Study of Vehicle Driving Characteristics and Safety on Different Asphalt Pavements Based on CarSim-MATLAB Co-simulation

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ABSTRACT: The objective of this paper is to explore the driving characteristics and safety of vehicle when driving on different pavements. Asphalt concrete (AC), open-graded friction course (OGFC) and stone mastic asphalt (SMA) samples are scanned by X-ray CT scanner and the macrotexture data of road surfaces is extracted and disposed by Geomagic Studio and MATLAB. Based on the tire adhesion theory and the Ergun friction coefficient prediction formula, the tire-pavement contact system was simulated by using MATLAB and CarSim. Then the vehicle-tire-pavement coupling system is established by CarSim-MATLAB co-simulation to study the braking and steering characteristics of vehicle on different pavements. The results indicate that on asphalt concrete pavement, the braking distance of vehicle with anti-lock braking system is 74.9m, which is longer than on open-graded friction course pavement (61.6m) and stone mastic asphalt pavement (64.9m). For the vehicle without anti-lock braking system, the braking distance on the asphalt concrete pavement is 110.0m, on open-graded friction course pavement it is 85.9m and on stone mastic asphalt pavement it is 91.6m. Steering in 120km/h on the three types of pavements and circle curve whose radius is 400m and superelevation is 6%, the vehicle presents instability and potential danger. When the velocity of vehicle reaches 126km/h, the asphalt concrete pavement will be not able to guarantee the driving security according to the simulation result. And the vehicle driving on stone mastic asphalt pavement will be in danger when the longitudinal speed is controlled in 134km/h.

Keywords: Driving characteristics; Safety; Macrotexture; Skid resistance; Co-simulation.

INTRODUCTION

With the rapid development of road traffic, traffic safety determined by skid resistance of pavement and vehicle driving status have attached much attention. Asphalt pavement is widely used around the world and different types of asphalt pavement such as asphalt concrete (AC), open-graded friction course (OGFC), porous asphalt (PA), and stone mastic asphalt (SMA) have different skid resistance. Driving on different asphalt pavements, the vehicle would present various safety and stability characteristics.

Using measurement devices to measure the friction force between a rubber wheel and the road surface is the routine and effective ways, and different countries have different pavement friction measurement methods and devices. Dissimilar to contact friction measurements between tire and pavement, skid resistance analysis without contact bases on the road surface texture data and the geometric parameters, which have been developed by a considerable amount...
of research. As the development and application of 3D scanning technology, 3D data of asphalt pavement macrotexture is extracted readily. The skid resistance could be predicted solely from texture measurements. Handheld 3D laser scanner is the useful tool to extract road surface data, which is widely used (Mathavan and Kamal et al., 2015; Slabej and Grinč et al., 2015). X-ray CT scanning technology is also used to get surface images and texture data (Qureshi and Khurshid et al., 2015; Zhang and Verwaal et al., 2015). Depending on optical measuring system in the laboratory, the skid resistance could be calculated based on the measured texture by means of Persson’ rubber friction model (Ueckermann and Wang et al., 2015). And the texture data can be used to represent the road surface characteristics and skid resistance (Hu and Yun et al., 2016).

However, predecessors just calculated the anti-skid indicators of pavements via the non-contact skid resistance analysis methods, rarely considering the effect of road surfaces on the driving vehicle. This study fills the gap of the influence of road surfaces on the driving characteristics of vehicle. In this study, the macro-texture data of road surface is extracted and the tire-pavement contact system was simulated by using MATLAB and CarSim. Co-simulation is conducted based on the tire mathematical model and measured pavement texture, then the vehicle-tire-pavement coupling system is established to study the braking and steering characteristics of vehicle on different pavements.

TEST METHOD IN LABORATORY

To evaluation the skid resistance of different pavement, three asphalt mixes were manufactured: asphalt concrete (AC), open-graded friction course (OGFC) and stone mastic asphalt (SMA). Basalt and AC 50# asphalt were used as aggregates and binder. The technical parameters of asphalt are showed in table 1.

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<th>Table 1. Technical Parameters of Asphalt.</th>
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<td>Softening point/℃</td>
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To collect macrotexture data of asphalt pavements, scanning works for three types of mixes based on X-ray CT probe scanner were conducted in Materials Analysis Laboratory of Southeast University. As showed in Fig. 1(a), X-ray computed tomography is based on the attenuation of X-ray within the objects. The structural information of sample is converted into gray distribution of image via image analysis technology, and then the two-dimensional slices and the three dimension structure can be rendered. It can clearly visualize the internal structure of sample, and precisely identify the location or size of defects in the sample.

