Chapter 8
Parameter Design of Vehicle–Road System with Low Dynamic Interaction

At present, parameter design of the vehicle and pavement with the aim of reducing the vehicle–pavement dynamic interaction is usually studied respectively in vehicle dynamics and road dynamics. It is seldom to study the low dynamic design of vehicle and road parameters simultaneously.

By using the new theory of vehicle–pavement coupled system proposed in Chap. 7, effects of system parameters on dynamic characteristics of vehicle and pavement are simulated and analyzed in detail. Based on the simulation results, some low dynamic design measures are suggested for choosing system parameters, which may contribute to the ride comfort of heavy vehicle and the life of asphalt pavement [1].

8.1 Verification of the New Theory of Vehicle–Road Coupled System

In order to investigate the low dynamic design of vehicle and road parameters, the validity of the new theory of vehicle–road coupled system must be verified first. A response comparison with the finite element method given by Wu [2] is made here. Wu considered the interaction between pavements and the underlying soil foundation and researched the effects of a finite element grid, pavement thickness and foundation stiffness on pavement displacement by using the 3D finite element method [2].

After applying the same parameters and boundary conditions to Wu's model, the pavement displacements are obtained by the above quick direct integral method based on the vehicle–pavement coupled model. Simulation results of this work are shown in Fig. 8.1 and Table 8.1[3].

From Fig. 8.1 and Table 8.1 it can be seen that the results in two methods are very close. Thus, the validation of this vehicle–pavement coupled model and the quick

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Fig. 8.1 Results of this work. **a** The effect of a mode superposition number. **b** The effect of pavement thickness. **c** The effect of foundation stiffness. Reprinted from ref. [3], with kind permission from Taylor & Francis Ltd

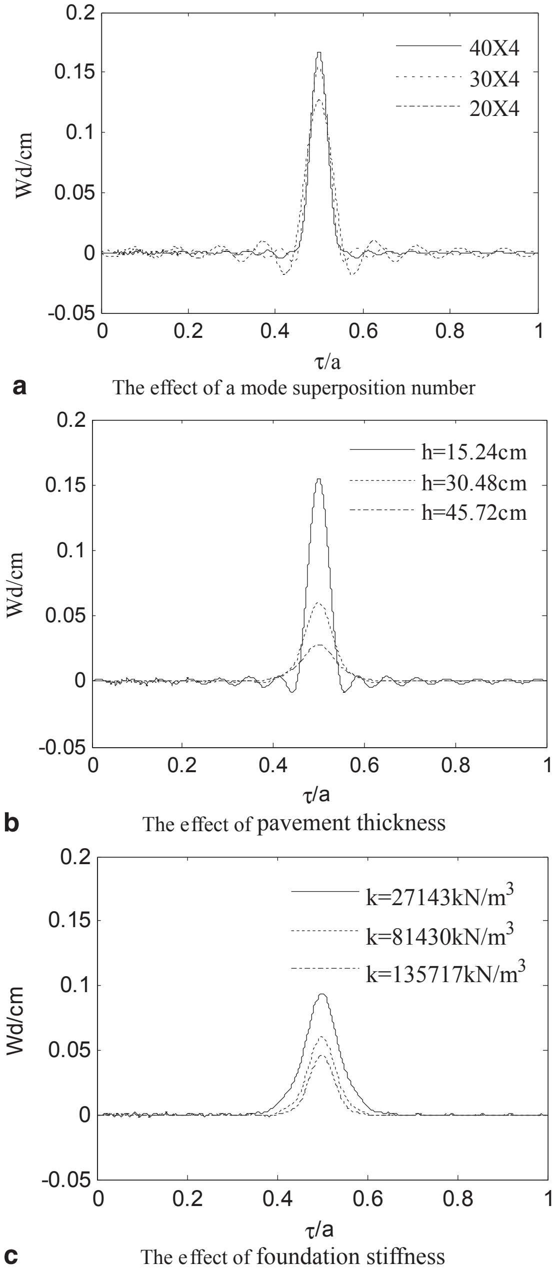

Table 8.1 The amplitude of pavement displacement at the midpoint obtained by two methods(cm). Reprinted from ref. [3], with kind permission from Taylor & Francis Ltd

Parameters Methods	h (cm)			K (kN/m^3)		
	15.24	30.48	45.72	27,143	81,430	135,717
Wu[2]	0.165	0.065	0.035	0.125	0.065	0.050
This work	0.155	0.060	0.028	0.100	0.060	0.046

direct integral method is tested. However, both methods have a sensitive parameter, grid division or mode superposition number, which influences the simulation results greatly. Hence, the numerical test is necessary to choose the suitable parameter in order to assure the correctness of the results and to improve computation efficiency.

8.2 Evaluation Criterions of Low Dynamic Interaction

The dynamic interaction between tire and pavement plays an important role in vehicle and road dynamic responses. Low dynamic interaction will lead to a better vehicle riding comfort and a longer road fatigue life. The research on rail vehicle/track systems with low dynamic interaction has attracted scholars' attention and some basic rules for reducing dynamic interaction have been proposed for designing parameters [4–5].

However, the research on low dynamic parameters design of vehicle–road systems is still seldom found. The present studies on vehicle and road parameters design are often separated in vehicle dynamics and road dynamics, respectively.

In vehicle dynamics, the dynamic load coefficient (DLC) has been widely adopted as an evaluation criterion for dynamic interaction, which is expressed by [6],

$$DLC = F_d / F_s \tag{8.1}$$

where, F_d is the root mean square (RMS) value of the dynamic tire force, and F_s is the static tire force.

However, DLC is unable to reflect the spatial distribution of tire forces and may lead to a calculation error. Hence, Cebon and Cole put forward a fourth power aggregate force to evaluate the road damage induced by tire dynamic forces [7–8].

