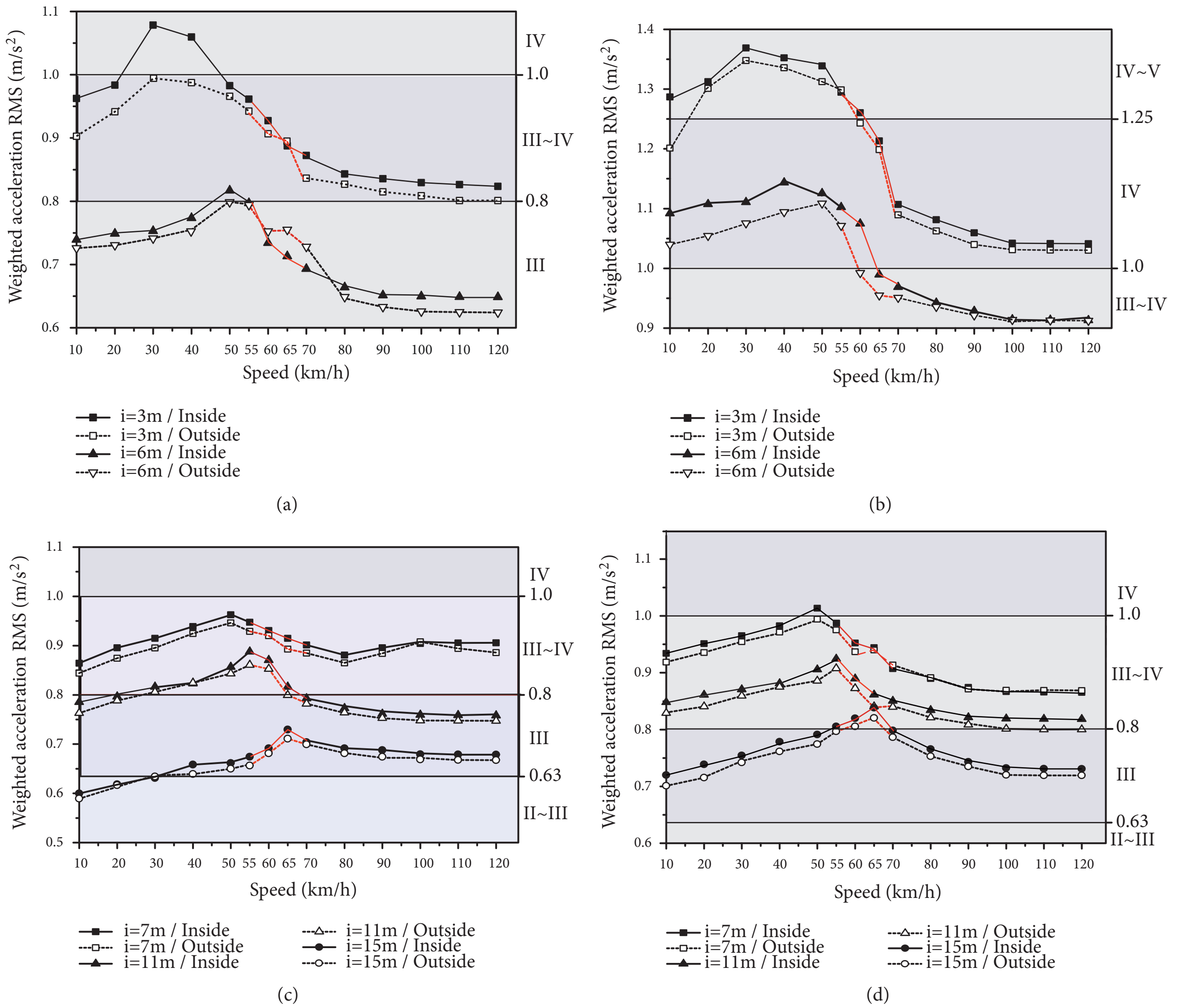

Figure 6: The combined total weighted acceleration RMS for the deceleration lane between 10 km/h and 120 km/h: (a) the linear deceleration lane (car); (b) the linear deceleration lane (semi-trailer truck); (c) the curved deceleration lane (car); (d) the curved deceleration lane (semi-trailer truck).

The combined total weighted acceleration RMS of the car and semi-trailer truck deviating toward the inside and outside of the lane both increases with the increase of the speed at first and then reaches a peak speed. Next, the combined total weighted acceleration RMS decrease with an increase in the speed and finally become flat. In other words, the vibration warning effect of the RPM first increases with an increase in the speed and then decreases with an increase in the speed after reaching a peak speed value; finally, the vibration warning effect tends to become flat when the speed exceeds 100 km/h. The red curves shown in Figures 6(a)–6(d) and 7(a) and 7(b) correspond to Figures 4(a)–4(d) and 5(a) and 5(b) in the Results section. At different spacings, the speed at which the vibration warning effect reaches its peak value is different, as shown in Table 7 (the values in the table are approximate values).

