The Open Mechanical Engineering Journal, 2014, *8*, 675-681 675

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Investigation on Emergency Brake Property of a Heavy-Duty Vehicle Based on Functional Virtual Prototyping Model

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Abstract: A Functional Virtual Prototyping full vehicle model for a tri-axial heavy-duty truck is built, and the non-linearity of suspension dampers and tires is also considered. With the trajectory of full vehicle gravity center, longitudinal tire force of front wheel, longitudinal acceleration, lateral acceleration, yaw rate and pitch angle as the evaluation indexes of brake property, the influences of system parameters including wheelbase, load shift, road surface roughness and separated road friction coefficient on brake efficiency, stability and ride comfort are analyzed. In addition, the interaction of brake and full vehicle dynamics is studied. Results show that small wheelbase and load shift may improve the brake efficiency of vehicles, small road surface roughness is beneficial to brake stability and ride comfort, and great frictional coefficient difference of separation road will worsen the brake efficiency and stability.

Keywords: Dynamic simulation model, Emergency brake, Heavy-duty vehicle, Stability, Traffic safety.

1. INTRODUCTION

Emergency brake has a great damage on vehicles and tires, and the inconsistence of the left and right wheel braking or the differences of friction coefficient will make the vehicle drift, turn around, lose directional control or even cause a traffic accident. Heavy-duty vehicles have large inertia, big body length and high roll center, and thus the emergency brake is a dangerous condition. It is difficult to fulfill the real vehicle’s emergency brake experiment. In addition, a lot of heavy-duty vehicles don't install ABS system, and their wheels are easily locked during braking, which would worsen the brake property. Hence, it is necessary to study the emergency brake property of heavy-duty vehicles by dynamic simulation.

At present, researches on vehicle braking performance are usually based on vehicle equations [1-3] or multi-degree freedom lumped parameter models [4-6]. These models are able to analyze the tire loads, vehicle speed and brake force distribution, but not able to show the specific structure of the vehicle and the dynamic interaction of full vehicle in each direction. Moreover, they can’t also study the brake property and the directional stability simultaneously. In recent ten years, with the development of multi-body system dynamics and computer technology, the Functional Virtual Prototyping (FVP) model has attracted the attention of scholars and automobile manufacturers. FVP model can describe the vehicle structure in detail and simulate virtual experiments under various conditions easily. At present, a lot of studies based on FVP model focus on vehicle handling stability and riding comfort [7-9]. While some other scholars laid their emphasis on vehicle brake properties and ABS control. They established different vehicle models in ADAMS/Car composed of suspension system, power train system, steering system, braking system, wheels system and frame system [10-12]. However, the modification of wheelbase, track, the center of gravity of the vehicle and other structural parameters are involved in vehicle's specific structure and a lot of vehicle parameters. Hence, the research on effects of structural parameters on vehicle brake property based on FVP model is still seldom found.

In this work, a dynamic model of a heavy tri-axial truck with eight rear wheels is established based on ADAMS/Car. By modifying the hard points' coordinate of the structure, the wheelbase, vertical loads and lateral position can be changed. According to the trajectory of full vehicle gravity center, longitudinal tire force of front wheel, longitudinal acceleration, lateral acceleration, yaw rate and pitch angle of vehicle body, the influences of wheelbase, load shift, road surface roughness and separation coefficient road on brake efficiency, stability and ride comfort are analyzed. Some suggestions on choosing parameters so as to improve vehicle driving safety are also given.

2. FUNCTIONAL VIRTUAL PROTOTYPING MODEL FOR A HEAVY-DUTY VEHICLE

A FVP model of a nonlinear heavy-duty vehicle is built on ADAMS/Car platform with object-oriented model method. Vehicle model includes front and rear suspension, steering system, body of vehicle, powertrain, braking system, wheels and tire model. The main vehicle parameters are chosen referred to [13,14] and listed in Table **1**, the assembled vehicle model is shown in Fig. (**1**). The nonlinear characteristics of vehicle suspension dampers and tires are considered. The tire

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forces are described by Fiala model. Tire cornering stiffness is 227.3 kN/rad, and longitudinal slip stiffness is 186.9 kN/mm. Suspension damping force is computed by exponential model:

$$F = C\dot{x} + \eta C\dot{x}^n \quad (1)$$

where the damping coefficient C is 50636 Ns/m, asymmetric coefficient η is 0.5, and the index n is 1.25.

