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Superhighway Virtual Track System Based on Intelligent Road Buttons

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ABSTRACT To improve the safety of superhighways, a virtual track system for superhighways based on intelligent road buttons is studied by means of a structural analysis and mathematical model. The system consists of a road subsystem, onboard subsystem and service center subsystem. When a vehicle equipped with an onboard subsystem nears the road buttons, they activate the virtual track system, and the reader reads location coordinates and road alignment information at that point from the label buttons. At the same time, the data processing module begins to function. First, the module reads the linear parameters and processes them to obtain the angle between the road tangent and vehicle body. Then, the module reads the angle of the front wheels, the vehicle speed and the distance between the adjacent two label buttons. Finally, the module obtains the rotational speed of the steering wheel while the vehicle is driving between two label buttons by using the computational model and sends the control parameters to the steering motor. The research results show that when the design speed of the superhighway is 140 km/h, 160 km/h and 180 km/h and the distances between the road buttons are less than 1.33 m, 1.50 m and 1.69 m, respectively, the distance between the centerline of the road and the vehicle can be restricted to less than 50 cm. Therefore, the virtual track system based on intelligent road buttons can restrict vehicles to travel in the virtual track and ensure the safety of superhighways.

INDEX TERMS Highway, superhighway, intelligent button, virtual track, traffic safety.

I. INTRODUCTION

In more than 10 countries in Europe, including France and the Netherlands, the maximum speed limit on highways is 130 km/h [1]; in Texas, USA, it is 137 km/h (85 mile/h) [2]; in Italy, Saudi Arabia, Poland, it is 140 km/h [3]; and in Germany, there is no speed limit on some highways [4]. *The Highway Engineering Design Guidelines (Draft)* published in 1951stipulated that the maximum design speed of highways in China was 120 km/h, and it has been used to date [5].

More than 60 years have passed, the technologies of highway construction and automobile performance have been considerably improved in China, and it is possible to construct superhighways with design speeds exceeding 120 km/h. The building of the first superhighway in China began in 2018; it was Hang-Shao-Yong Highway, which extends from Hangzhou to Ningbo via Shaoxing, and it will open in 2022 before the opening of the Asian Games in Hangzhou. Construction of this highway began only two years after the definition of a superhighway was proposed by us in 2016 [6]. In March 2019, the construction of a second superhighway with a special lane for automatic driving began; it was the Jing-Xiong Highway, which is from Beijing to Xiong'an. The development speed of the superhighway is considerably faster than expected [7].

To improve the safety and efficiency of the highways, we established a speed guidance system by the method of experiment and simulation. The results show that the highway speed guidance system can effectively improve the safety and running speed [7]. Considering that the speed limit of highways in many countries exceeds 120 km/h, automobile and highway construction technologies in China have made

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considerable progress, and we put forward the concept of the superhighway for the first time. In the same paper, we divided the technical grade of the superhighway and demonstrate its feasibility and necessity [6]. Subsequently, we published several papers to conduct in-depth research on the safety, economy, and traffic capacity of superhighways. We demonstrated the safety of the superhighway from three aspects: automobile technology, highway technology and foreign experiences of the safe operation of superhighways [8]. To evaluate the economic efficiency of the superhighway, we compared the cost of traveling by superhighway with the cost of traveling by bus, by train and by plane. The results show that the cost of traveling by superhighway for a single person is between 0.29 and 0.47 Yuan /km. This mode of travel is less expensive than traveling by bus but more expensive than by train and by plane [9]. To study the capacity of the superhighway, we compared it with ordinary highways. The results show that improving the design speed of the superhighway cannot improve its traffic capacity; however, a special highway for automatic driving vehicles can improve the design speed and also improve the traffic capacity [10].

Under our influence, some scholars have begun to study the superhighway. Fenfei and Peng focusing on the characteristic advantages and disadvantages, opportunities and threats of the external environment of superhighways during the construction and operation management period, provided suggestions for the future development of superhighways by using the SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis method [11]. ZHAO You-chao *et al.* proposed high safety requirements for the superhighway based on an investigation of the frequent problems in the existing highway horizontal curve design. Starting from meeting the safety requirements, these researchers established an obstacle identification model for the geometric analysis of flat curves and calculated the safety horizontal curve radius for a superhighway, which provides a basis for the study of the superhighway and its flat curve [12].

