This article has been accepted for publication in IEEE Journal of Radio Frequency Identification. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JRFID.2022.3203694

Digital Twin Analysis for Driving Risks Based on Virtual Physical Simulation Technology

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***Abstract*—A digital twin is a mapping of real world objects in virtual space. For the study of traffic safety issues, digital twins have great potential to facilitate more accurate and detailed risk analysis. In this study, a digital twin method for highway driving safety analysis is proposed, which consists of three parts: Extracting vehicle motion information in the real world, constructing vehicle motion scenes in the virtual world, and analyzing vehicle driving risks. Firstly, aerial video of vehicle motion is captured by drone, while the microscopic vehicle trajectories are extracted from the video using machine vision algorithms. Secondly, the digital twin of vehicles and roads is constructed, while the motion behavior of vehicles is mapped in a digital space based on virtual physical simulation technology. Finally, according to the stability and trajectory deviation, the driving risks of the vehicle are evaluated, including sideslip, rollover, and guardrail collision. Through a case study, the effectiveness of the proposed digital twin method in driving risk assessment is verified, and one vehicle is found to have a higher driving risk.**

Keywords—digital twin, traffic safety, micro-trajectories, driving dynamics, driving risk assessment

I. Introduction

Traffic safety has always been one of the key issues restricting the development of expressways. The safety problem of expressway is different from that of ordinary highway, because it has the characteristics of closed management and fast vehicle speed. In contrast, the problem of vehicle loss of control (accidents such as sideslip, tail drift, rollover, etc.) caused by road geometry and road surface conditions is more prominent in expressways [1]. Due to the limitation of various factors, it is difficult to simulate the expressway driving environment for real vehicle test indoors, which makes virtual simulation an important method to study traffic safety issues [2,3]. However, both dynamic simulation and virtual driving simulation are different from the real-world vehicle motion state.

A digital twin is defined as a digital replica of a real entity in the physical world, which has more interaction and fusion with real-world data than traditional virtual simulation [4]. Digital twins present new ideas for the study of traffic safety issues. A large number of scholars have applied the concept of digital twins in autonomous driving research, and judged the risk of a vehicle crash through data collection and analysis, so as to realize vehicle active safety control [5,6]. Dygalo et al. [7] applied virtual and physical simulation techniques to active vehicle safety systems and designed a braking model that controls each wheel. Pagliari et al. [8] develop a complete digital twin model of Cor-Ten road barriers to simulate vehicle collisions. In addition, some scholars build vehicle simulators and environment virtual systems through virtual reality (VR) technology to examine the prediction of vehicle driving states [9].

Monitoring the state data of the vehicle during driving is essential to building a digital twin model of the vehicle [10]. With the development of technologies such as drone and machine learning, it is becoming easier and easier to observe continuous indicators of vehicle motion states (speed, trajectory, etc.). Drones and BIM technology have been applied to digital twin scenarios in inland waterways, which can provide an effective method for analyzing vessel traffic safety [11]. It also makes it possible to construct a digital twin of vehicle motions on highways. In this study, a digital twin method for highway driving safety analysis is proposed. Objects of digital twin include roads and vehicles. Based on the driving dynamics, the physical rules are established in the virtual world. While the real-world vehicle motion is mapped to the virtual world, which can realize the real-time acquisition of vehicle mechanics state indicators.

The remainder of this paper is organized as follows: Section II introduces a method for building the digital twin of scenario, which specifically introduces the data acquisition method in the real world, the construction method of physical rules in the virtual world, and the driving risk assessment method. Section III presents case studies on a real world roads. Finally, the paper is concluded with some future directions in section IV.

II. Methodology

The digital twin of scenario proposed in this study is vehicle motion in an expressway environment. The method framework of scenario digital twin construction and driving risk analysis is shown in Fig. 1. There are three parts: data collection (real world), scenario digital twin construction (virtual world), and driving risk analysis. In the data collection, aerial videos of the vehicle driving in the expressway are obtained by drone, and the trajectory and speed data of the vehicle are extracted by the machine learning algorithm. In the scenario digital twin construction, the digital twin scene of vehicle driving is constructed by combining Matlab Simulink and Carsim/Trucksim software. In the driving risk analysis, the vehicle trajectory is input through the controller established by Simulink. Finally, the driving risk is evaluated by analyzing the stability and trajectory deviation of the vehicle.