In road dynamics, the tensile strain at the bottom of an asphalt surface has been a widely used evaluation criterion for dynamic interaction. Road fatigue life can be predicted using the tensile strain [9]

$$N_f = k_1 \left(\frac{1}{\varepsilon_t} \right)^{k_2} \tag{8.2}$$

where N_f is the fatigue life of the pavement structure, represented by the number of loading cycles, ε_t is the tensile strain at the bottom of the surface course, k_1 and k_2 are experimentally measured constants.

In addition, the stiffness modulus of the asphalt mixture and longitudinal tensile strain at the bottom of the asphalt concrete surface course has been used to predict road fatigue life [5, 10]. When the pavement material is geometrically linear, the pavement displacement can also be used as an evaluation criterion for road damage.

In this work, four criteria are used for evaluating the dynamic interaction between tire and pavement. The pavement displacement and DLC are computed to evaluate the influence of system parameters on the road damage. In addition, RMS of the vertical and pitching vehicle body acceleration are chosen as the criterions for vehicle riding comfort.

8.3 Effects of Vehicle System Parameters

Let the integral step be 0.1 ms and the mode superposition order NM = 20. Effects of vehicle parameters, such as vehicle speed, vehicle load, wheel mass, tire stiffness, suspension stiffness, tire damping, suspension damping, wheelbase and wheel tread, on RMS of the vertical vehicle body acceleration A_1, RMS of the pitching vehicle body acceleration A_2, DLC of the wheels, and the maximum amplitude of the pavement displacement w are obtained. In the DLC results, the square marker stands for the DLC of the front wheel and the circle marker stands for the DLC of the rear wheel.

8.3.1 The Effect of Vehicle Speed

The effect of the vehicle running speed on vehicle riding comfort and pavement damage is shown in Fig. 8.2. It can be seen from Fig. 8.2 that the effect of the vehicle speed on vehicle riding comfort and pavement damage is fluctuant and the front wheel DLC is greater than the rear wheel DLC. The reason for this fluctuation is that the change in road excitation frequency induced by a change in vehicle speed leads to resonance of the vehicle system.

8.3.2 The Effect of Vehicle Load

Figure 8.3 shows the effect of the vehicle load on vehicle riding comfort and pavement damage. It can be seen from Fig. 8.3 that

1. With an increase in the vehicle load, the vertical acceleration of the vehicle body first increases and then decreases, while the pitching acceleration changes a little. Thus, there may exist a load value at which the vehicle's riding comfort is the worst.

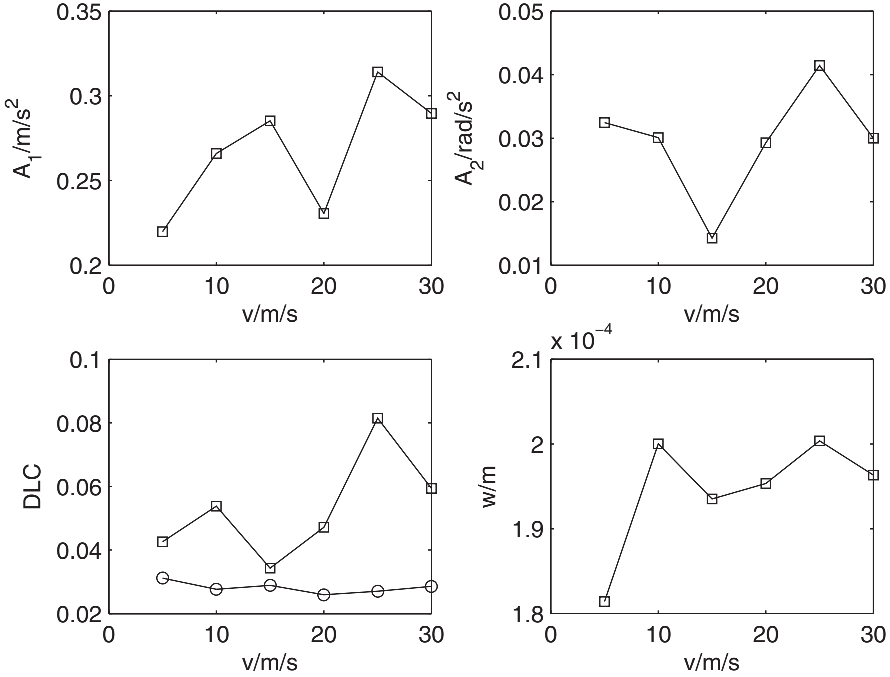

Fig. 8.2 The effect of vehicle speed. Reprinted from ref. [1], with kind permission from Inderscience Enterprises Limited

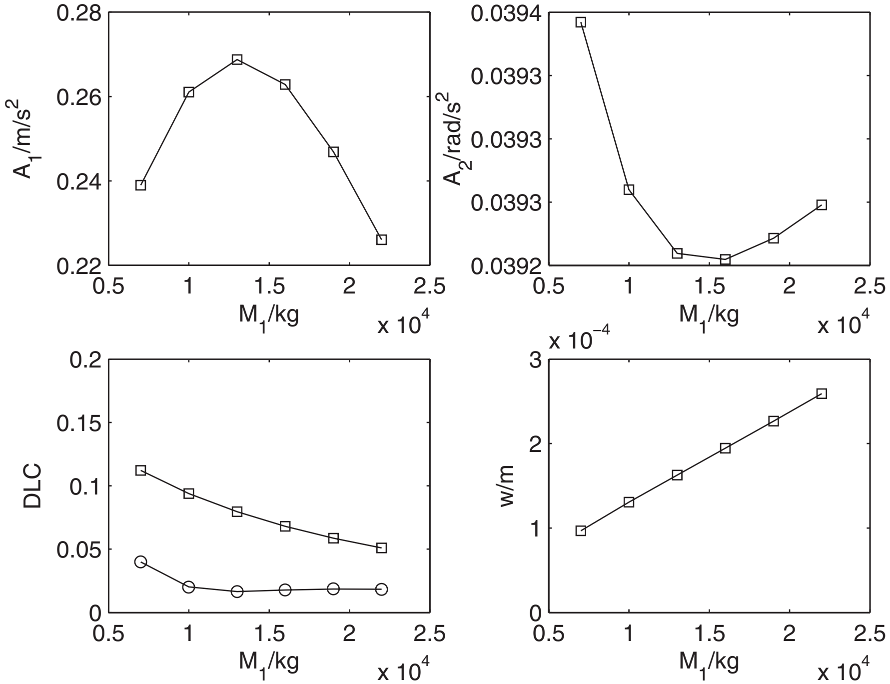

Fig. 8.3 The effect of the vehicle load. Reprinted from ref. [1], with kind permission from Inderscience Enterprises Limited