There are numerous studies on highways (including expressways and freeways) at home and abroad, especially studies related to safety. However, there are notably few separate studies on highways with design speeds exceeding 120 km/h. The research related to safety mainly includes fatigue driving, over speed and overload, brake failure, tire bursts, geometric design and safety facilities. The Lane Keeping System (LKS), Lane Keeping Assist (LKA) and Lane Departure Warning System (LDWS) keep cars in the lane they should be in. The LKS, LKA and LDWS can effectively avoid traffic accidents caused by fatigue driving. The Superhighway Virtual Track System (SVTS) has functions similar to those of the LKS, LKA and LDWS. The difference is that the LKS, LKA and LDWS identify the lane by cameras, but SVTS identifies the lane by road buttons. In addition, the LKS, LKA and LDWS are mainly used for ordinary roads, whereas the SVTS is mainly used for superhighways with design speeds exceeding 120 km/h. Therefore, it is necessary to introduce research on the LKS, LKA and LDWS related to this paper.

Michael I *et al.* invented a lane keeping system suitable for use with an automated vehicle that includes a camera, a ranging-sensor, and a controller. The camera is used to capture an image of a roadway traveled by a vehicle. The ranging-sensor is used to detect a signal reflected by an object proximate to the roadway. The controller is in communication with the camera and the ranging-sensor. The system can operate an automated vehicle using a ranging-sensor when the lane-marking is not detected by a camera [13]. Christopher L *et al.* invented a lane centering system for use in vehicles driving in a lane on a road and includes a camera and a controller. The system not only keeps the car in the lane but also keeps it in the middle of the lane [14]. Kibeom Lee *et al.* investigated the limits and tradeoffs between three performance criteria (lane tracking, stability robustness, and passenger comfort) by exploring the entire design space of three prominent controllers. Based on these studies, these researchers concluded that a robust controller can provide the maximum performance limit with respect to the lane tracking and stability robustness when properly designed [15]. Abdelhamid *et al.* discussed the design of a lane keeping assist system regarding the following stages: preprocessing, detection, and tracking. For each stage, a short description of its working principle, as well as its advantages and shortcomings, were introduced. Their paper could help in designing new systems that overcome and improve the shortcomings of current architectures [16]. Chouki Sentouh *et al.* presented a shared control concept for LKA systems of intelligent vehicles. The effectiveness of the proposed shared control method is clearly demonstrated through various hardware experiments with human drivers [17]. JonginSon *et al.* proposed a real-time and illumination invariant lane detection method for an LDWS. The proposed method works well in various illumination conditions, such as in bad weather and at night. The experimental results show a satisfactory performance with an average detection rate of 93% under various illumination conditions [18].

Pradnya N *et al.* presented an LDWS based on the Hough transform and Euclidean distance. These researchers used histogram equalization to enhance the contrast level of the input image, used the Hough transform for lane detection, and carried out lane departure identification using lane related parameters. The experimental results indicated that the proposed system provided a high lane detection and low false warning rate [19].

Most of the abovementioned security facilities are based on camera technology. Camera-based lane keeping technology is relatively mature and widely used. However, research on virtual track systems based on road buttons is only beginning. The virtual track system limits vehicles on the virtual track formed by road buttons, making it safer and more reliable.

The virtual track system we studied is similar to the current LKS that keeps vehicles in the lane. We also found that there were studies on the application of virtual rail trains in urban public transportation. However, compared to LKSs and virtual rail trains, our research has many innovations. First, the LKS uses video recognition to keep the vehicle in the lane, while we use intelligent road buttons to create a virtual track. Second, the virtual rail train is mainly used for low-speed urban public transportation, while our virtual rail system based on intelligent road buttons is mainly used for highways. Finally, the virtual track system based on intelligent road buttons uses vehicle-road coordination technology, which greatly improves its security and reliability.

II. OVERVIEW OF SUPERHIGHWAYS

A. BACKGROUND OF SUPERHIGHWAYS

The speed and quality of infrastructure construction projects, such as highways and railways, in China have attracted worldwide attention and are known as the "Construction Super Star" [20]. By the end of 2018, the total highway mileage in China had exceeded 140,000 km, ranking first in the world for eight consecutive years, and it was far ahead of the second-place country [21]. The mileage for high-speed railways was 29,000 km, which was more than 60 % of the total mileage for high-speed railways around the world [22].

From 1997 to 2007, railways in China experienced six speed increases, and the average speed increased from 48.1 km/h to 70.18 km/h [23]; in 2008, the first High-Speed Railway from Beijing to Tianjin with the designed speed of 350 km/h was opened [24]; in 2006, the first maglev line in China was opened, with a running speed of 430 km/h [25]. Railways have achieved leapfrog breakthroughs in both mileage and operation speed.