The value and innovation of the proposed digital twin analysis method are mainly in the following aspects:

- Real-time analysis: Most of the previous research on vehicle digital twins is analyzed after data acquisition is completed. Our proposed method can be analysed in real time. Images collected by the drone are transmitted in real time through the 4G network, enabling real-time vehicle identification and tracking.
- Complete frame: In the proposed method, the whole process of digital twin is fully demonstrated from data collection to method analysis.
- Driving risk for road factors: Current research on driving risk focuses on vehicle performance or driver, and our proposed method is to identify high-risk locations on the road. The results of the study can assist in road design and traffic management, and improve driving safety in essence.

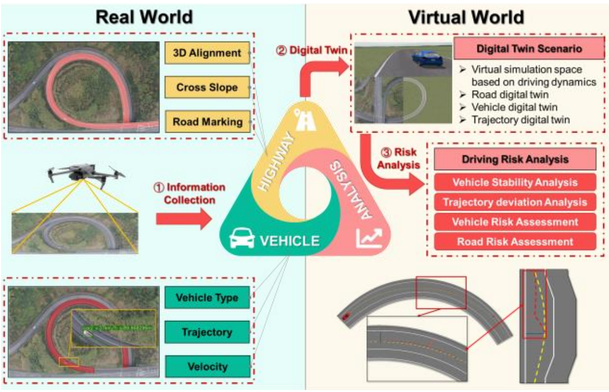

Fig. 1. The architecture of the driving safety analysis method based on digital twin

A. Data collection

Accurate data in the real world is an essential foundation for digital twins. In this study, the objects to be considered for digital twins are roads and vehicles. The data required in the digital twin generally include static data such as geometric data and performance indicators. In addition to static data, this study requires two continuously changing time series data: the trajectory and velocity.

The road information to be collected in this study includes geometric data and road friction coefficient. Since the road geometry data is fixed and has detailed design drawings. Therefore, the research team obtained accurate and detailed road geometry data by collecting design drawings, including horizontal alignment, vertical alignment, road width, and lateral slope. However, the friction coefficient of pavement is changed by factors such as rainfall. In this study, the road friction coefficients under different weather conditions were collected by the road friction tester.

In this study, the tethered drone is used to shoot the vehicle motion video, and the SIFT algorithm is used to deal with the shaking problem during the shooting process. Then the vehicle's position at different times is extracted by the YOLOV5 algorithm, and the vehicle's speed at different positions is further calculated. Finally, trajectory and speed data during vehicle motion are obtained.

B. Scenario digital twin construction

The main tasks of constructing the scenario digital twin are as follows: (1) Building a virtual space based on driving dynamics rules. (2) Building static digital twins of roads and vehicles based on real-world collected data. (3) Create a vehicle motion controller and input continuous trajectory and velocity data to achieve a digital twin of a dynamic scene.

In this study, the driving dynamics simulation software Carsim and Trucksim are used as the basis for constructing twin scenarios. Carsim and Trucksim have built-in rich and reliable driving dynamics simulation algorithms, which can simulate vehicle stability with multiple degrees of freedom. Among them, Carsim has a variety of small vehicle models, and Trucksim has a variety of large vehicle models. The "Path and road surface" module in the software can quickly build a road model based on road geometry and friction coefficient.

In this study, the digital twin of a scene is constructed by combining Matlab Simulink and Carsim/Trucksim software. Firstly, build a virtual space with physical rules based on Carsim/Trucksim. Simultaneously build a digital twin of the road. Secondly, build a vehicle model matching algorithm in Simulink to retrieve the appropriate vehicle model. Subsequently, a vehicle motion controller is constructed to input continuous trajectory and speed data as variables to control vehicle motion to achieve a digital twin of dynamic scenes. Finally, the vehicle motion process is simulated to output the force state of the vehicle at each position.

C. Scenario digital twin construction

The research object is the risk of vehicle loss of control, such as vehicle sideslip, rollover and tail drift, which are prone to occur in highways. The force state and trajectory changes of the vehicle during driving are analyzed to evaluate the driving risk of the vehicle and the safety level of the road.

