A Study of Robustness in Handling Performance for Light Weight Vehicle

Yusuke UDAGAWA[*1], **Kyosuke TAKEKOSHI**[*1], **and Taichi SHIIBA**[*1]
*1 Department of Mechanical Engineering, Meiji University
1-1-1 Higashi-Mita, Tama-ku, Kawasaki, 214-8571 JAPAN
ee03121@meiji.ac.jp, ce32031@meiji.ac.jp, shiiba@isc.meiji.ac,jp

Abstract

The behavior and the steering stability of a light weight vehicle are more affected by the weight variation depending on the number of passengers and the loadage compared with that of a regular passenger car. The purpose of this study is to evaluate the change of the handling characteristics of a light weight vehicle due to the weight variation. The handling characteristic of the light weight vehicle was evaluated by using a four-wheel vehicle model with the rolling motion. The behavior of the vehicle was evaluated with different value of the roll stiffness distribution, the roll center height and the height of the center of gravity. The robustness in handling performance against the weight variation was investigated by steady circular turning simulation.

Keywords: light weight vehicle, weight variation, handling characteristics, handling performance, robustness

1 Introduction

A weight reduction of a vehicle is profitable to improve the accelerating and the braking performance and the fuel efficiency. On the other hand, the total weight of the vehicle and the position of the center of gravity are more variable in a light weight vehicle compared with those of a conventional vehicle depending on the loadage and the number of passengers. They affect the vehicle handling characteristics such as the cornering performance and the handling stability at high speed. Therefore, a light weight vehicle requires the robustness against the weight variation [1].

The purpose of this paper is to evaluate the change of the vehicle handling characteristics due to the weight variation by simulations. The weight of the target vehicle was set to 600 kg, and the weight of the regular passenger car for comparison was set to 1000 kg. In this study, a four-wheel vehicle model with rolling motion [2] was used. With this vehicle model, the effect of the vehicle parameters such as the roll center height on the robustness against the weight distribution was evaluated in handling performance.

2 Four-wheel Vehicle Model with Rolling Motion

2.1 Planar motion model

The vehicle model in the two-dimensional plane is discussed in this section. The coordinate system shown in **Fig. 1** was used in this study. The equations of motion for the planar motion can be described as follows:

$$m(\dot{v}x - vyr) = F_{xfl} + F_{xfr} + F_{xrl} + F_{xrr} \quad (1)$$

$$m(\dot{v}y + vxr) = F_{yfl} + F_{yfr} + F_{yrl} + F_{yrr} \quad (2)$$

$$Iz\dot{r} = l_f(F_{yfl} + Fyfr) - l_r(F_{yrl} + Fyrr) \quad (3)$$

where m is the vehicle mass, I_z is the moment of inertia around the yaw axis, v_x is the velocity in the x-direction, v_y is the velocity in the y-direction, r is the yaw rate, F_{xfl}, F_{xfr}, F_{xrl} and F_{xrr} are the longitudinal forces acting on each tire, F_{yfl}, F_{yfr}, F_{yrl} and F_{yrr} are the lateral forces of each tire, and l_f and l_r are the distances from the center of gravity point to front and rear wheel axle.