The total mileage of roads and highways in China is also constantly breaking historical records. The opening mileage already ranked first in the world, and a number of super projects have been built. For example, of the ten longest sea-crossing bridges in the world, five are in China, and the Hong Kong-Zhuhai-Macao Bridge ranks first [26]. However, the highest designed speed for highways in China has never been improved and is locked at 120 km/h. This speed limit has not changed in 68 years, and there is no relevant research on raising the speed limit of highways.

The development of the High-Speed Railway in China has provided valuable experience for the construction of superhighways. The safe operation of highways with operation speeds over 120 km in foreign countries has established confidence in the safe operation of superhighways in China. Therefore, the author proposes the idea of a "superhighway."

B. THE DEFINITION OF A SUPERHIGHWAY

A superhighway is defined as a highway with a design speed of more than 120 km/h. A superhighway is different from an ordinary highway. To ensure the safety of the superhighway, the pavement on superhighways is flatter, the route is smoother, and the facilities are more complete.

TABLE 1. Classification of the highway for the first time.

Grade	Superhighway			Ordinary highway
	Grade III	Grade II	Grade I	
Design speed/km/h	240 220 200	200 180 160	160 140 120	120 100 80

TABLE 2. Classification of the highway after adjustment.

Grade	Superhighway			Ordinary highway
	Grade III	Grade II	Grade I	
Design speed/km/h	180 160 140	160 140 120	140 120 100	120 100 80

TABLE 3. Comparison of superhighways of different grades.

Grade	Service object	Construction mode	Implementation time
Grade I	For cars and trucks	Retrofitting existing highways	15 years
Grade II	Only for cars	Build refer to passenger dedicated railway	30 years
Grade III	Only for autonomous vehicles	Build refer to high speed railway	40-50 years

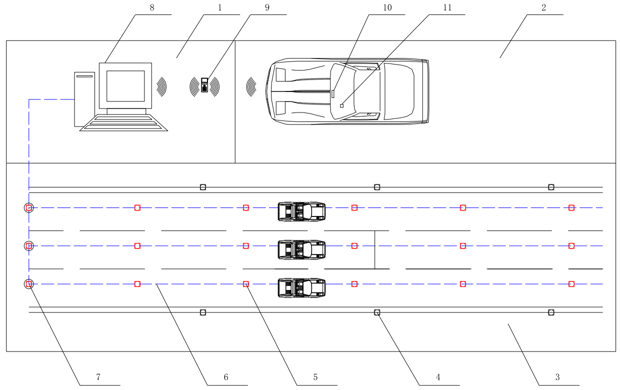
Since the definition of a superhighway was proposed, it has been approved by many professors from Tongji University, Southeast University and Chang 'an University and aroused extensive interest of scholars attending the First World Transportation Conference in June 2017. In January 2018, the report titled "Feasibility Study of Superhighway Based on Expenses" at the Donglin-Tongji Academic Conference caused a heated discussion among the participating scholars. Currently, the Intelligent Network and Transportation Joint Research Institute of the Southeast University-University of Wisconsin is engaged in research on autonomous driving lanes based on vehicle-road collaboration technology and has applied for a number of patents in the United States and China, providing technical support for the development of superhighways.

C. CLASSIFICATION OF SUPERHIGHWAYS

While proposing the definition of a superhighway for the first time, the author also proposed the technical grade of the superhighway and the maximum design speed. The technical grade of the superhighway proposed for the first time is shown in Table 1.

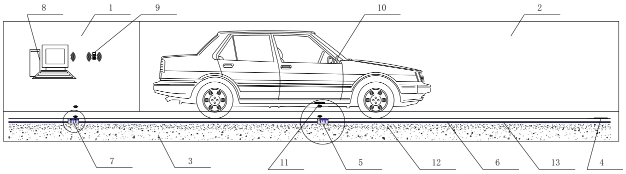
Considering the safety and economic problems, after several rounds of expert argumentation, the classification speed was considered to be too high; therefore, the classification and design speed of superhighways were adjusted. The technical grade and maximum design speed of the demonstrated superhighway are shown in Table 2.

While dividing the grades of superhighways, the classification also proposes the service object, construction mode and expected implementation years at all levels. A comparison of superhighways at all levels is shown in Table 3.