Fig. 1(b) provides a picture of laboratory scanning process. The samples waiting to be scanned must be dry and be attached to a piece of clean paper to dodge contacting with CT stage directly before they are put onto CT stage. The scanning time of each sample is about one hour, which counts on the samples’ size and the complexity of the tested samples’ structure.
EXTRACT AND DISPOSE ROAD SURFACE DATA

To describe the macrotexture of three pavements: asphalt concrete (AC), open-graded friction course (OGFC) and stone mastic asphalt, the point clouds data was extracted from the images of pavement samples, then the point clouds data was imported into reverse engineering software Geomagic Studio. Fig. 2 shows the X-ray CT image of OGFC. After disconnecting the component connection, and performing external acnode removal command more than three times in Geomagic Studio, the number of red acnode can be decreased significantly. The samples is denoised and encapsulated into the polygonal stage. At this stage, the images are loosened, the nails are removed, and then the smoothing process is accelerated to enhance surface meshing to create a NURBS surface. Finally, using the crop tool to cut the sample images to form regular rectangles. The disposed point cloud surface of OGFC in Geomagic Studio is showed in Fig. 3.

Then the rectangle samples are saved as .asc file and imported to MATLAB for following process. MATLAB, which is a scientific and engineering computation tool, is utilize to fit point cloud of road surface to form a grid with 0.5mm interval, asphalt pavement grid is built in MATLAB as pavement model.

Fig. 4 shows the texture profiles in one direction of the three mixtures, which embody the structural features of different types of pavement surfaces. For the vehicle traveling on the road, they are the pavement structure that in vehicle’s traveling direction (longitudinal direction). In different structures on the road surface, the tire deformation and size of the contact area is different,
thus the tire slip, side and dumping effect is different, and the vehicle’s driving transitions is various. Fig. 5 shows the variation of mean profile depth (MPD) of pavement along the driving direction. Mean profile depth is the parameter related to pavement position, in different profile of pavement the MPD value is change. In general, the value of OGFC pavement is larger than AC and SMA pavement.

Mean profile depth can be calculated by the following formula:

$$MPD = \frac{(Peak1 - Average) + (Peak2 - Average)}{2}$$  \hspace{1cm} (1)

Where $Peak1$ is the peak level of first half of a baseline, $Peak2$ is the peak level of the second half of the baseline, $Average$ is the average level of the profile texture, as is showed in Fig. 6.

Full-car structure models are established in the mechanical simulation software CarSim, as showed in Fig. 7. The full-car structure parameters include structure geometry and physical parameters, aerodynamics parameters, powertrain system parameters, braking system parameters, steering system parameters and suspension system parameters. To study the braking characteristics of high speed car in two braking conditions on different pavements, full-car models with anti-lock braking system (ABS) and without anti-lock braking system was established. Apart from the braking system, other structure parameters of the two vehicle models is required to be fully consistent, for the road surface parameter is the main factor to analyze.

E-class sedan in CarSim was used to study the vehicle driving characteristics in the following running statuses:
(1) The sedan with anti-lock braking system drives in a normal straight road on a highway, encounters an accident and brakes immediately until the vehicle completely stops. The initial speed of the car is 120km/h, which is the design speed of a highway. The car brakes urgently in 15MPa cylinder pressure when the time is zero. The driver drives straightly with closed-loop shift control at 7th mode. The road surface is designed as a straight line, the longitudinal slope of road is 0%. That is, the center line of the road is set to a straight line and the cross section is preset without transverse gradient. The rolling resistance defined in CarSim is taken as the reference value of hot mix asphalt proposed in CarSim, which is 1.5.

(2) The sedan without anti-lock braking system drives in a normal straight road on a highway and suffers an emergency situation, then brakes immediately until the vehicle completely stopped. The initial speed is 120km/h and the cylinder pressure is 15MPa when t = 0. The driver drives straightly with closed-loop shift control at 7th mode. The road alignment is the same as (1).

(3) The sedan drives respectively in 120km/h, 126km/h and 134km/h on a circular curve whose radius is 400m. The driver hasn’t braking behavior with constant speed control and closed-loop shift control at AT 8th mode. The curve superelevation is set as 6%. The circular curve design in CarSim is showed in Fig. 8.
of the road surface to the tire is produced by the adhesion and the hysteresis. However, the adhesion and hysteresis is difficult to calculate. It can only be a theoretical explanation and can’t calculate the actual force of tire the road surface. Thus, as for specific calculations, tire and road surface friction coefficient is needed. In 2005, according to data fitting, Ergun (Ergun and Iyinam et al., 2005) obtained the relationship between $F$, $S$ and macroscopic coefficient and microcosmic coefficient of road surface:

$$F(S) = (0.37 + \frac{0.11}{MPD_{mac}} + \frac{0.15}{La_{mic}}) \times \exp\left(\frac{S}{149 + 81\log(MPD_{mac}) + 80\log(Rq_{mic})}\right)$$  \hfill (2)

Where $MPD_{mac}$ is the mean profile depth of road surface, $La_{mic}$ is the average wavelength of surface profile, $Rq_{mic}$ is the root-mean-square deviation of surface profile, and $S$ is the slip velocity. The formula can be used to predict the friction coefficient between wheel and road surface effectly according to Ergun’s research.