2. With an increase in the vehicle load, the DLC decreases and the amplitude of pavement displacement increases.

It should be noted that the conclusion concerning the DLC and pavement displacement contradict each other. Many present studies show that the increase of the vehicle load will aggravate the probability of road damage. Hence, it may be said that the pavement displacement is more suitable to be a criterion for road damage than the DLC.

8.3.3 The Effect of Wheel Mass

The effects of the front and rear wheel masses are given in Figs. 8.4 and 8.5.

Figures 8.4 and 8.5 show that

1. With the increase in the front wheel mass, the vertical acceleration of the vehicle body and pavement displacement increases, the front wheel DLC decreases, but the pitch acceleration of the vehicle body rises first and then decreases.
2. With the rise of rear wheel mass, all responses increase, such as the vertical and pitch acceleration of the vehicle body, the front and rear wheel DLC, and the pavement displacement.

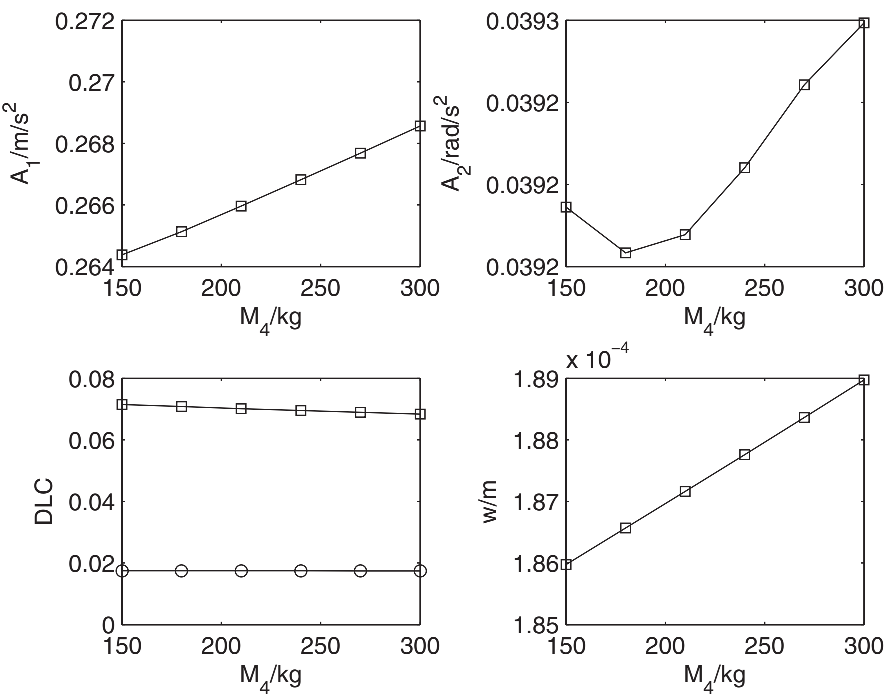

Fig. 8.4 The effect of the front wheel mass

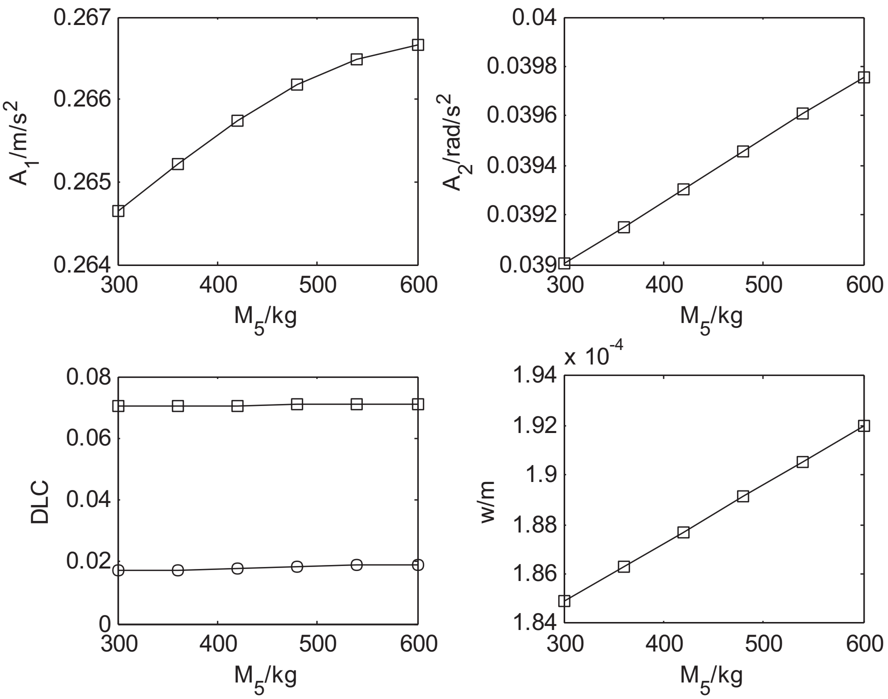

Fig. 8.5 The effect of the rear wheel mass

Thus, a light wheel is beneficial to riding comfort and road fatigue life. However, the design of the wheel mass should also consider other factors, including structure strength and tire–road adhesion characteristics.