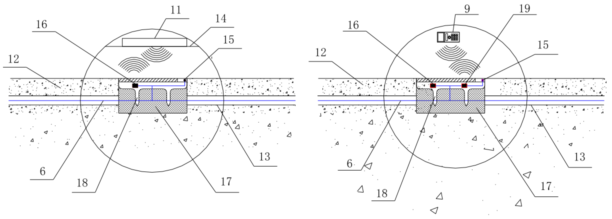


1. Service center subsystem; 2. Onboard subsystem; 3. Road subsystem; 4. Reflective marking; 5. Label button; 6. Power data cable; 7. Written button; 8. Server; 9. Handheld terminal; 10. Displayer; 11. Reader;

FIGURE 1. **Structure composition of the virtual track system.**



(a) Installation of road subsystem and vehicle



(b) Written button structure (c) Label button structure

1. Service center subsystem; 2. Onboard subsystem; 3. Road subsystem; 4. Reflective marking; 5. Label button; 6. Power data cable; 7. Written button; 8. Server; 9. Handheld terminal; 10. Displayer; 11. Reader; 12. Pavement structure layer; 13. Line pipe; 14. Automobile chassis; 15. LED lamps; 16. RFID tags; 17. Sealing glue 18. Nail feet;

FIGURE 2. **Installation of road subsystem and onboard subsystem.**

The service objects, construction modes and expected implementation years of superhighways at all levels shown above are only the preliminary assumptions for the first definition of superhighways, and there will be large discrepancies in the actual development. For example, we planned that superhighways of grade I would be built in 15 years, but construction began only two years after the superhighway definition was presented. With the transformation of highway construction from high speed to high quality and the rapid development of automatic driving technology, superhighway construction at all levels will soon be placed on the agenda.

III. STRUCTURE COMPOSITION OF THE VIRTUAL TRACK SYSTEM

A. OVERALL STRUCTURE OF THE VIRTUAL TRACK SYSTEM

The highway virtual track system based on an intelligent road button is composed of the road subsystem, onboard subsystem and service center subsystem. The road subsystem consists of written buttons and label buttons; the onboard subsystem consists of a reader, displayer, detector for front wheel deflection, data-processing module and steering motor; the service center subsystem consists of a server and handheld terminal. In addition, each subsystem also includes a power supply and connection lines. The readers of the intelligent button system and label buttons communicate through UHF (902-928 MHz) RFID radio frequency identification technology. The structure is shown in Figure 1.

B. STRUCTURE COMPOSITION OF THE ROAD SUBSYSTEM

The road subsystem consists of written buttons, label buttons and its wiring. The road subsystem is buried in the pavement structure layer during the pavement paving construction, and the top of the buttons is flush with the pavement, thereby avoiding the bumps during the rolling of vehicles. The buried position of the written and label buttons is directly below the driver while the car is running in the center of the lane. The written buttons are installed at the beginning of the road or the entrance of the lane, where a good line of sight induction is required. In addition to the light-emitting structure of the conventional light-emitting road buttons, a written button also has a written interface and a storage space. This system can write the location of the buttons and the parameters of the road sections, which are flat parameters, vertical parameters and horizontal parameters, through a handheld terminal or the server of the service center subsystem. The label buttons and the written buttons are connected by wires, and the label buttons have radio frequency emission structures in addition to the light-emitting structure of the conventional light-emitting road button. The structure of the road subsystem is shown in Figure 1. The structure and installation of the road subsystem, the written buttons and the label buttons are shown in Figure 2.

C. STRUCTURE COMPOSITION OF ONBOARD SUBSYSTEM

The onboard subsystem consists of a reader, a display, a detector for front wheel deflection, a data-processing module and a steering motor. The reader, composed of the on-board subsystem, is installed at the bottom of the vehicle, directly below the driver. While the vehicle is running in the center of the lane, the reader is located directly above the label road button. At this time, the reader is closest to the label buttons.

The displayer that comprises the onboard subsystem is compatible with the car navigation system; however, it has more features. The displayer collects not only longitude and latitude information from satellites but also collects design parameters from the road buttons, such as the flat, vertical and horizontal parameters of the road. The map in the displayer is drawn with the horizontal, vertical and horizontal parameters read from the label buttons. The displayer can replace the GPS coordinate information with coordinate information read from the label buttons, to achieve more accurate and rapid positioning. The steering motor of the onboard subsystem can be shared with the motor of the electric power steering system of the vehicle itself. The structure and installation of the onboard subsystem are shown in Figure 1 and Figure 2.