Vehicle braking control is mainly controlling braking torque. To output data from Matlab/Simulink to ADAMS/CAR, some input state variables should be established. Taking the left front wheel as an example, two steps are taken as follows,

(1) Opening the template of brake in ADAMS/CAR and selecting System Elements option in Build, a state variable whose name is left_ front_drive_trigger_signal can be established.

(2) Modify the left_brake_torque_VAR variable in the System Elements option. After modification, the braking torque equation is as follows:

M=varval(._msc_truck_air_drum_brakes.left_front_drive_trigger_signal)*varval(._msc_truck_air_drum_brakes.brake_line_pressure)*varval(._msc_truck_air_drum_brakes.load_sensitive_pressure_metering_front_drive)*._msc_truck_air_drum_brakes.pvs_brake_mu*._msc_truck_air_drum_brakes.pvs_pressure_to_torque_cnvt*STEP(VARVAL(._msc_truck_air_drum_brakes.left_front_drive_wheel_omega), -0.0175,1,0.0175,-1)

The left_brake_torque_VAR variable in above equation provides an interface of data exchange with other systems, and can brake the vehicle during the simulation.

Table 1. Parameters of vehicle model.

Parameters	Value/Type
Dimensions (L×W×H) (mm)	11650×2462×2880
The total mass (kg)	25000
Wheelbase (mm)	5900+1300
Curb weight (kg)	7240
Number of axes	3
Braking Systems	Drum
Front/rear suspension (mm)	1245/2315
Approach/departure angle (°)	32/13
Front track (mm)	1940
Rear track (mm)	1860/1860
Number of front/rear leaf spring	8/12
Number of tires	10
Tire Type	10.00R20
Axle load	7,000/18,000

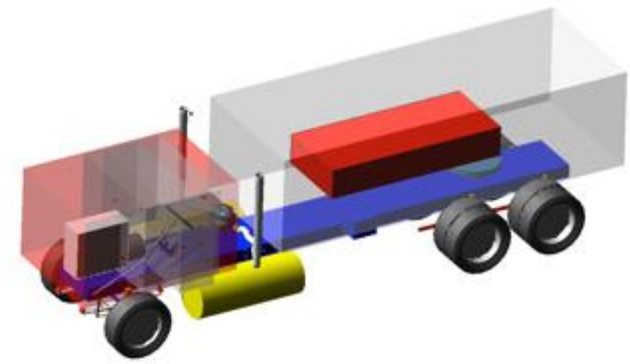


Fig. (1). FVP model for a heavy-duty vehicle.

3. EFFECTS OF VEHICLE AND ROAD PARAMETERS ON BRAKE PROPERTY

The evaluation indexes of vehicle braking property include: braking time, braking distance, braking deceleration and braking directional stability. Since a full-vehicle model was established, the influences of braking on dynamics in different directions can be simulated easily. With the trajectory of full vehicle gravity center, longitudinal tire force of front wheel, longitudinal acceleration, lateral acceleration, yaw rate and pitch angle of vehicle body as the evaluation indexes of brake property, the influences of vehicle and road parameters on brake property are analyzed. Since many present researches focus on the influences of vehicle speed and load on braking property, this work will only research the effects of vehicle structural parameters on braking property.

With other parameters unchanged, the coordinates of hard points related to one parameter are modified and thus the effect of this parameter on vehicle responses can be obtained. During simulation, the vehicle runs along a straight line at an initial speed 60 km/h, starts braking at 2s, and the brake force reaches the maximum value at 0.5s. The simulation time is set to 10s and the number of the simulation steps is set to 1000.