1) Vehicle stability analysis: This study mainly analyzes the accident risk of sideslip and rollover during vehicle motion.

a) Sideslip risk: Sideslip risk is assessed according to the centroid sideslip angle β, which is defined as the angle between the direction of vehicle motion and the direction of the vehicle body, as shown in (1).

$$\beta = \cot(\frac{v_y}{v_x})$$

$$when \begin{cases} |\beta| \in [0,5], \text{ low sideslip risk.} \\ \beta < -5, \text{ understeering severely.} \\ \beta > 5, \text{oversteering severely.} \end{cases} \quad (1)$$

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Where: v_x is the longitudinal speed of the vehicle (km/h); v_y is the lateral speed of the vehicle (km/h).

b) Rollover risk: Rollover risk was assessed based on the lateral load transfer rate LTR, which is defined as the ratio of the load transferred from the inner wheel to the outer wheel to the total load, as shown in (2).

$$LTR = \frac{\sum_{i=1}^{n}\left(F_{Ri} - F_{Li}\right)}{\sum_{i=1}^{n}\left(F_{Ri} + F_{Li}\right)}$$

$$when\begin{cases} LTR \in [0, 0.6], \text{low rollover risk.} \\ LTR \in [0.6, 0.8], \text{medium rollover risk.} \\ LTR \in [0.8, 1], \text{high rollover risk.} \end{cases} \quad (2)$$

Where F_{Ri} is the vertical load on the right wheel of the vehicle; F_{Li} is the vertical load on the left wheel of the vehicle; *i* is the axle position, n is the total number of axles.

2) Trajectory deviation analysis: Analyze the variation of the vehicle's offset from the center of the road during vehicle motion. The risk of guardrail collision is assessed according to the side distance SD,which is defined as the distance between the vehicle and the road edge during the vehicle driving, as shown in (3).

$$SD = 0.5W_{Road} - 0.5W_{Car} - VOS$$

$$when\begin{cases} SD > 0, \text{low guardrail collision risk.} \\ SD \leqslant 0, \text{high guardrail collision risk.} \end{cases} \quad (3)$$

Where W_{Road} is the width of the road (m); W_{Car} is the width of the vehicle (m); *VOS* is the distance from the vehicle's center to the center of the road.

3) Risk assessment: Comprehensive vehicle stability assessment results and trajectory deviation analysis results to assess the driving risk of a single vehicle. Further on this basis, the risk distribution of the road is measured.

III. CASE STUDY ON DRIVING RISK ASSESSMENT

In this section, the LK expressway is used as a case study. A digital twin of the vehicle driving scene on the LK expressway was constructed, and the driving risks of 13 vehicles were analyzed.

A. Data description

The study data is from the DG interchange C ramp of the LK expressway in the mountainous area of southwest China, as the road marked in Fig. 2. The ramp is a one-way, one-lane, and the speed limit for this section is 40km/h. Its length is 345m, and the shunt and confluence noses are located at 151m and 316m. The width of the ramp varies. The horizontal radius of the curve section is 52m. The maximum longitudinal slope is -3.7%, and the maximum transverse slope is 7%. In addition, the aerial video was 11 minutes long, during which a total of 13 vehicles passed the C ramp.

This research was funded by National Key Research & Development Program of China (No.2021YFB2600103, No.2020YFC1512005, No.2021YFB2301602), Sichuan Science and Technology Program (No.2022YFG0048).

Fig. 2. Aerial photo of ramp C of DG interchange

B. Driving risk assessment

The digital twin of the vehicle driving scene is constructed according to the method described in the second part, and driving stability and trajectory deviation are analyzed.

Fig. 3 shows the variation of the centroid slip angle β of 13 vehicles on the C ramp. The centroid slip angle β of most vehicles is in the range of -1.5~1, which is relatively stable during the driving process, and the sideslip risk of the vehicle is low. Near the 200m, The centroid slip angle β of Car10 reached 2.97. Although the centroid slip angle β is within the safe range, and no serious turning out of control problem occurs. The vehicle stability is poor, resulting in poor driving comfort for the driver.

Fig. 4 shows the variation of the lateral load transfer rate LTR for 13 vehicles on the C ramp. The LTR of most vehicles is less than 0.4, which are relatively stable during driving, and the risk of vehicle rollover is low. Near the 150m, the LTR of Car10 reached 0.84, which has exceeded the safe range and has a serious risk of rollover.

Fig. 5 shows the variation of side distance *SD* of 13 vehicles on the C ramp. The *SD* of most vehicles greater than 0 and are able to stay in the lane. Near the 210m, the SD of Car8 is lower than 0 for a short time, and it invaded the adjacent lane.