D. STRUCTURE COMPOSITION OF THE SERVICE CENTER SUBSYSTEM

The service center subsystem consists of a server and hand-held terminals. The server of the service center subsystem manages many roads with intelligent road buttons and many onboard subsystems. The service center subsystem has the functions of written information, similar to the road subsystem, and functions of map generation, similar to the onboard subsystem. The server can connect with the road subsystem through wires and wireless to write and read the location information from the label buttons and the linear information of roads. The subsystem can also write and read road subsystem information by a hand-held terminal in remote areas. The structure of the service center subsystem is shown in Figure 1.

IV. WORKING PRINCIPLE OF THE VIRTUAL TRACK SYSTEM

A. WORKING PRINCIPLE OF THE ROAD SUBSYSTEM

When the vehicle passes the position of the label buttons, the flat, vertical and horizontal parameters of the road stored in the written buttons can be accurately read through the 4G or 5G networks or RFID. At the same time, the position parameters of the label buttons are read, indicating the exact location of the vehicle. Compared with the GPS positioning system and mobile phone base station positioning system, the intelligent road button system has a high positioning accuracy, short delay time and strong real-time performance.

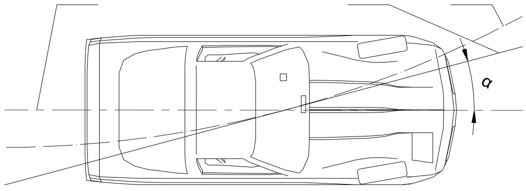
B. WORKING PRINCIPLE OF THE ONBOARD SUBSYSTEM

The data-processing module can read the speed $V_{\mathrm{n}-1}$ (km/h) from vehicle's electronic control unit (ECU) when passing the (n–1)th label button. The data-processing module can also process the road alignment parameters read by the reader and obtain the tangent equation of each point. At the (n–1)th label button, the angle between the road tangent and vehicle body is α_{n-1}/rad:

- While $\alpha_{\mathrm{n}-1} < 0$, the road tangent is on the left side of the vehicle body centerline, and the vehicle will turn left;
- While $\alpha_{\mathrm{n}-1} \cdot \alpha_{\mathrm{n}-1} = 0$, the road tangent line is parallel to the vehicle body centerline, and the vehicle will go straight;
- While $\alpha_{\mathrm{n}-1} \cdot \alpha_{\mathrm{n}-1} > 0$ the road tangent is on the right side of the vehicle body centerline, and the vehicle will turn right.

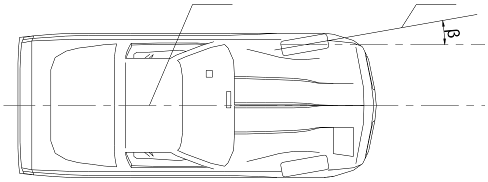
When the vehicle passes the (n–1)th label road button, the detector for the front wheel deflection detects and obtains the front wheel deflection angle $\beta_{\mathrm{n}-1}$ (rad):

- While $\beta_{\mathrm{n}-1} < 0$, the vehicle travels along the curve and turns to the left;
- While $\beta_{\mathrm{n}-1} = 0$, the vehicle travels in a straight line;



1. Vehicle body centerline; 2. Lane centerline tangent; 3. Lane centerline

FIGURE 3. **Angle between the front wheel and vehicle body.**



1. Vehicle body centerline; 2. Steering wheel centerline

FIGURE 4. **Angle between the vehicle body and lane centerline.**

- While $\beta_{\mathrm{n}-1} \cdot \beta_{\mathrm{n}-1} > 0$, the vehicle travels along the curve and turns to the right.

During vehicle operation, the front wheel declination of the vehicle should be parallel to the tangent of the road, that is, $\theta_{\mathrm{n}} = \alpha_{\mathrm{n}}$-$\beta_{\mathrm{n}} = 0$. When a vehicle passes through the (n–1)th labeled button, if $\theta_{\mathrm{n}-1} = \alpha_{\mathrm{n}-1}$-$\beta_{\mathrm{n}-1} \neq 0$, the front wheel needs to be rotated. When the vehicle passes through the nth labeled road button, $\theta_{\mathrm{n}} = \alpha$-$\beta = 0$, then the rotation angle is $\Delta\theta = \theta_{\mathrm{n}}$-$\theta_{n-1} = (\alpha_{\mathrm{n}}$-$\beta_{\mathrm{n}})$- $(\alpha_{\mathrm{n}-1}$-$\beta_{\mathrm{n}-1}) = \beta_{\mathrm{n}-1}$-$\alpha_{\mathrm{n}-1}$.