8.3.4 The Effects of Tire Stiffness

The effects of the front and rear tire stiffness are shown in Figs. 8.6 and 8.7. From these two figures, it can be seen that

1. The effect of the tire stiffness on vertical acceleration of the vehicle body is contradicted by that on the pitching acceleration of the vehicle body. In order to guarantee vehicle riding comfort, a reasonable value for rear suspension stiffness should be chosen according to a compromise between the vertical and pitching acceleration of the vehicle body.
2. With the increase of front or rear tire stiffness, the DLC of the front or rear wheel and the pavement displacement increase. Moreover, the increase in front tire stiffness hardly influences the DLC of the rear wheel and vice versa. Thus, small tire stiffness contributes to a decrease in road damage.

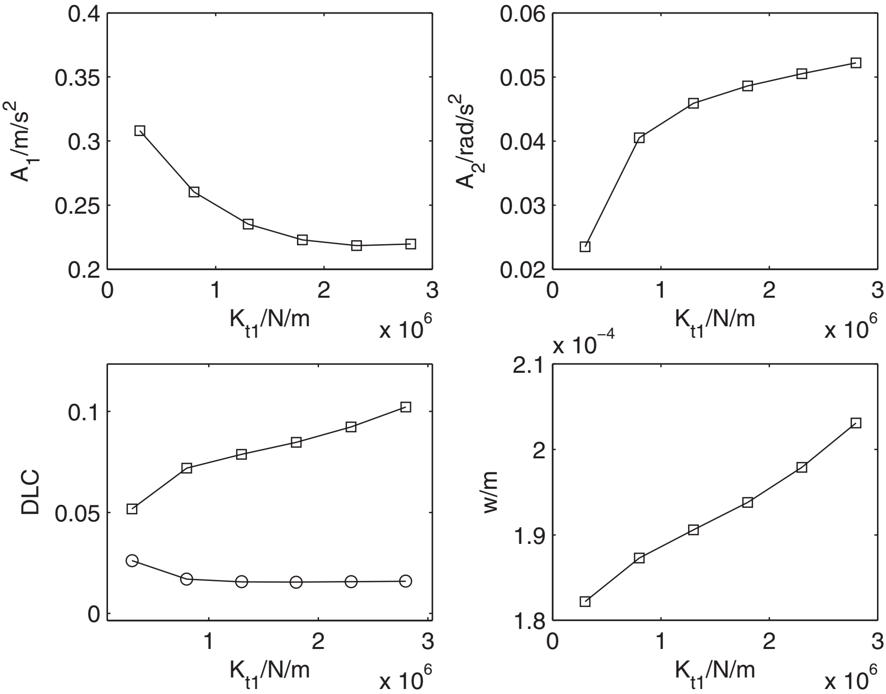

Fig. 8.6 The effect of front tire stiffness

8.3.5 The Effects of Suspension Stiffness

The effects of the front and rear vehicle suspension stiffness are shown in Figs. 8.8 and 8.9. From these two figures, it is found that

1. With the rise in the front suspension stiffness, the vertical and the pitching accelerations of the vehicle body, DLC and pavement displacement all increase. Thus, small front suspension stiffness is a benefit to both vehicle riding comfort and a reduction in road damage.
2. With the rise in rear suspension stiffness, the vertical acceleration of the vehicle body and DLC increase, but the pitching acceleration of the vehicle body decreases slightly, and the pavement displacement first decreases and then increases. Thus, the effect of rear suspension stiffness on riding comfort is complicated and a reasonable value for rear suspension stiffness should be chosen through a trade-off between vertical and pitching accelerations of the vehicle body. In addition, the small rear suspension stiffness may increase road damage.

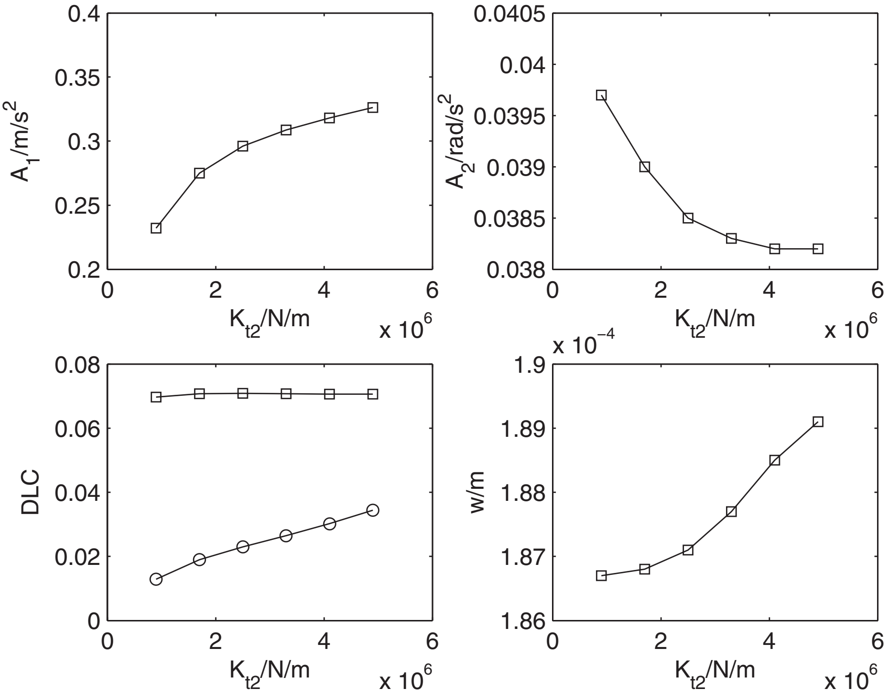

Fig. 8.7 The effect of rear tire stiffness. Reprinted from ref. [1], with kind permission from Inderscience Enterprises Limited

8.3.6 The Effects of Tire Damping

The effects of front and rear tire damping are shown in Figs. 8.10 and 8.11. From these two figures, it is found that

1. With an increase in front or rear tire damping, the vertical and pitch accelerations of the vehicle body decrease which is beneficial to vehicle riding comfort.
2. With an increase in front tire damping, the DLC of the front wheel and the pavement displacement decrease, but the DLC of the rear wheel rises slightly.
3. A rise in rear tire damping leads to an enlargement of pavement displacement, but reduces the DLC of the rear wheel.