3.1. Effect of Wheelbase

The change of wheelbase will influence axle loads and the locking turn of each axle. Thus wheelbase is an important vehicle structural parameter influencing braking property. Fig. (**2**) is the schematic diagram of the tri-axial heavy vehicle's wheelbase. L_1 is the distance from front axle and L_2 is the distance from front axle to rear axle. Five kinds of L_1, including 4900 mm, 5400 mm, 5900 mm, 6400 mm and 6900 mm, are simulated by modifying the related hard points coordinates. The distance from middle axle to rear axle is calculated by L_2-L_1 and set to a constant 1300 mm. The hard points related to the front drive axle are listed in Table **2**.

The straight-line emergency braking responses of the heavy vehicle with different wheelbase are shown in Fig. (**3**). It can be seen from Fig. (**3**) that,

Table 2. Hard points related to the front drive axle wheelbase.

Hard Point Name	Type	Meaning of Hard Point	x_Value
center_of_drive_axles	Single	Drive axle center	7810.9
origin	Single	Global coordinates	405.0
panhard_link_to_rod	Single	Stabilizer bar	7845.0
panhard_rod_loc	Single	Stabilizer bar center	7842.6
panhard_rod_to_frame	Single	Contact point between stabilizer bar and frame	7845.0
airbag_to_frame	left/right	Contact point between spring and frame	8173.6
airbag_to_hockeystick	left/right	Contact point between spring and vertical rod	8173.6
drive_axle_loc	left/right	Drive axle	7864.0
hockeystick_loc	left/right	Vertical stabilizer	7810.9
hockeystick_to_axle	left/right	Contact point between vertical stabilizer bar and axle	7810.9
hockeystick_to_frame	left/right	Contact point between vertical stabilizer bar and frame	7163.6
hub_loc	left/right	Spoke Center	7810.9
hub_to_axle	left/right	Contact point between spoke and axle	7810.9
inside_whl_cntr	left/right	Inner wheel center	7810.9
outside_whl_cntr	left/right	Outer wheel center	7810.9
shock_to_frame	left/right	Contact point between damper and frame	8030.5
shock_to_hockeystick	left/right	Contact point between vertical rod and damper	7925.2

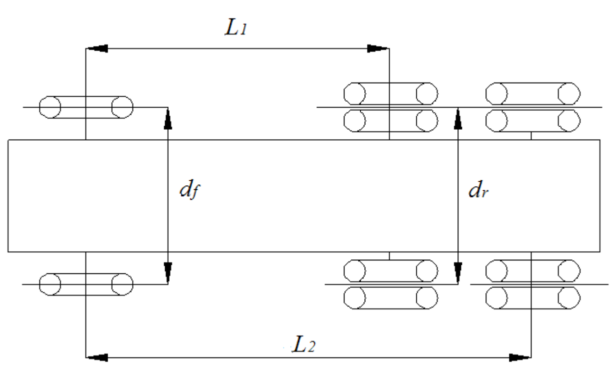


Fig. (2). Schematic diagram of tri-axial heavy-duty vehicles wheelbase.

(1) Braking can cause vehicle body's pitch, slip and yaw motion, which reduces the riding comfort and directional stability of the vehicle.

(2) With the increase of the wheelbase, the side slip, braking deceleration, yaw rate and pitch angle is reduced, longitudinal tire force of the front wheel is increased, while the peak of lateral acceleration changes slightly. Therefore, large vehicle wheelbase will worsen the brake efficiency, but improve the handling stability and riding comfort.

3.2. Effect of Load Shifting

Due to carrying passengers and cargo, the vehicle will have a longitudinal or lateral offset on center of gravity compared with the empty one, which may affect the braking property. The offset on center of gravity is also caused by the error of vehicle design and manufacture. In fact, the position of vehicle center of gravity cannot always remain the same value as the original design. Therefore, it is really necessary to analyze the influence of load shifting on braking property.

Braking responses with five longitudinal load shifting are shown in Fig. (**4**). The position offset is taken as 0 mm, -200 mm, -400 mm, -600 mm, -800 mm, and the offset direction is forward. It can be seen from Fig. (**4**) that with the increase of longitudinal load shifting, the braking distance and pitch angle increase, the braking acceleration and the front wheel's longitudinal tire force decrease, but the yaw rate and lateral acceleration hardly change. Therefore, a big longitudinal load offset will worsen the brake efficiency and ride comfort, but hardly influence the vehicle steering stability.