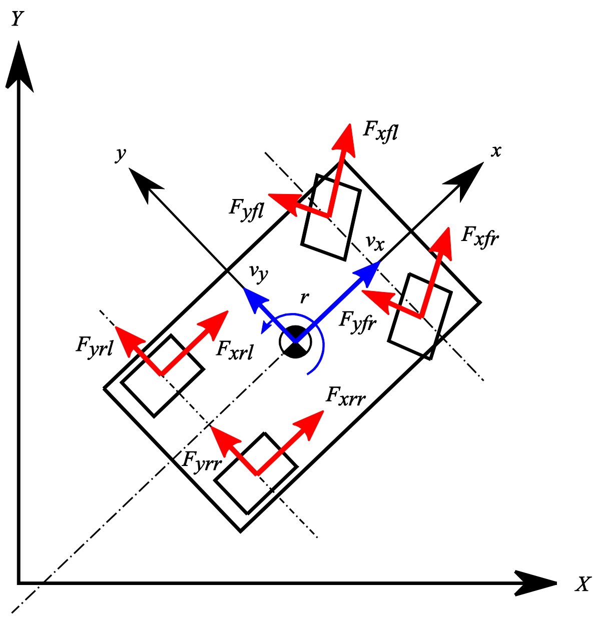


Fig. 1 Coordinate system of the vehicle model

2.2 Rolling motion

The rolling model used in this study is shown in **Fig. 2**. The roll stiffness distribution in front and rear wheels, the roll axis inclination, and the height of the center of gravity were considered as modifiable parameters in this study. In **Fig. 2**, m_s is the sprung mass, h_s is the height from the roll axis to the center of gravity position, h_f and h_r are the roll center height and d_f and d_r are the tread width of the front and rear. The roll axis is the line joining the front and rear roll centers [3].

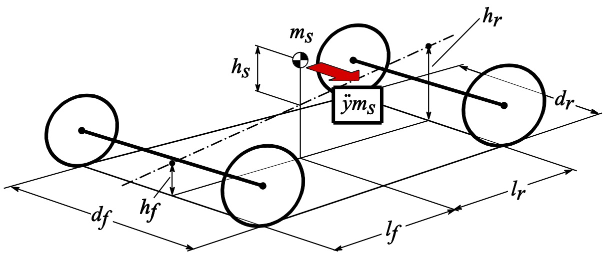


Fig. 2 The rolling model

The equation of motion for the rolling motion is shown as follows:

$$\left(K_{\phi f}+K_{\phi r}\right)\phi=\ddot{y}m_s h_s+m_s g h_s \sin\phi \tag{4}$$

where ϕ is the roll angle of vehicle body, $K_{\phi f}$ and $K_{\phi r}$ are the front and rear roll stiffness, $C_{\phi f}$ and $C_{\phi r}$ are the front and rear roll damping, g is the acceleration of gravity, and $\ddot{y}$ is the acceleration of the y-direction.

Finally, the load shift of the vehicle model with roll motion is shown in **Fig. 3**. The vertical load of each tire can be calculated with eqs. (5) and (6):

$$K_{\phi f}\phi+C_{\phi f}\dot{\phi}=\Delta F_{zf}d_f-\left(F_{yfl}+F_{yfr}\right)h_f \tag{5}$$

$$K_{\phi r}\phi+C_{\phi r}\dot{\phi}=\Delta F_{zr}d_r-\left(F_{yrl}+F_{yrr}\right)h_r \tag{6}$$

where ΔF_{zf} and ΔF_{zr} are the vehicle load shift between the left and right tires.

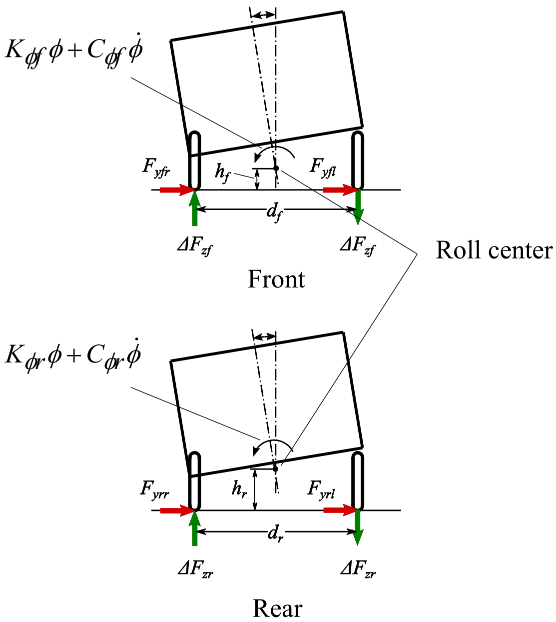


Fig. 3 Load shift of the vehicle

2.3 Tire model

It is known that the tire forces affect the handling characteristics of a vehicle [4]. The lateral force generated in a tire varies nonlinearly in response to the slip angle of the tire. The slip angle of the tire is formed between the velocity that occurs in the tire and its heading direction, and it is calculated from the yaw rate, the velocity and the slip angle of the vehicle. In addition, the contact area between the tire and the ground is generally changed by the ground load and the tire pressure, which influence the lateral force characteristics. Therefore, it is necessary to consider the vertical load shift caused by the rolling motion of the vehicle. In this study, the Pacejka Magic Formula tire model [4] was used for the calculation of the tire lateral force. The lateral force can be calculated with eq. (7):