Therefore, to achieve a better vibration warning effect, it is necessary to select different spacing according to different road alignments and reasonably adjust the spacing of the RPM according to the speed limits.

5. Conclusions

This study chose the total weighted acceleration RMS as an indicator to analyze the vibration warning effect of RPMs along an expressway exit ramp based on ADAMS in reference to the ride comfort evaluation method. During the experiment, the vibration warning effect changed with the spacing of the RPM, vehicle speed, and vehicle type, among other parameters, and the change laws are as follows:

(1) When the vehicle speed and vehicle type are both fixed, the vibration warning effect weakens as the spacing increases.

(2) When the spacing is fixed, the vibration warning effects for a car and a semi-trailer truck increase with an

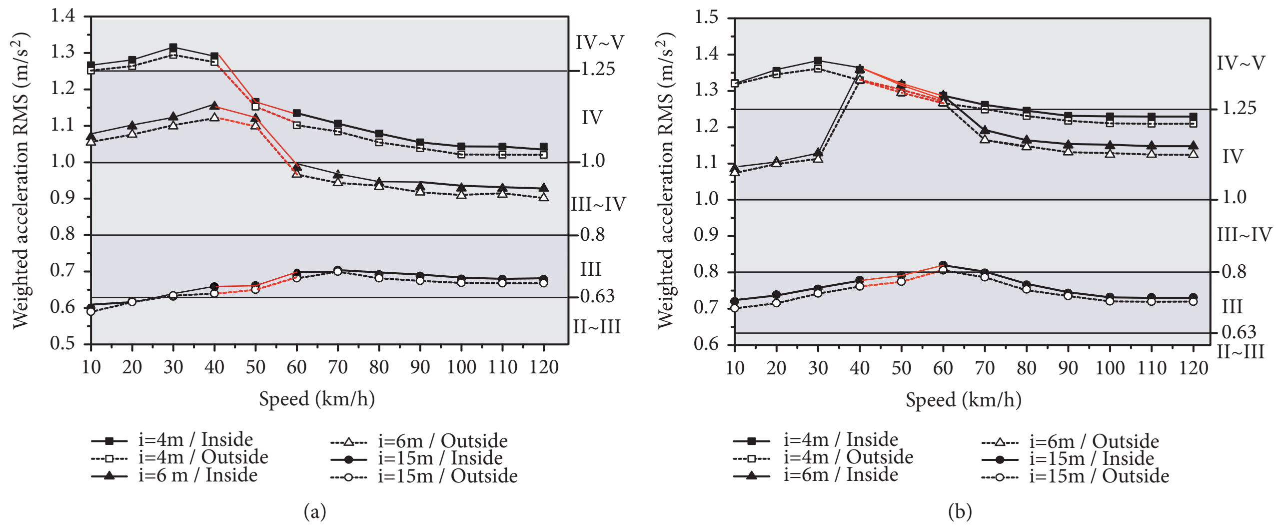

FIGURE 7: The combined total weighted acceleration RMS for the curved ramp section between 10 km/h and 120 km/h: (a) the curved ramp section (car); (b) the curved ramp section (semi-trailer truck).

TABLE 7: The velocity of the vibration warning effect reaching peak values at different spacings.

Section		Spacing [m]	Car speed peak [km·h^{-1}]	Semi-trailers speed peak [km·h^{-1}]
Deceleration lane	Linear	3	30	30
		6	50	40
	Curved	7	50	50
		11	55	55
		15	65	65
Ramp curve section		4	30	30
		6	40	40
		15	70	60

increase in the speed initially, after which the effects decrease with an increase in the speed after a certain peak is reached; finally, the effect gradually becomes gentle after the speed reaches 100 km/h.

(3) When the spacing and speed are both fixed, the vibration warning effect for the semi-trailer truck is stronger than that for the car.

This study provides suggestions for the spacing of RPMs situated along the exit ramp of an expressway. These suggested spacings are conducive to improving road traffic safety and therefore contribute to reducing traffic accidents. Highlighting the vibration warning effect, the proposed spacing for a linear deceleration lane is 3 m when considering traffic safety, whereas the recommended spacing is 6 m when considering the economy. Furthermore, for the curved deceleration lane and the curved ramp, according to the actual curve radius, the spacing of RPMs can refer to the spacing recommended in Table 1.

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 there are no conflicts of interest regarding the publication of this paper.

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