- While $\Delta\theta < 0$, the steering wheel needs to be turned counterclockwise;
- While $\Delta\theta = 0$, keep the steering wheel angle;
- While $\Delta\theta > 0$, the steering wheel needs to be turned clockwise.

If the front wheel of a certain vehicle declination β changes from 0 to $\beta_{\max}$, the steering wheel rotation angle changes from 0 to $\gamma_{\max}$, and then the transmission ratio of the steering wheel angle to the front wheel declination is $I = \gamma_{\max}/\beta_{\max}$. The angular velocity ω (rad/s) of the steering wheel rotation is related to the time t(s) of the vehicle traveling between the two buttons and the required angle of rotation, as shown in Equation (1).

$$\omega = \frac{I\Delta\theta}{t} \tag{1}$$

which is determined by the length L_{n} (m, which can be read by the reader) between the two buttons and the vehicle traveling speed V (km/h), $t = L_{\mathrm{n}}$ / 3.6V (1 m/s = 3.6 km/h substituted into Equation (1), that is Equation (2).

$$\omega = \frac{I\Delta\theta}{t} = \frac{3.6V\Delta\theta\gamma_{max}}{L_n\beta_{max}} = \frac{3.6V(\beta_{n-1}-\alpha_{n-1})\gamma_{max}}{L_n\beta_{max}} \tag{2}$$

Therefore, while the vehicle is traveling on different linear roads, the rotational angular velocity (ω) of the steering wheel can be determined such that the data-processing module can control the steering motor to turn the steering wheel to drive the vehicle along the virtual track formed by the label buttons.

C. WORKING PRINCIPLE OF THE SERVICE CENTER SUBSYSTEM

The service center subsystem is composed of a server and handheld terminals. The server of the service center subsystem manages multiple roads with intelligent road buttons and numerous on-board subsystems. The subsystem of the service center has the functions of written information, similar to the road subsystem, and map generation, similar to the onboard subsystem. The server of the service center subsystem can be connected with the road subsystem through wires or wireless to write the location information and the road alignment information from the label buttons and can write the road subsystem information with handheld terminals in remote areas. An onboard subsystem completes the map generation of the onboard subsystem through the handheld terminals of the service center subsystem.

V. VERIFICATION BY COMPUTATION

A. BASIC ASSUMPTIONS

To verify the critical condition of a derailment on the virtual track, the following assumptions are made:

1) The vehicle travels in a straight line at first, then turns right into the circular curve through the transition curve, and finally enters the straight line through the transition curve to complete a full turning process.
2) The slope of the verified section is zero, and the driving of vehicles is not affected by other vehicles and small obstacles on the road surface.
3) The radius of the circular curve is R, the maximum steering angle of the transition curve is $\beta = 0.5$ rad, and the length of the transition curve $l_s = R$ is calculated from $\beta = l_s/2R$.
4) The wheel travels along the centerline of the track. When the wheel is 50 cm away from the centerline of the track, the derailment threshold is considered to be reached.
5) The distance between every two labels is the same; the distance between the two labels is L_n, and $L_n < R$.
6) The steering wheel starts to rotate at a constant speed at the beginning of the transition curve, it stops rotating at the starting point of the circular curve, and the front wheel yaw angle is tangent to the circular curve.
7) The steering wheel transmission ratio is 20, which means that the 360° rotation of the steering wheel causes the wheel to turn 18°, and the angular velocity ω of the driver's comfortable steering wheel is $\beta V/l_s = \beta V/R$(rad /s).

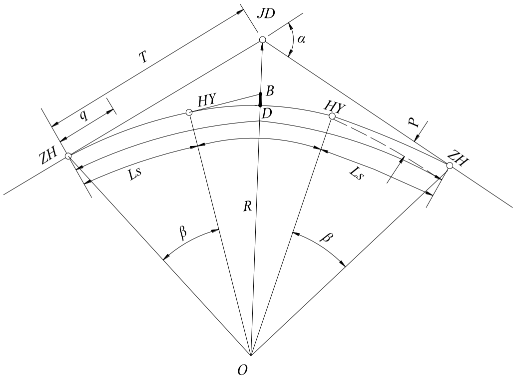


FIGURE 5. Wheel offset distance from the transition curve to circular.