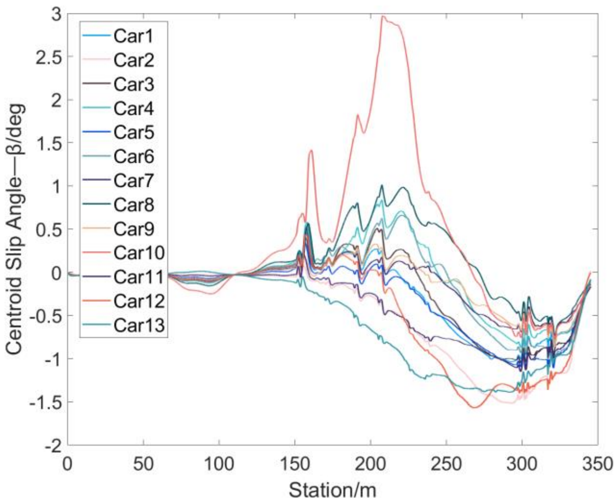

Fig. 3. The centroid slip angle *β* of the vehicles

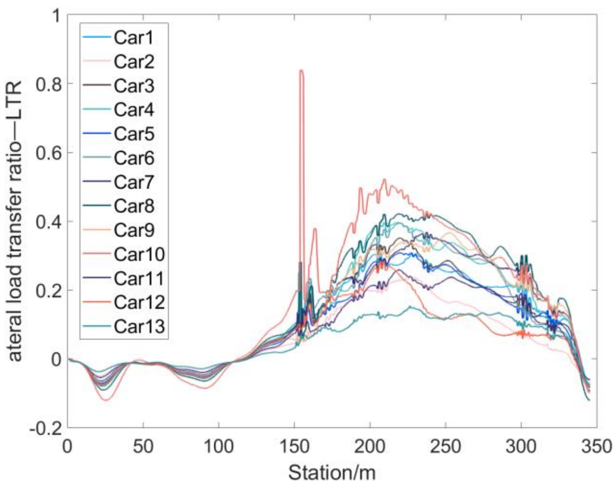

Fig. 4. The lateral load transfer rate *LTR* of the vehicles

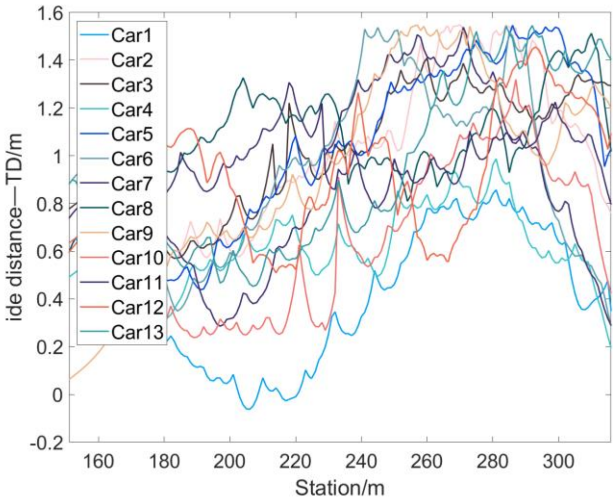

Fig. 5. The the side distance *SD* of the vehicles

There are a total of two vehicles in this section of the road with a greater risk of driving. The main risks of Car10 are sideslip and rollover. The reason is that the speed is too high. When entering the C ramp, the speed is 89km/h, when leaving the ramp, the speed is 48km/h, and the speed at 150m and 200m is 87km/h and 75km/h. The main risk of Car8 is the risk of guardrail collision. After inspection, it is found that the vehicle intruding into the lane is the emergency stop zone, and the risk of collision with the inner guardrail is low. In addition, the distribution of the β, the *LTR* and the *SD* in the road shows that the widening of the C ramp in the curve section effectively reduces the risk of guardrail collision, but the stability of the vehicle is poor within the range of 150-220m.

IV. Conclusions And Future Works

In this study, a digital twin method for highway driving safety based on virtual physical simulation technology is introduced, which can realize the digital twin of vehicle driving scenes. This method comprehensively uses technologies such as drone, machine vision, and driving dynamics simulation, and can carry out driving safety analysis in closed environments such as expressways. The results show that the analysis of driving risk based on the digital twin method can more accurately monitor various state indicators in the process of vehicle movement. Further, combined with the driving risk analysis method proposed in this study, the driving risk status of a single vehicle and the risk on the road can be accurately assessed. In future work, the method proposed in this study will further combine fixed cameras, consider an all-weather road section driving safety monitoring and risk assessment, to improve the safety level of existing roads.

Acknowledgment

The authors appreciate National Key Research & Development Program of China (No.2021YFB2600103, No.2020YFC1512005, No.2021YFB2301602), Sichuan Science and Technology Program (No.2022YFG0048), Engineering Research Center of Highway Infrastructure Digitalization of Ministry of Education.

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