Thus, the effect of rear suspension stiffness on riding comfort is complicated and a reasonable value for rear suspension stiffness should be chosen through a trade-off between the vertical and pitching acceleration of the vehicle body. In addition, it should also be noted that the conclusion concerning the DLC and pavement displacement is contradictory. Taking the pavement displacement as a criterion, big front tire damping and small rear tire damping may contribute to a reduction in road damage.

On the other hand, big front or rear tire damping can improve riding comfort.

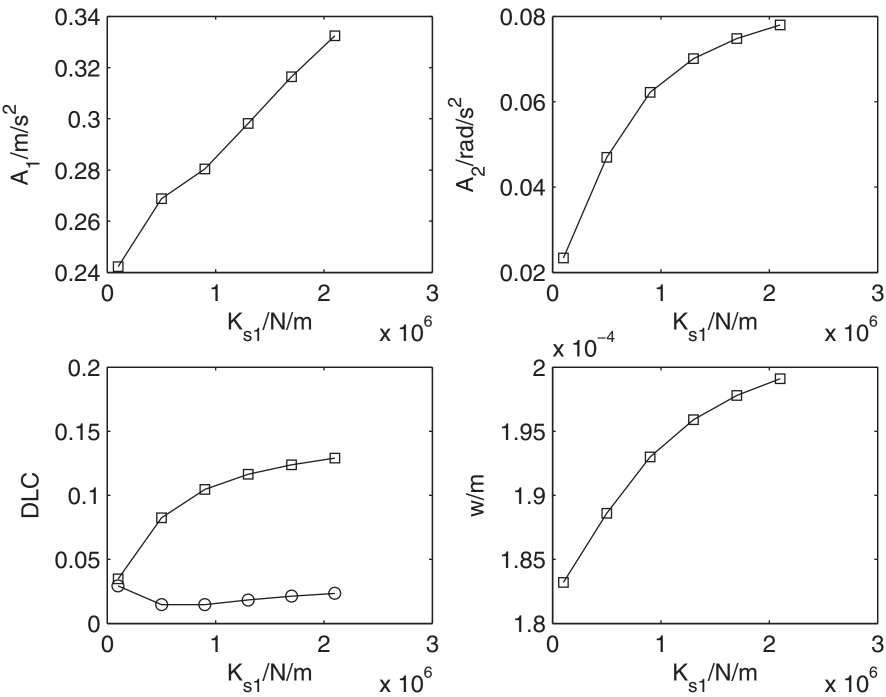

Fig. 8.8 The effect of front suspension stiffness. Reprinted from ref. [1], with kind permission from Inderscience Enterprises Limited

8.3.7 The Effects of Suspension Damping

The effects of front and rear suspension damping are shown in Figs. 8.12 and 8.13. From these two figures, it is found that

1. With the increase of front suspension damping, the vertical acceleration of vehicle body decreases but the pitch acceleration increases.
2. With an increase in front suspension damping, the DLC of the front wheel and the pavement displacement first goes down and then goes up, but the DLC of the rear wheel rises slightly.
3. With an increase in rear suspension damping, the vertical acceleration of the vehicle body increases but the pitch acceleration decreases.
4. With an increase in rear suspension damping, the DLC of the rear wheel and the pavement displacement increase, but the DLC of the rear wheel decreases slightly.

Hence, a small amount of suspension damping is beneficial in reducing road damage. While there exists a most suitable value for the front suspension damping in order to reduce road damage, the effect of suspension damping on comfort is compli-

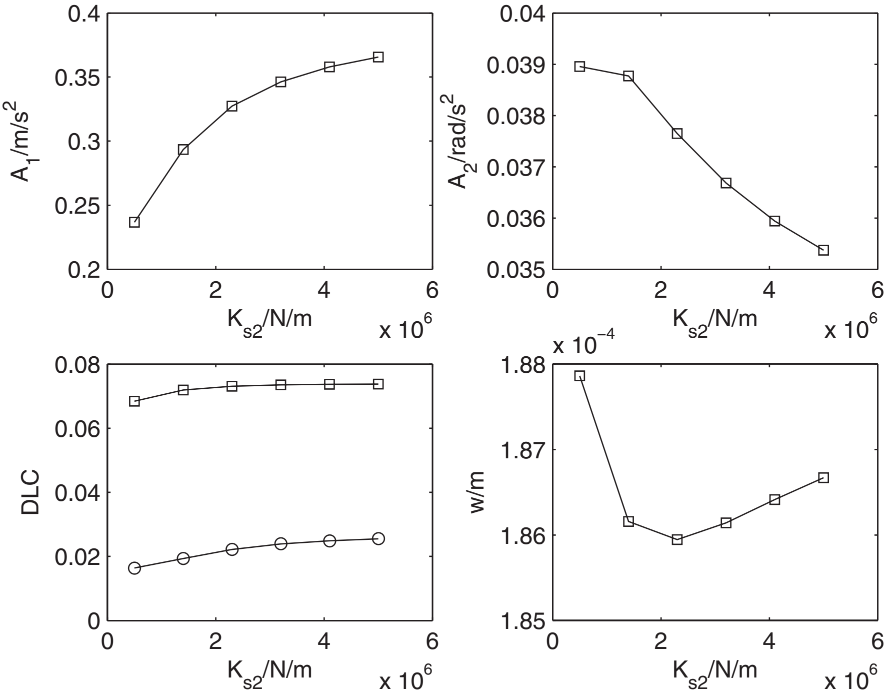

Fig. 8.9 The effect of rear suspension stiffness. Reprinted from ref. [1], with kind permission from Inderscience Enterprises Limited

cated. A reasonable value for rear suspension damping should be chosen according to a compromise between the vertical and pitching acceleration of the vehicle body.