When tire model in CarSim is utilized to calculate the force caused by road surface, we not only need to consider the contact between road surface and the wheel, but also need to specify the road surface friction coefficient to represent the contact strength of the wheel and road surface and road surface material properties, and then the adhesion, hysteresis and shear effect is indirectly expressed in the simulation contact definition. Thus, the friction coefficient between road surface and the wheel is calculated by Ergun's friction coefficient prediction formula, i.e. equation (1). The microscopic characterization parameters $Rq_{mic}$ and $La_{mic}$ is related to aggregates properties. For the asphalt pavement samples tested in the Laboratory of Southeast University, the values of $La_{mic}$ and $Rq_{mic}$ are set as 0.15 refer to Ergun’s research. So the formula becomes:

$$F(S) = (1.37 + \frac{0.11}{MPD_{mic}}) \times \exp\left(\frac{S}{83.09 + 81\log(MPD_{mic})}\right)$$  \hfill (3)

Based on equation (2), the friction coefficient is no longer a constant value related to the road surface, but a variable parameter that varies with the state of the vehicle and the depth of the lateral road surface profile in different areas. The setting of the variable friction parameter makes the simulation more practical. The transverse structure depth of pavement was represented by the macroscopic characterization parameter MPD, which is calculated by measured road surface texture data. The parameter MPD is only related to the position of the vehicle. The tire slip velocity is related to the vehicle speed and braking behavior, it is the cumulative effect of running vehicle. It is calculated by

$$S = V_{WC} \cdot \kappa$$  \hfill (4)

Where $\kappa$ is the longitudinal slip ratio, $V_{WC}$ is the velocity of wheel center. The slip speed affects the speed of the vehicle at the next moment by influencing the friction coefficient and the feedback speed of vehicle change the slip speed at the next moment. The interactive feedback effect is continuously processed on and the simulation of the vehicle running process is realized.

The vehicle-tire-pavement coupling system, which was established by MATLAB and CarSim co-simulation, is shown Fig. 9. In each simulation step ($1\times10^{-5}$s), the tire model in CarSim obtains pavement coordinate in tire coordinate system transformed by road surface data and friction coefficient from pavement model. The kinetic characteristic of tire is determined by the velocity of the instantaneous CG (center of mass) of the vehicle, the braking
torque managed by driver and the powertrain of vehicle. Then the tire model calculates the running parameters of all tires represented the status of tires, then export the velocity of wheel center and the longitudinal slip ratio to pavement model to get the real-time friction coefficient. The shear forces ($F_x$, $F_y$), the vertical force $F_z$ and the moments ($M_x$, $M_y$, $M_z$) caused by road surface are presented then the status of vehicle changes. The vehicle-tire-pavement coupling system has realized the integrated research between person, vehicle and pavement.

![Diagram of Vehicle-tire-pavement coupling system](image)

**Figure 9. Vehicle-tire-pavement coupling system.**

**SIMULATION RESULTS AND DISCUSSION**

The variation of longitudinal slip ratio of left front wheel are showed in Fig. 10 (a) and (b) and other tires of vehicle demonstrate the same law because of the four-wheel braking system of E-class sedan. The longitudinal slip ratio of tires reach to 1 (100%) sharply when the vehicle hasn’t anti-lock braking system and there are no remark differences between different pavements. However, for tires of vehicle with anti-lock braking system controlling the longitudinal slip ratio to range from 0.1 to 0.15, the longitudinal slip ratio fluctuates with time and the fluctuation frequency on open-graded friction course (OGFC) pavement is higher than on stone mastic asphalt (SMA) and asphalt concrete (AC) pavement.