$$Y=D\sin\left\{C\tan^{-1}\left[Bx-E\left[Bx-\tan^{-1}(Bx)\right]\right]\right\}+S_v$$
$$x=\alpha+S_H$$
$$C=a_0$$
$$D=(a_1F_z+a_2)F_z$$
$$BCD=a_3\sin\left(2\tan^{-1}(F_z/a_4)\right)\left(1-a_5|\gamma|\right)$$
$$B=BCD/CD$$
$$E=a_6F_z+a_7$$
$$S_H=a_8\gamma+a_9F_z+a_{10}$$
$$S_v=a_{11}F_z\gamma+a_{12}F_z+a_{13} \tag{7}$$

where Y is the tire lateral force, α is slip angle, B is the stiffness factor, C is the shape factor, D is the peak value, E is the curvature factor, S_H is the horizontal shift, and S_V is vertical shift. The parameters of the Magic Formula model used in this study are depicted in **Table 1**. The lateral tire force can be calculated with these parameters as **Fig. 4**.

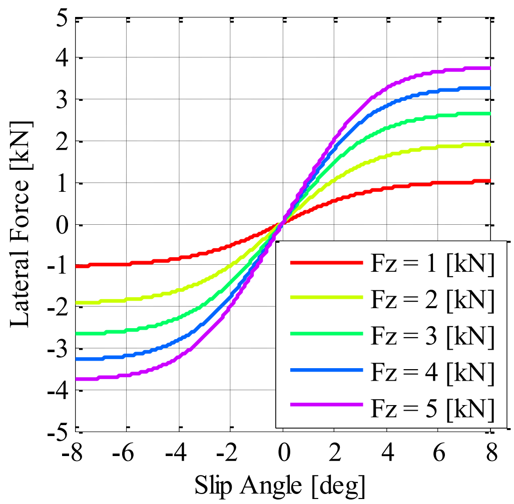


Fig. 4 Nonlinear tire model

Table 1 Magic formula parameters

$a_0 = 1.30$	$a_7 = 2.40\times10^{-2}$
$a_1 = -7.00\times10^{-2}$	$a_8 = 2.53\times10^{-2}$
$a_2 = 1.10$	$a_9 = 0.00$
$a_3 = 1.18$	$a_{10} = 0.00$
$a_4 = 7.80$	$a_{11} = 3.57\times10^{-3}$
$a_5 = 0.00$	$a_{12} = 0.00$
$a_6 = -0.20$	$a_{13} = 0.00$

3 Simulation Method and Result

3.1 Steering characteristic

The steady-state cornering characteristic is affected by the vehicle properties. The terms of understeer, oversteer and neutralsteer are often used to describe the fundamental cornering characteristics. When the velocity increases with a fixed steer angle, vehicles with the understeer characteristic turn out from the original circular path, and make a circular path with an even larger radius. On the contrary, vehicles with the oversteer characteristic turn into the inner side of the original circular path, and make a circular path with an even smaller radius [5]. Finally, the radius is not dependent on velocity and the vehicle has neutral steer characteristics. These concepts are shown in **Fig. 5**. It is known that an excessive oversteer and understeer characteristics is not suitable for a driver.

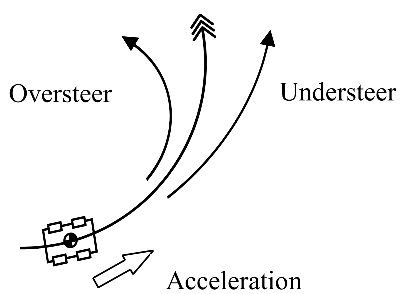


Fig. 5 Understeer and oversteer [6]

3.2 Steady circular turning simulation

In this study, to analyze the handling characteristics of a light weight vehicle, the simulations of a steady circular turning were carried out. In this simulation, the vehicle velocity was gradually increased with keeping a constant turning radius [7]. From the change of the steer angle at this simulation, the steering characteristics of the light weight vehicle and the regular passenger car were evaluated. The turning radius was 30 m. The loadage, the weight distribution and the vehicle parameters of the base model were represented in **Table 2** to **Table 4**. The roll stiffness distribution, the inclination of the roll axis and the center of gravity height were varied as shown in **Table 5** to **Table 7**. The inclination of the roll axis was varied by changing the roll center height of the front and rear wheels.