8.3.8 The Effect of Wheelbase

The effect of wheelbase is shown in Fig. 8.14. From Fig. 8.14, it is found that

1. A large wheelbase leads to a small vertical acceleration and a big pitch acceleration for the vehicle body, and a small pavement displacement.
2. An increase in wheelbase will result in the enlargement of the front and rear wheel DLC.

Here, it should also be noted that the conclusion concerning the DLC and pavement displacement is contradictory. Taking the pavement displacement as a criterion, a large wheelbase may contribute to a reduction in road fatigue damage. The effect of wheelbase on riding comfort is complicated. Thus, a reasonable value for the wheelbase should be chosen according to a compromise between the vertical and pitching acceleration of the vehicle body.

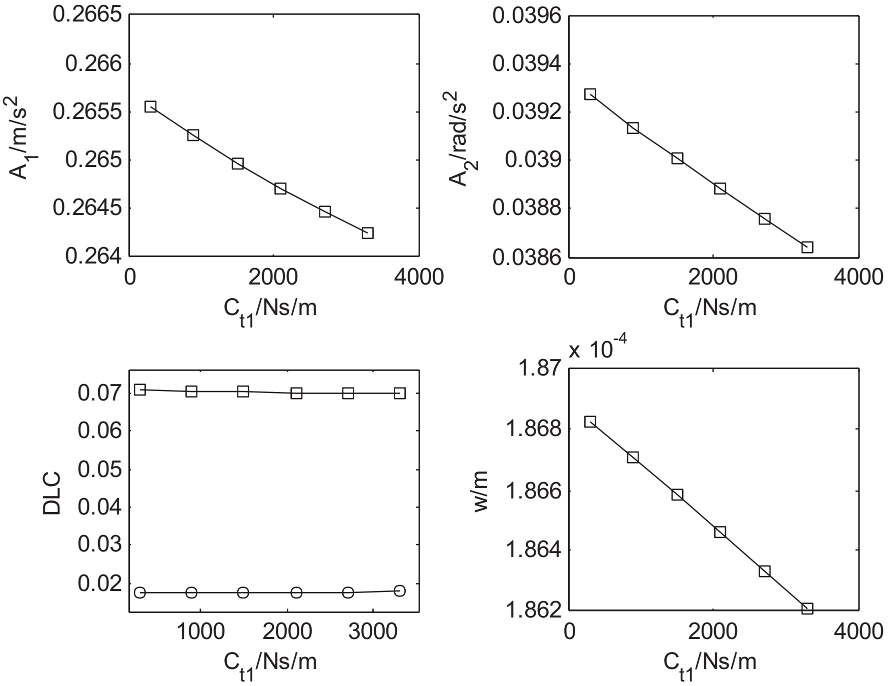

Fig. 8.10 The effects of front tire damping