Vehicle braking responses with different lateral load shifting are shown in Fig. (**5**). The lateral offset of the vehicle center of gravity is selected as 0 mm, 50 mm, 100 mm, 150 mm, 200 mm and 250 mm, and the offset direction is left. It can be seen from Fig. (**5**) that,

(1) With the rise of lateral load offset, the braking distance and braking time do not change significantly, the sideslip goes up before braking, but goes down after braking, and the longitudinal acceleration decreases. Therefore, a great lateral load offset is harmful to brake property and probably leads to the vehicle's driving drift.

(2) With the increase of lateral load offset, the longitudinal braking force of the front tire and the pitch angle of vehicle body will increase, while the lateral acceleration and yaw rate only increase a little. Hence, the lateral load offset is unfavorable to the steering stability and riding comfort.

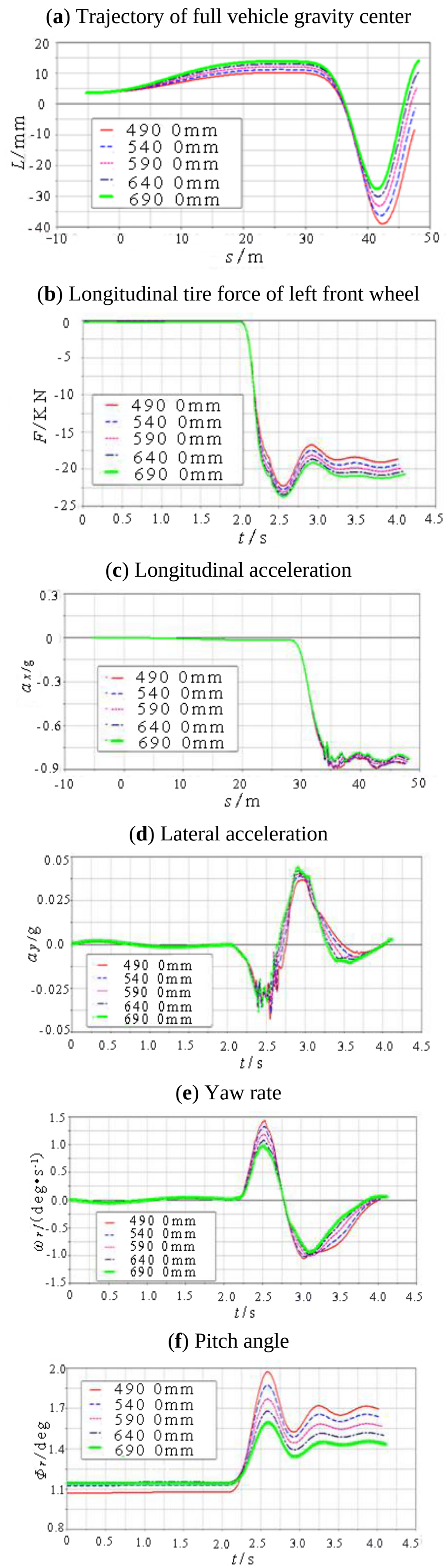


Fig. (3). Vehicle straight-line braking responses with different wheelbase.