Table 2 Parameter for light weight vehicle

	1 person	5 persons + fully loaded
Total weight [kg]	668	980
Weight distribution (front : rear)	65 : 35	55 : 45
Moment of inertia [kgm^2]	1000	1467

Table 3 Parameter for regular passenger car

	1 person	5 persons + fully loaded
Total weight [kg]	1068	1380
Weight distribution (front : rear)	65 : 35	58 : 42
Moment of inertia [kgm^2]	1400	1809

Table 4 Parameter of the base model

Front roll stiffness	$K_{\phi f}$ [N/rad]	300
Rear roll stiffness	$K_{\phi r}$ [N/rad]	300
Front height of roll center	h_f [mm]	150
Rear height of roll center	h_r [mm]	150
Height of center of gravity	h_g [mm]	600

Table 5 Variation of the roll stiffness distribution ratio

$K_{\phi f} : K_{\phi r}$	60 : 40	50 : 50	40 : 60

Table 6 Variation of inclination of the roll axis

h_f [mm]	120	150	180
h_r [mm]	180	150	120

Table 7 Variation of height of center of gravity

h_g [mm]	550	600	650

The relation of the lateral acceleration and the steer angle ratio are shown in **Fig. 6**. These relations are known to be nonlinear in high lateral acceleration. The steer angle ratio is the ratio of the steering angle to the initial steer, and the initial steer is the steering angle at low speed.

In order to understand the nonlinear characteristics of the steady-state cornering comprehensively, we define two indices of ”the boundary acceleration” and “the maximum acceleration”. As is depicted in **Fig. 7**, the boundary acceleration is defined as the lateral acceleration when the steering angle ratio deviates more than 5 % from the extension of the characteristics in the linear range. The maximum acceleration is defined as the lateral acceleration when the steering angle ratio