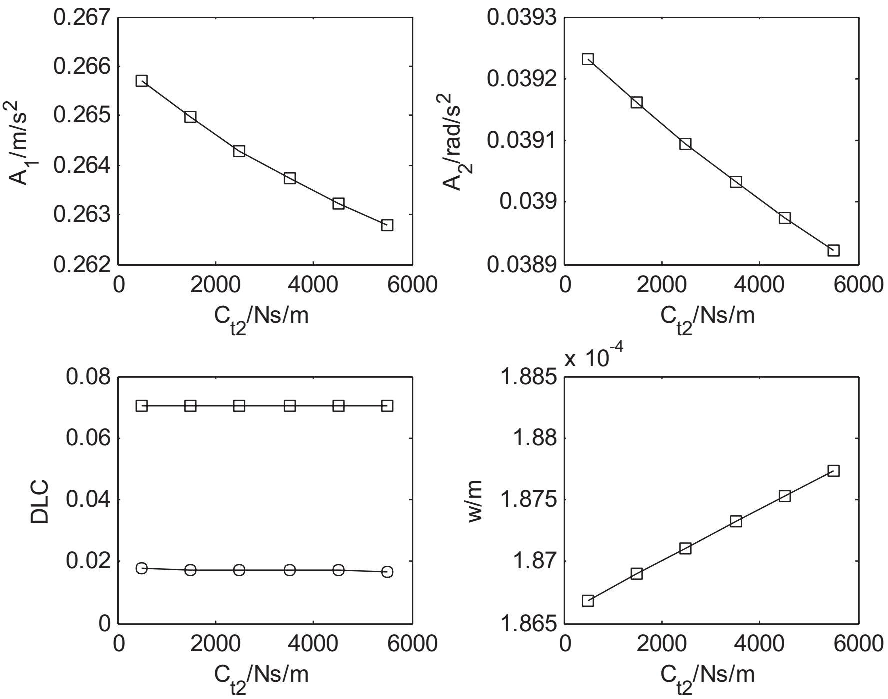

Fig. 8.11 The effects of rear tire damping

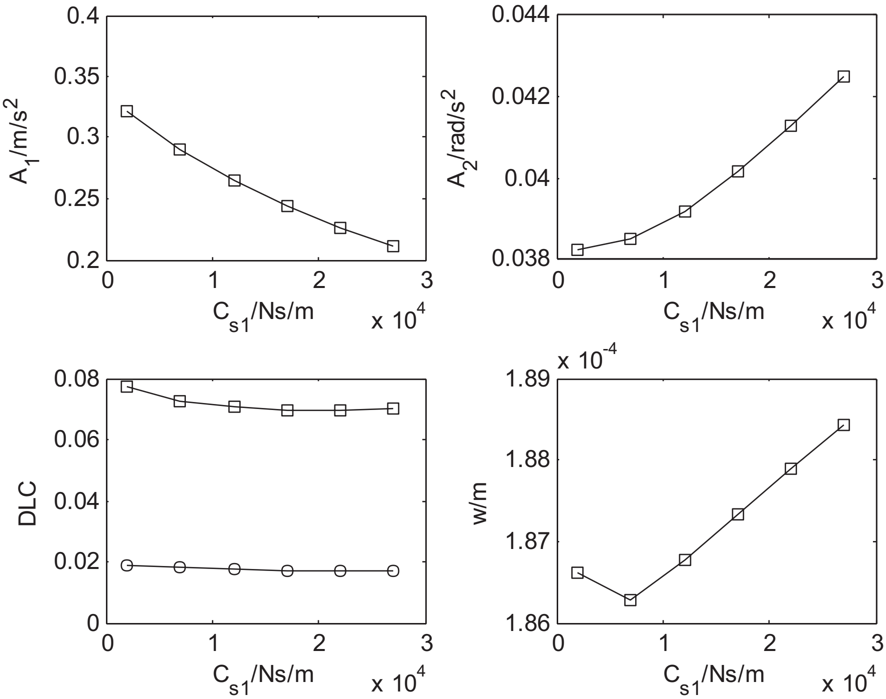

Fig. 8.12 The effects of front suspension damping

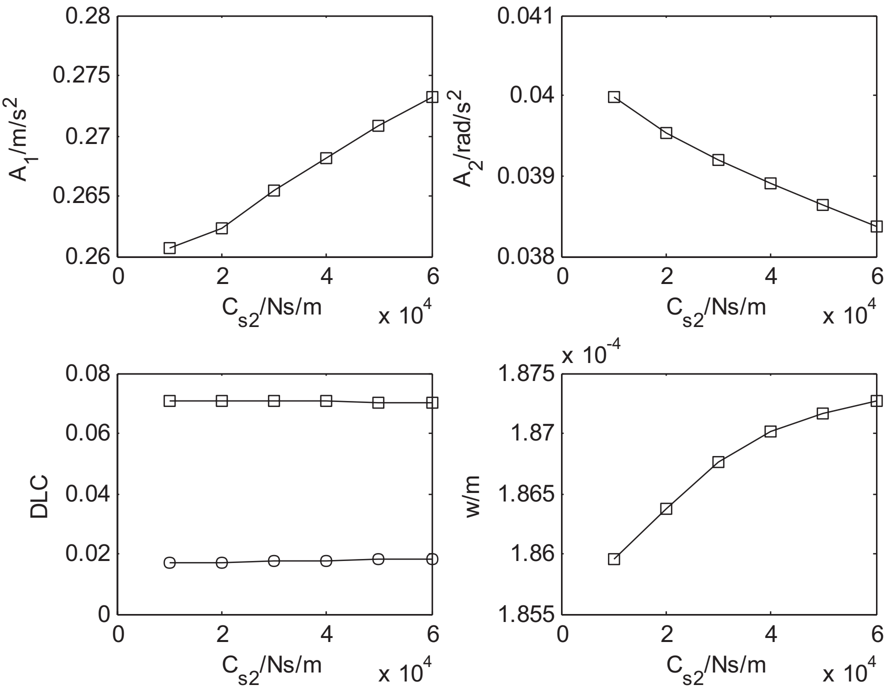

Fig. 8.13 The effects of rear suspension damping

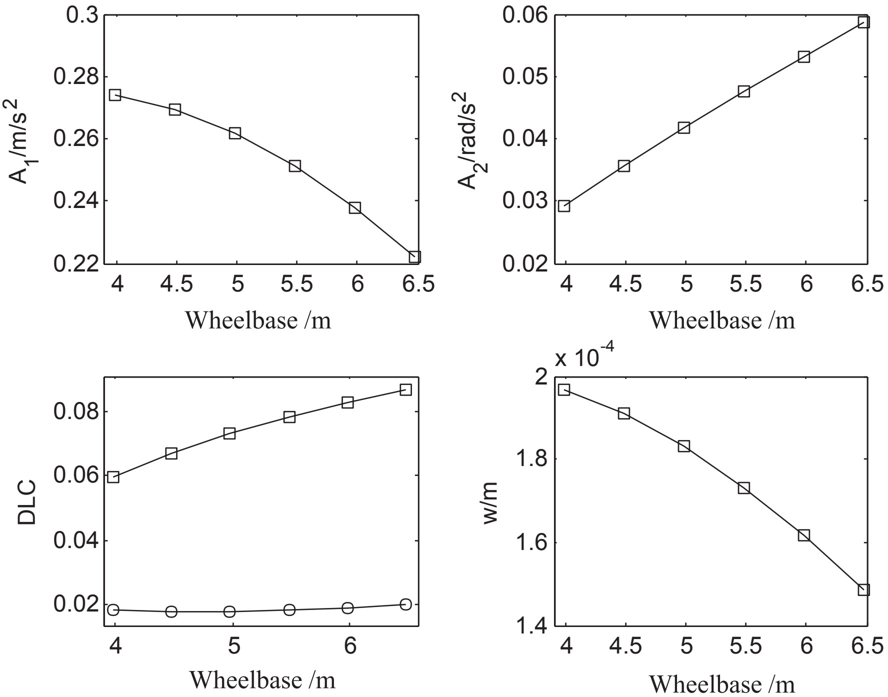

Fig. 8.14 The effect of wheelbase. Reprinted from ref. [1], with kind permission from Inderscience Enterprises Limited

8.3.9 The Effect of Wheel Tread

The effect of wheel tread is shown in Fig. 8.15. From Fig. 8.15, it is found that

1. A large wheel tread leads to a large vertical acceleration and a small pitch acceleration for the vehicle body, but the effect is very small.
2. With an increase in wheel tread, the pavement displacement decreases, the front wheel DLC increases slightly and the rear wheel DLC decreases slightly.