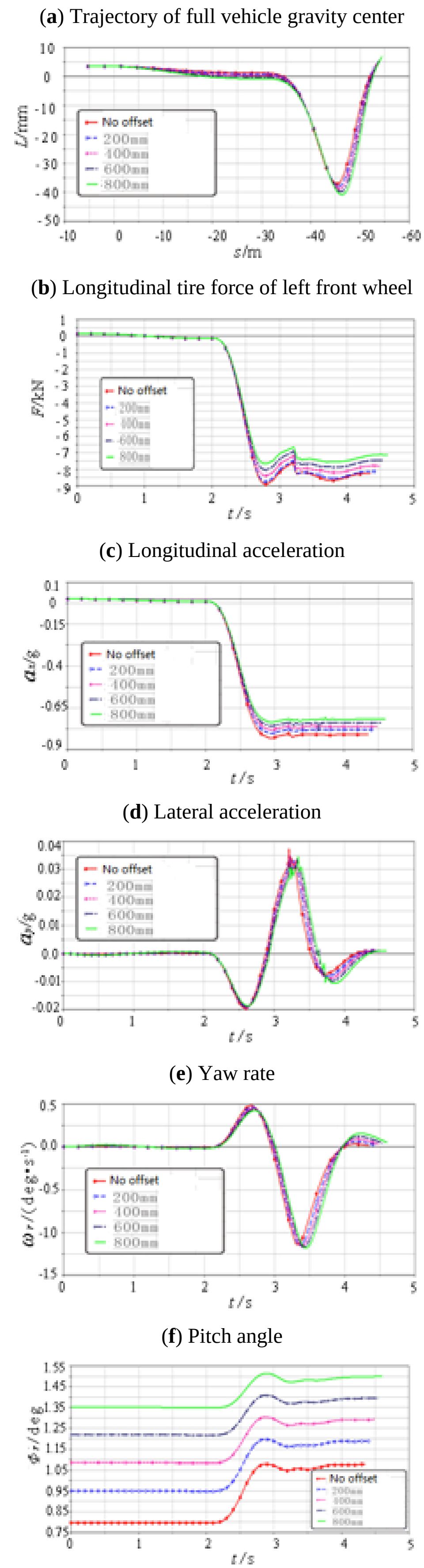
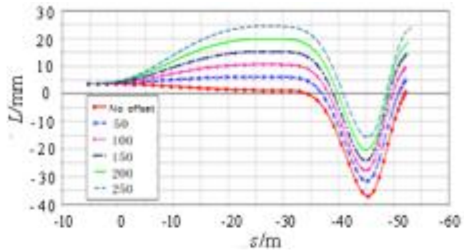
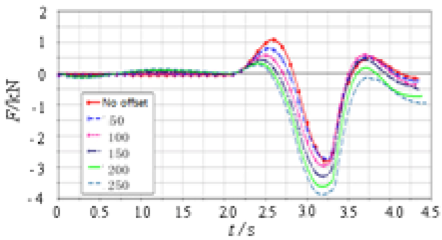


Fig. (4). Vehicle straight-line braking responses with different longitudinal load shifting.

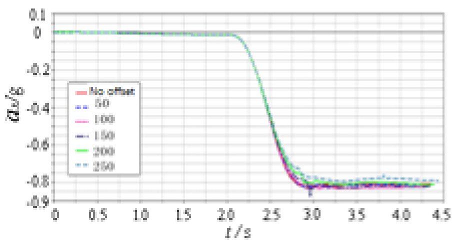
(**a**) Trajectory of full vehicle gravity center



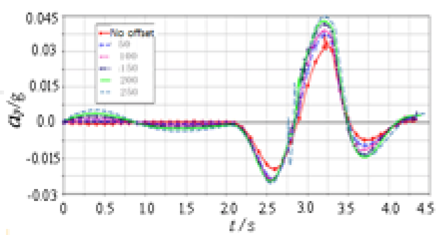
(**b**) Longitudinal tire force of left front wheel



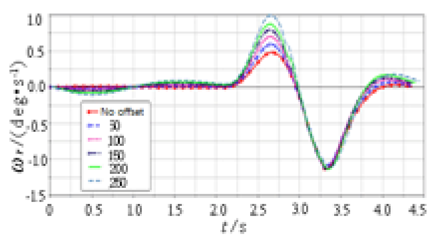
(**c**) Longitudinal acceleration



(**d**) Lateral acceleration



(**e**) Yaw rate



(**f**) Pitch angle

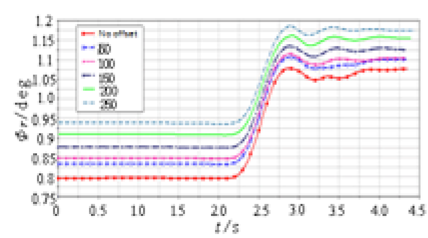
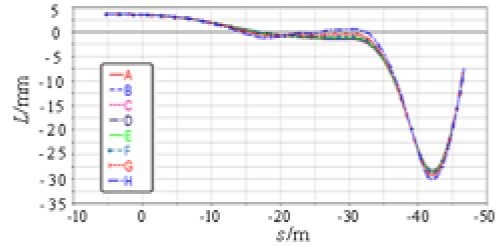
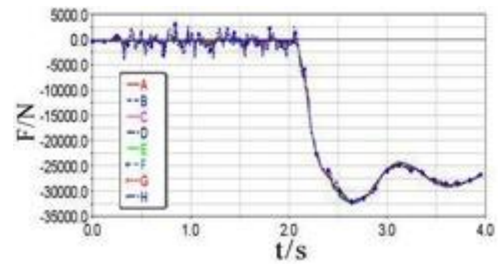