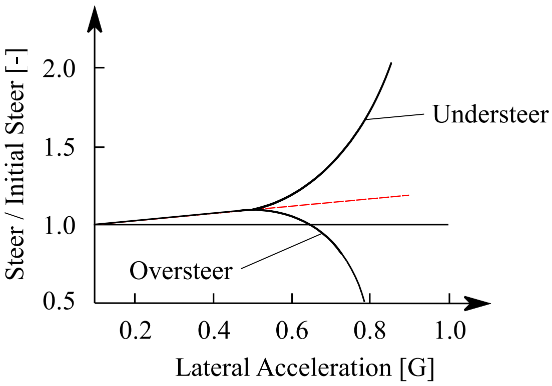


Fig. 6 Steering characteristics

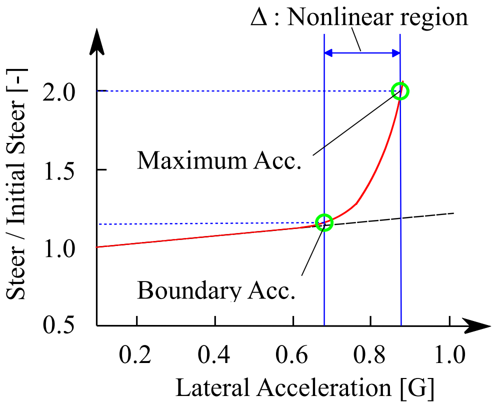


Fig. 7 Comparing of lateral acceleration

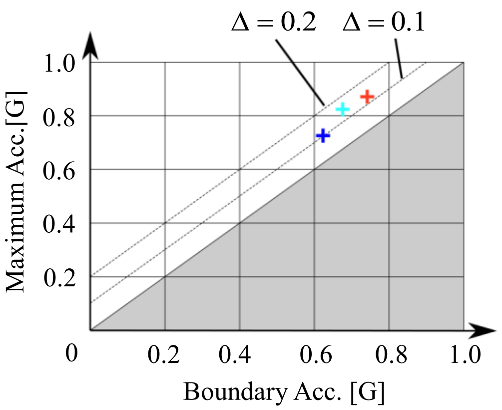
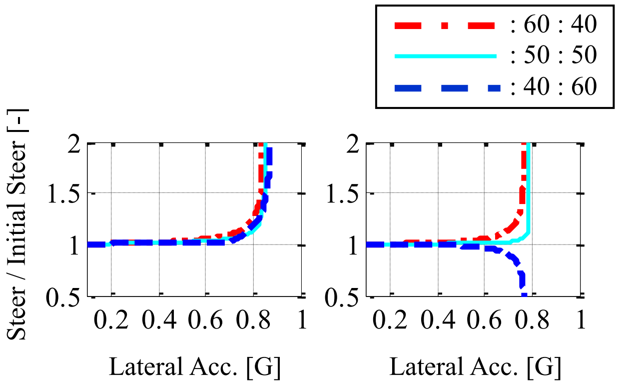


Fig. 8 Relation of boundary acceleration and maximum acceleration

becomes the value of 2.0. The nonlinear region is defined as the difference between the boundary acceleration and the maximum acceleration. The relation of the boundary acceleration and the maximum acceleration is compared with a chart shown in **Fig. 8**. When the nonlinear region is narrow, it means that the steering characteristics rapidly changes, which is undesirable in the sense of the drivability.

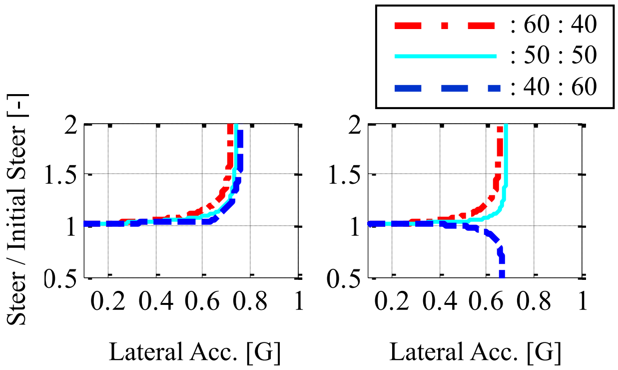
3.3 Effect of roll stiffness distribution

The effect of the variation of the roll stiffness distribution is discussed in this section. The simulation results are shown in **Figs. 9** and **10**. **Figure 11** represents the results of the boundary acceleration and maximum acceleration in the simulation.



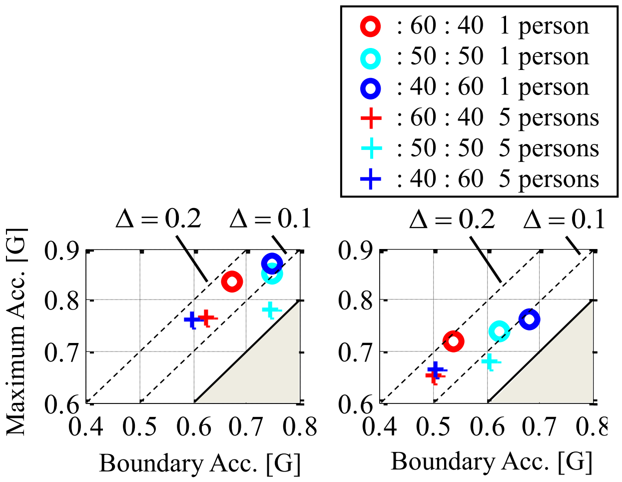
(a) 1 Person **(b) 5 Persons with full load**