B. CALCULATION VERIFICATION

To explain in detail the working process of the virtual track during turning, the calculation steps are as follows:

1) It is assumed that the vehicle will turn right, the front road tangent is on the right side of the vehicle centerline, $\alpha_{n-1} > 0$, the front wheel off-angle is 0 when the vehicle is on the straight line, and the front wheel off-angle becomes β when the round curve starts.
2) The time required for the vehicle to travel between the two buttons is $t_1 = L_n/3.6$ V, and the time the vehicle travels on the transition curve is $t_2 = l_s/3.6$ V$= R/3.6$ V, as $L_n < R$, then, $t_1 < t_2$; therefore, t_1 is taken as the time unit for evaluating the deviation distance.
3) Because the steering wheel is rotated at a constant speed, the front wheel angle $\Delta\beta$ is the same between every two road buttons, $\Delta\beta = \beta \cdot L_n/ R$.
4) According to experience and analysis, the unit length deviation is the largest when the transition curve segment enters the circular curve segment; therefore, a small segment is taken at that point for analysis, as shown in Figure 5.
   If a button signal is lost, the offset distance can be achieved by Equation (3).

$$L_{BD} = \frac{R}{cos\Delta\beta} - R = \frac{R}{cos(\beta L/R)} - R = R\left[\frac{1}{cos(\beta L/R)} - 1\right] \tag{3}$$

5) According to the assumption that an offset distance of 50 cm is a derailment, it means $L_{BD} < 0.1$, shown as Equation (4).

$$L_{BD} = R\left[\frac{1}{cos(\beta L_n/R)} - 1\right] < 0.5 \tag{4}$$

   Simplified:

$$L_n \leq \frac{R}{\beta} \arccos \frac{2R}{2R+1} \tag{5}$$

As assumed, $\beta = 0.5$ rad, $R = R_{min}$, and R_{min} is the general minimum radius of the circular curve calculated according

TABLE 4. Minimum distance between road buttons [8].

Design speed /km/h	Grade III			Grade II			Grade I		
	180	160	140	160	140	120	140	120	100
$R_{\min}$/m	2350	1850	1450	1850	1450	1050	1450	1000	700
Minimum distance /m	1.69	1.50	1.33	1.50	1.33	1.13	1.33	1.10	0.92

TABLE 5. Superhighway parameters of the simulation models.

Design speed /km/h	180	160	140
General minimum radius (transition curve) $R_{\min}(l_s)$/m	2350	1850	1450
Minimum distance between road buttons L_n/m	1.69	1.50	1.33

to the superhighway design speed V. The minimum distance between the roads button is calculated, as shown in Table 4.

The above calculations and analysis show that as long as the installation distance of the intelligent road buttons meets the conditions in Table 4, it can be ensured that the vehicle travels less than 50 cm from the centerline.

VI. VERIFICATION BY SIMULATION

A. BASIC ASSUMPTIONS

To facilitate the establishment of the simulation model and make the simulation data comparable to the calculated verification data, the following assumptions are required:

1) Similar to the calculation verification, it is assumed that the car first travels along a straight line, then turns right to enter a circular curve through a transition curve, and finally enters a straight line through the other transition curve to complete a turning process.
2) The slope of the verified section is zero, and the driving of vehicles is not affected by other vehicles and small obstacles on the road surface.
3) The general minimum radius corresponding to the maximum design speed of each grade of superhighways is taken as the modeling radius. If the maximum turning angle of transition curve $\beta = 0.5$ rad; then, the length of the transition curve $l_s = R$ can be obtained from $\beta = \frac{l_s}{2R}$.
4) The vehicles move along the virtual track centerline. When the vehicle centerline deviates 0.5 m from the track centerline, the vehicle is considered to be derailed.
5) The distances between every two buttons are the same, L_{n}, and $L_n < R$.
6) The vehicle starts to turn at a constant speed at the beginning of the transition curve, and the deflection angle of the front wheels are tangent to the circular curve.

B. ESTABLISHMENT OF SIMULATION MODELS

1) CALIBRATE SIMULATION MODEL PARAMETERS

According to the basic assumptions and calculation verification, the road parameters of the simulation models $R = R_{\min}$ and the values of l_s and L_{n} are shown in Table 5.

TABLE 6. Vehicle parameters of the simulation model.