Fig. (5). Vehicle straight brake responses with different load lateral shifting.

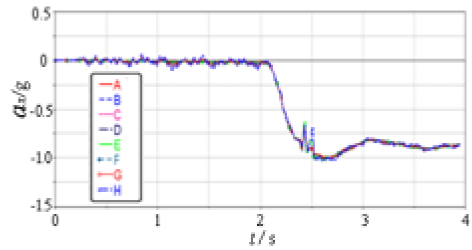
(**a**) Trajectory of full vehicle gravity center



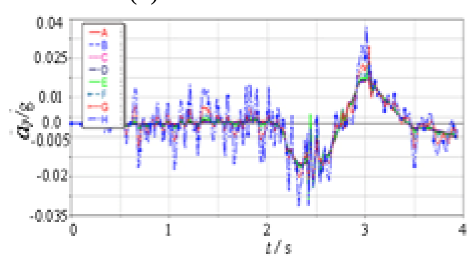
(**b**) Longitudinal tire force of left front wheel



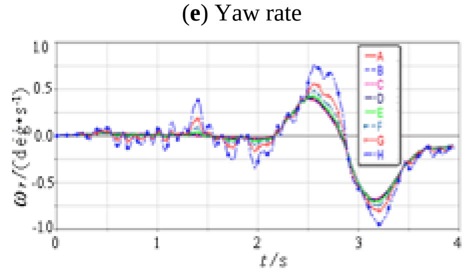
(**c**) Longitudinal acceleration



(**d**) Lateral acceleration



(**e**) Yaw rate



(**f**) Pitch angle

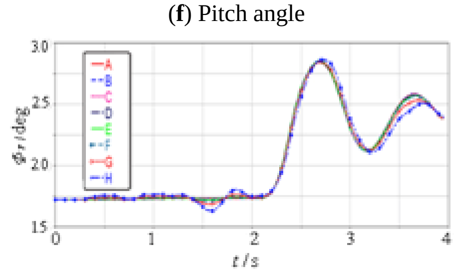
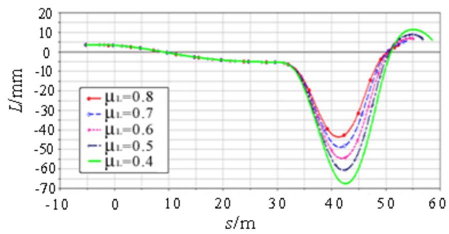
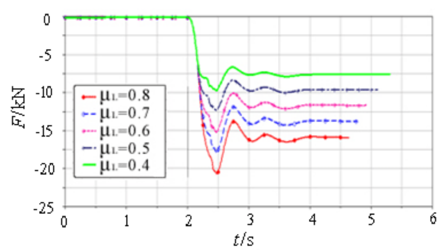


Fig. (6). Vehicle straight-line braking responses with different road surface roughness.

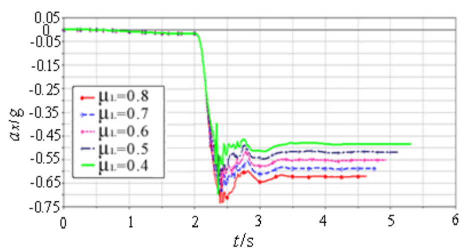
(**a**) Trajectory of full vehicle gravity center



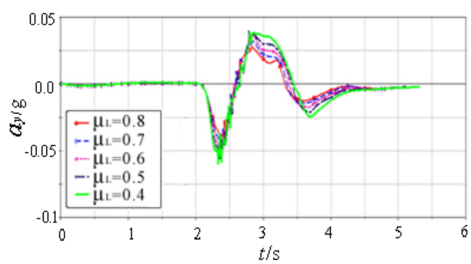
(**b**) Longitudinal tire force of left steering wheel