Fig. 9 Effect of the roll stiffness distribution for light weight vehicle



(a) 1 Person **(b) 5 Persons with full load**

Fig. 10 Effect of the roll stiffness distribution for regular passenger car



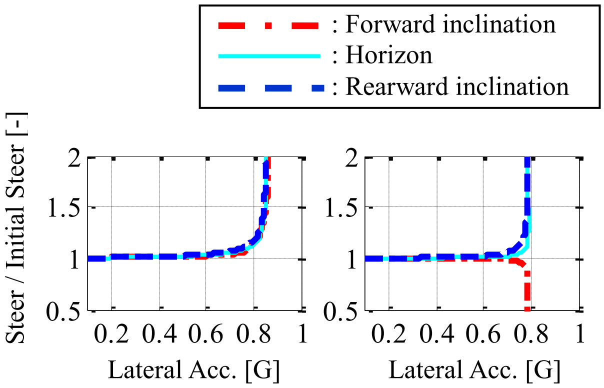
(a) 1 Person **(b) 5 Persons with full load**

Fig. 11 Lateral acceleration effected of the roll stiffness distribution

These figures show that the steer angle ratio increases from the lower lateral acceleration when the front roll stiffness is larger. That is, the vehicle tends to have strong understeer characteristics. **Figure 11** shows that the maximum acceleration of the vehicles with 5 persons and fully loaded are lower than vehicles with 1 person. Also, regardless of the vehicle, the change of the nonlinear region according to the weight variation is the smallest when the roll stiffness distribution is 60:40. That is, this condition realizes high robustness against the weight variation.

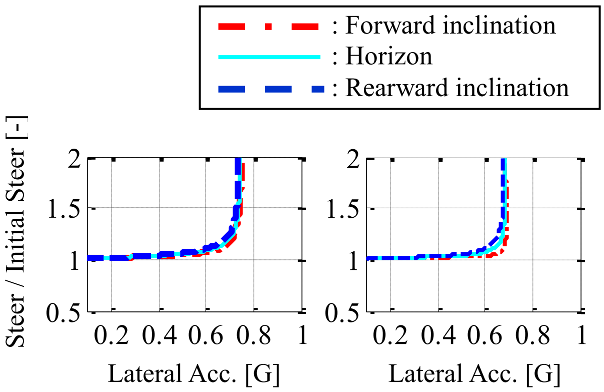
3.4 Effect of the roll axis

The effect of the variation of the roll axis inclination distribution is discussed in this section. The simulation results are shown in **Figs. 12** and **13**. **Figure 14** represents the results of the boundary acceleration and maximum acceleration.



(a) 1 Person **(b) 5 Persons with full load**

Fig. 12 Effect of the roll axis in light weight vehicle

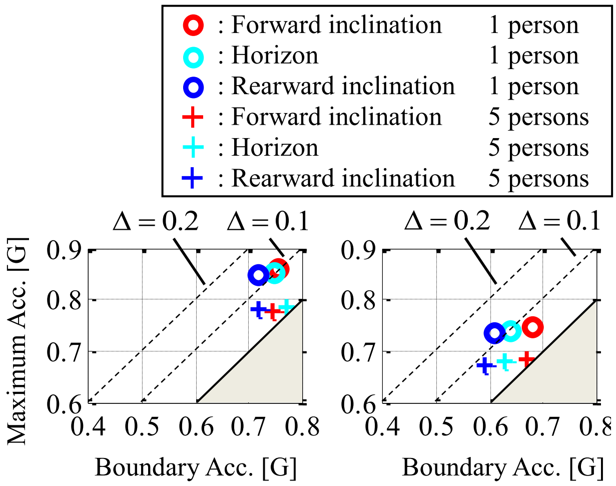


(a) 1 Person **(b) 5 Persons with full load**

Fig. 13 Effect of the roll axis for regular passenger car

These figures show that the vehicle tends to have strong understeer characteristics in the case of 1 person when the roll axis is rearward inclination, and the effect of changing the inclination of the roll axis was not so big. In addition, **Fig. 12 (b)** shows that the vehicle tends to have the oversteer characteristics when the roll axis is the forward inclination. **Figure 14** shows that the boundary acceleration and the maximum acceleration of both vehicles with 5 persons and fully loaded are lower than those of the vehicles with 1 person.

Also, regardless of the vehicle, the change of the nonlinear region is the smallest when the roll axis is rearward inclination.