As depicted in Fig. 11, the friction coefficient between pavement and tire varies with the motion of vehicle. On the whole, either in the braking condition with ABS and or in the braking condition without anti-lock braking system, the friction coefficient of AC is lower than SMA and OGFC. The friction coefficient of OGFC is almost equal to SMA but OGFC is a little higher than SMA. As is expected, generally the vehicle with anti-lock braking system have better braking performance than the vehicle without anti-lock braking system viewing of the friction coefficient, for the ABS can control the slip ratio to range from 0.1 to 0.15 and the friction becomes higher in this interval in the same road surface condition. Fig. 11 (a) shows the appearance of peak friction for all pavement, it is caused by the ABS of vehicle. When the slip ratio reach the upper limit value (for the simulation it is 0.15), the braking torques release and the friction of tire reach to a peak value without the hinder of braking system at a fleeting time. When the braking torques continue to apply quickly, the friction recover to the basic levels.
Fig. 10. Variation of longitudinal slip ratio of left front wheel (a) with ABS; (b) without ABS.

Fig. 11. Variation of friction coefficient between left front wheel and pavement (a) with ABS; (b) without ABS.

Fig. 12 shows that the braking distance of vehicle with ABS on AC pavement is 74.9m, which is longer than on OGFC pavement (61.6m) and SMA pavement (64.9m). The braking distances display a small difference between OGFC and SMA pavement, and on OGFC pavement, the distance is a little shorter. But the braking distance on AC pavement is 10m longer than on SMA pavement, which is large relatively. For the vehicle without anti-lock braking system, the braking distance on the AC pavement is 110.0m, on OGFC pavement it is 85.9m and on SMA pavement it is 91.6m. Compared to vehicle with anti-lock braking system, the vehicle without anti-lock braking system provides a marker distinction in braking distance between different pavements. Thus, it is concluded that the vehicle with anti-lock braking system running on OGFC and SMA pavement provide a safer braking distance compared to other conditions. Though their braking distances are all not over 120m when driving in 120km/h on the highway, the accident may occur owing to other factors such as the defects of vehicle and the drivers’ poor status.

When the vehicle drives on a circular curve of highway, the skid resistance related to road surface texture affect the vehicle’s steering stability and security. In the simulation, the radius is set as 400m and the lateral acceleration and relative lateral offset are used to represent the stability and security. The lateral acceleration reflects the lateral stability of vehicle and the relative lateral offset reflects the sideslip trend of vehicle. Fig. 11(a) display that on OGFC and SMA pavement, the average lateral acceleration are smaller than on AC pavement. The average lateral acceleration on AC pavement is about 0.284, on OGFC and SMA pavement they are about 0.282 which are large. Thus, when driving in 120km/h on circular curve whose radius is 400m, the vehicle becomes unstable. From Fig. 11(b) we can see that the vehicle’s relative lateral offsets on AC
pavement are larger than on OGFC and SMA pavement. On AC pavement it is about 0.5m which is so large. In the case vehicle driving on AC pavement presents potential danger.

Figure 12. Braking curves of E-class sedan (a) with ABS; (b) without ABS.

When the longitudinal speed of vehicle are increased to 126km/h, vehicle driving on AC pavement will lose its stability and accident occurs, while vehicle driving on OGFC and SMA pavement retain stable. When the longitudinal speed is up to 134km/h, vehicle on SMA pavement also lose its stability but on OGFC pavement, the vehicle still drive safely. As the speed grows, the vehicle on OGFC pavement will ultimately be subject to danger.

Figure 13. Vehicle’s steering characteristics when driving in 120km/h (a) lateral acceleration; (b) relative lateral offset.

Figure 14. Longitudinal speed of vehicle (a) control speed 126km/h; (a) control speed 134km/h.
CONCLUSIONS

According to extract macrotexture data of three types of asphalt pavements and establish vehicle-tire-pavement coupling system, the braking and steering characteristics and security of vehicle with anti-lock braking system and without anti-lock braking system are studied and analyzed, then the difference of skid resistance between three types of asphalt pavement was summarized. In general, open-graded friction course provide a better skid resistance than asphalt concrete, while the difference of skid resistance between open-graded friction course and stone mastic asphalt is not so obvious considering macrotexture of road surface. And in the condition of braking with anti-lock braking system, the distinction of skid resistance is marked than in the condition of no anti-lock braking system from the perspective of emergency braking distance. When the vehicle has anti-lock braking system, the braking distance is shorter than the braking distance of vehicle without anti-lock braking system in emergency brake condition. 0.1 to 0.15 is the appropriate interval for slip ratio control of vehicle’s brake system, for the braking distance can be reduced markedly compared to no anti-lock braking system condition. When the vehicle drives in 120km/h on circular curve whose radius is 400m, the vehicle presents bad steering stability and security and potential danger on asphalt concrete, open-graded friction course and stone mastic asphalt pavement. When the vehicle’s longitudinal speed is control in 126km/h, asphalt concrete pavement will no longer be able to ensure vehicle’s safety. If the speed is raised up to 134km/h, the vehicle on stone mastic asphalt pavement will also face danger, while the vehicle is safe on open-graded friction course pavement.

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