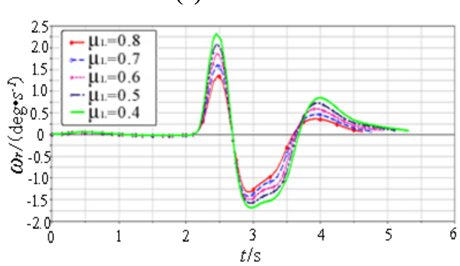
(**c**) Longitudinal acceleration



(**d**) Lateral acceleration



(**e**) Yaw rate



(**f**) Pitch angle

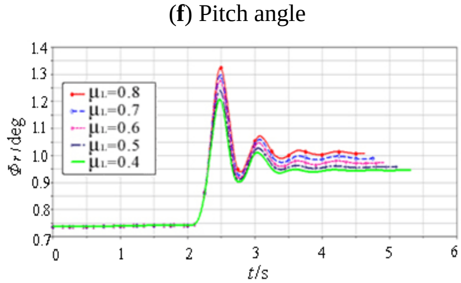


Fig. (7). Vehicle straight-line braking responses on separated roads.

To summarize, the drivers should pay attention to minimize the longitudinal and lateral load offset so as to improve brake property and ride comfort. As for steering stability, the lateral load offset plays a more important role than the longitudinal one.

3.3. Effect of Road Surface Roughness

The braking responses of the vehicle on different rough surface road are shown in Fig. (**6**). Eight classes of random rough road from A-class to H-class according to GB/T 7031-2005/ISO 8608:1995 [15] are simulated by modifying the file of road properties. It is clear from Fig. (**6**) that,

(1) The braking distance, braking time and longitudinal acceleration are hardly influenced by road roughness. With the increase of road roughness, the sideslip and front-wheel's longitudinal tire force have a slight increase.

(2) The rise in road roughness will brought about an obvious increase in lateral acceleration and yaw rate, and a slight rise in the pitch angle.

Thereby, the road roughness has little effect on vehicle brake property, but will reduce the steering stability and ride comfort of the vehicle when braking.

3.4. Effect of Road Separation Coefficient

Creating a new file of road characteristics and selecting the menu "Simulate → Full Vehicle Analysis → Set Road for Individual Tires", the roads under left and right wheels can be separated. The road surface friction coefficient under the right wheels is chosen as 1.0, and the left friction coefficient is set to 0.8, 0.7, 0.6, 0.5 and 0.4 respectively. The vehicle braking responses on separated roads are simulated and compared in Fig. (**7**). It can be noticed from Fig. (**7**) that,

(1) Due to the growth of the coefficient difference between left and right road, the sideslip, braking distance and braking time are greater, and the longitudinal force of left front wheel and longitudinal acceleration decrease.

(2) With the increase of the friction coefficient difference between left and right roads, the lateral acceleration and yaw rate increase, but the pitch angle decreases slightly.

It is clear that the increase of the road surface friction coefficient difference between left and right roads will worsen brake property and steering stability greatly, but influence the ride comfort slightly.

CONCLUSION

Based on Functional Virtual Prototyping full model for a heavy vehicle, the influences of vehicle structural parameters and road parameters on brake property, steering stability and ride comfort during emergency braking are analyzed. It can be concluded that

(1) A smaller wheelbase may cause a better brake efficiency and a smaller sideslip, but will worsen the steering stability and ride comfort of the vehicle.

(2) The increase of the road roughness has little effect on the vehicle's brake property, but will reduce the stability and ride comfort of the vehicle in braking.

(3) When a vehicle is running on the separated road, a big surface friction coefficient difference between the left and right roads will be quite harmful to brake property and steering stability.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

The National Natural Science Foundation of China (11472180) the Natural Science Foundation of Hebei Province (E2012210025) and the New Century Talent Foundation of Ministry of Education (NCET-13-0913) support this work.

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Received: January 8, 2015 Revised: January 15, 2015 Accepted: January 16, 2015