Traffic conditions			Parameters
Car following model (Wiedeman98)	Mean stop space /m		2
	Maximum forward sight distance/m		250
The driveway transform (Free lane option)	Maximum deceleration/m/s^2	Itself	-4
		Vehicle ahead	-3
	Minimum head space/m		0.5
Minimum transverse spaces	V<50 km/h		0.5
	V≥50 km/h		1.0

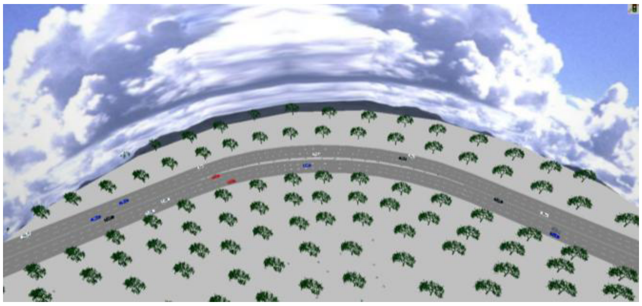


FIGURE 6. Virtual track simulation model.

According to the requirements of the simulation software and the simulation speeds, Wiedemann99 is selected as the simulation model of the virtual track of the superhighway. Wiedemann99 is a car following model proposed by Wiedemann in 1999, and it is suitable for road traffic simulation. The simulation parameters are set in Table 6.

2) ESTABLISHMENT OF SIMULATION MODELS

According to the basic assumptions above, and the parameters in Table 5 and Table 6, the general minimum radius corresponding to the maximum design speed of each level of superhighway is taken as the modeling radius. Therefore, 3 simulation models need to be established. When the design speed is 140 km/h, the simulation model is shown in Figure 6.

The model is a two-way six-lane superhighway with a rigid concrete guardrail at the center of the straight section and a green belt at the center of the transition curve and the circular curve section. The superhighway simulation models with design speeds of 160 km/h and 180 km/h can be established by the same method.

To evaluate the operation of the vehicle in the virtual track system, the distances from the track centerline obtained by the simulation are taken as the evaluation index. Therefore, it is necessary to set up the vehicle transverse position collector at the cross-section of the center point of the circular curve after the simulation models are built.

C. ANALYSES OF SIMULATION RESULTS

Through analyzing the vehicles' position data collected by the transverse position collector from the cross-section of the track center point of the circular curve, the distances that each

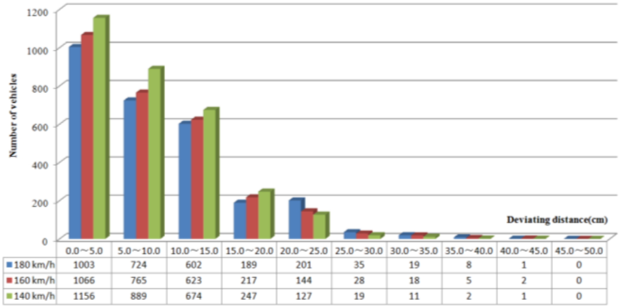


FIGURE 7. **Deviation distance from the centerline and number of vehicles.**

vehicle deviates from the track centerline when passing the point can be obtained. In order to make the simulation results more accurate, we conducted 10 simulation runs and averaged the simulation results. The average deviation distance from the virtual track centerline and the number of vehicles is shown in Figure 7.

As seen from Figure 7, while the vehicles are driving along the virtual track system, the deviation distances from the lane centerline are no more than 50 cm. A further analysis of the simulation data shows that the deviation distances for most vehicles are less than 25 cm. When the design speed of the superhighway is 180 km/h, 160 km/h and 140 km/h, the proportions reach 97.74%, 98.15% and 98.94%, respectively.

VII. CONCLUSION

According to the calculation and simulation results, when the designed speeds of the superhighway are 140 km/h, 160 km/h and 180 km/h, the distances between the road buttons are less than 1.33 m, 1.50 m and 1.50 m, respectively, and the distance from the centerline of the vehicle can be ensured to be less than 50 cm. Therefore, the vehicle can be restricted to the virtual track by the virtual track system based on the intelligent road buttons, and the safety of the superhighway can be ensured.

Because the Virtual Track System does not need to have a physical track constructed, there is no need to build a new road; the only need is to add the intelligent road button system to the original road surface; therefore, the cost is considerably reduced. Users only need to install onboard subsystems on their vehicles, and the cost is also notably low. For the vehicles with existing onboard navigation systems and electric power steering systems, only the reader and data processing module are needed; therefore, the cost is even lower.

The research on virtual rail systems is still in its infancy and is limited by road construction and vehicle performance. In the future, we will further simplify the structure of the road subsystem, improve the reliability of the on-board subsystem, improve the function of the service center subsystem, and gradually apply the virtual rail system.

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