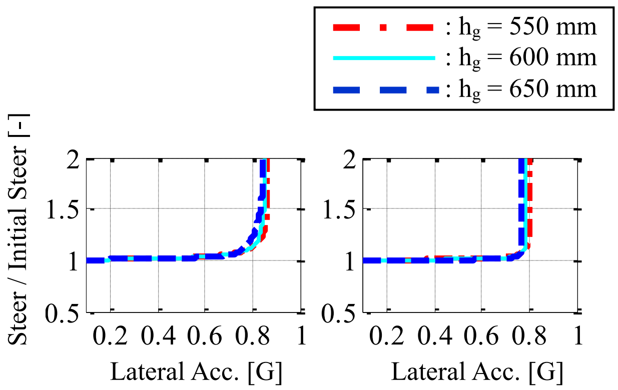


(a) Light weight vehicle **(b) Regular passenger car**

Fig. 14 Lateral acceleration effected of the roll stiffness distribution

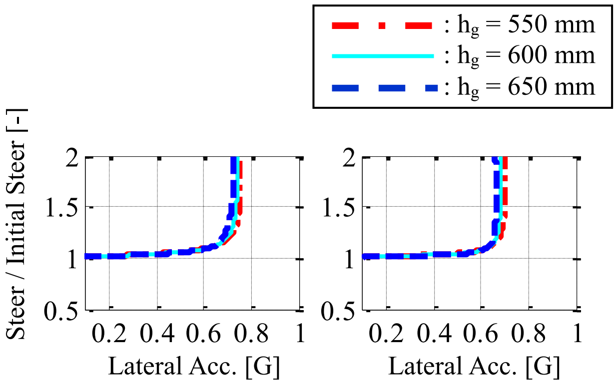
3.5 Effect of the center of gravity height

The effect of the variation of the center of gravity height is discussed in this section. The simulation results are shown in **Fig. 15** to **Fig. 16**. **Figure 17** represents the results of the boundary acceleration and the maximum acceleration.



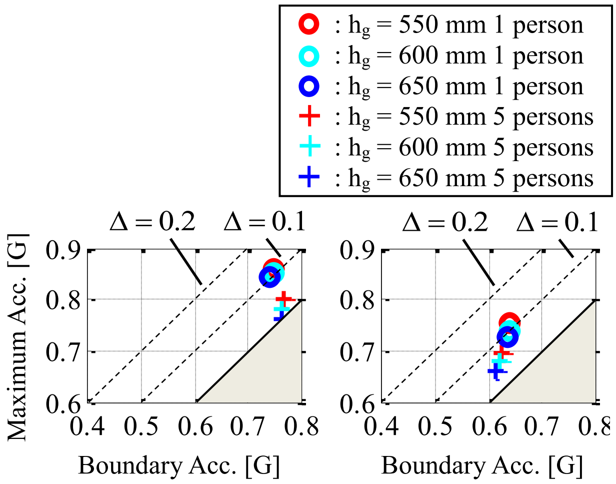
(a) 1 Person **(b) 5 Persons with full load**

Fig. 15 Effect of the center of gravity height for light weight vehicle



(a) 1 Person **(b) 5 Persons with full load**

Fig. 16 Effect of the center of gravity height for regular passenger car



(a) Light weight vehicle **(b) Regular passenger car**

Fig. 17 Lateral acceleration effected of the center of gravity

These figure show that the steer angle increases from the lower lateral acceleration when the height of the center of gravity is higher. **Figure 17** shows that the change of the nonlinear region according to the weight variation is smaller when the center of gravity height is lowered in the light weight vehicle. Therefore, the light weight vehicle is sensitive to the center of gravity height comparing with the regular passenger car.

4 Conclusion

In this study, the steady-state handling characteristics of a light weight vehicle were evaluated by simulations with a four-wheel vehicle model in which the rolling motion was taken into account. In this simulation, the effect of the change of the total vehicle weight and the weight distribution was examined. The roll stiffness distribution, the roll axis inclination, and the center of gravity height were considered as the modifiable parameters. The parameter setting to realize the robust handling performance against the weight variation was discussed by focusing on the nonlinear region.

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