Here, it should also be noted that the conclusion concerning the DLC and pavement displacement is contradictory. Taking the pavement displacement as a criterion, a large wheel tread will improve road fatigue life but does harm to riding comfort.

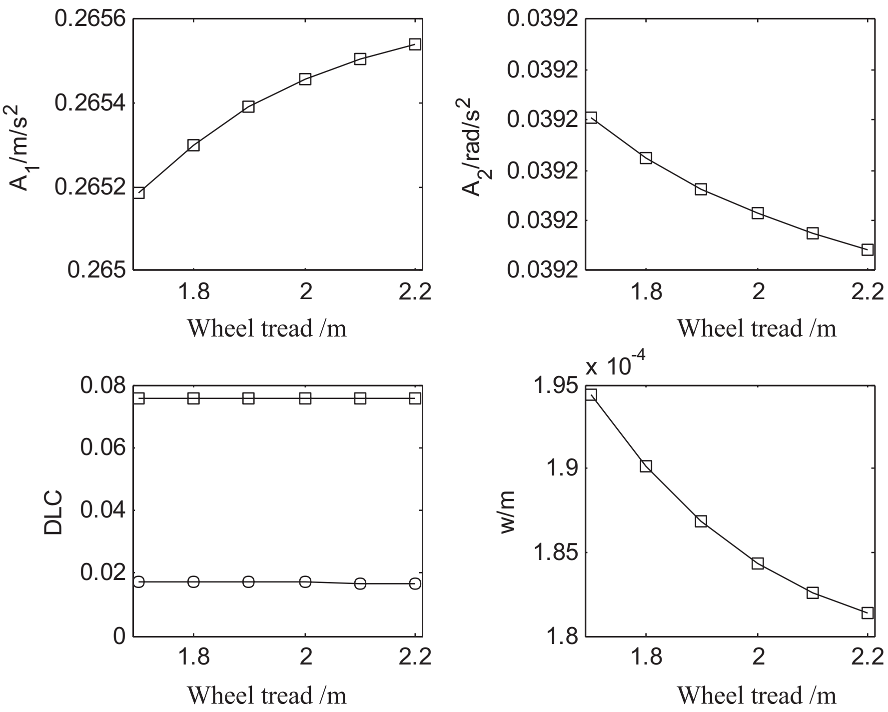

Fig. 8.15 The effect of wheel tread. Reprinted from ref. [1], with kind permission from Inderscience Enterprises Limited

8.4 Effects of Road System Parameters

Effects of road parameters on vehicle riding comfort and road fatigue damage are also obtained, including density, height, elastic modulus, and Poisson ratio of pavement, the foundation response modulus and the foundation damping coefficient. In the DLC results, the square marker stands for the DLC of the front wheel and the circle marker stands for the DLC of the rear wheel.

8.4.1 The Effects of Pavement Density

The effects of pavement density are shown in Fig. 8.16 and 8.17. From these two figures, it is found that

1. The effects of pavement density on vehicle responses, such as the vertical and pitch acceleration of the vehicle body and DLC of the wheels, is slight.
2. With a rise in pavement density, the pavement displacement fluctuates slightly.

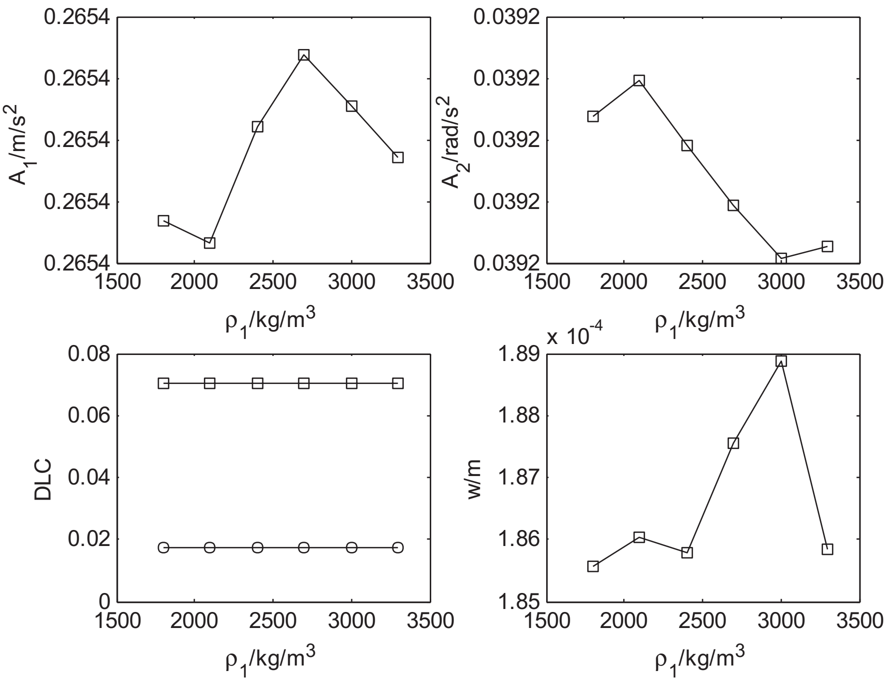

Fig. 8.16 The effect of the topping course density. Reprinted from ref. [1], with kind permission from Inderscience Enterprises Limited

Hence, in order to reduce road damage, the density of the topping and base course should be chosen reasonably and a parameter value inducing peak pavement displacement must be avoided. The effect of the pavement density on riding comfort is too small to be considered.

8.4.2 *The Effects of Pavement Height*

Figures 8.18 and 8.19 show the effects of the pavement topping height and base course height. From these two figures, it can be noted that

1. With an increase in the topping or base course height, the vertical acceleration of the vehicle body increases. But the effect of these two parameters on the pitching acceleration of the vehicle body is slight.
2. With an increase in the topping or base course height, the DLC of the front wheel increases and the DLC of the rear wheel changes slightly.
3. An increase in the topping or base course height leads to a decrease in the pavement displacement.

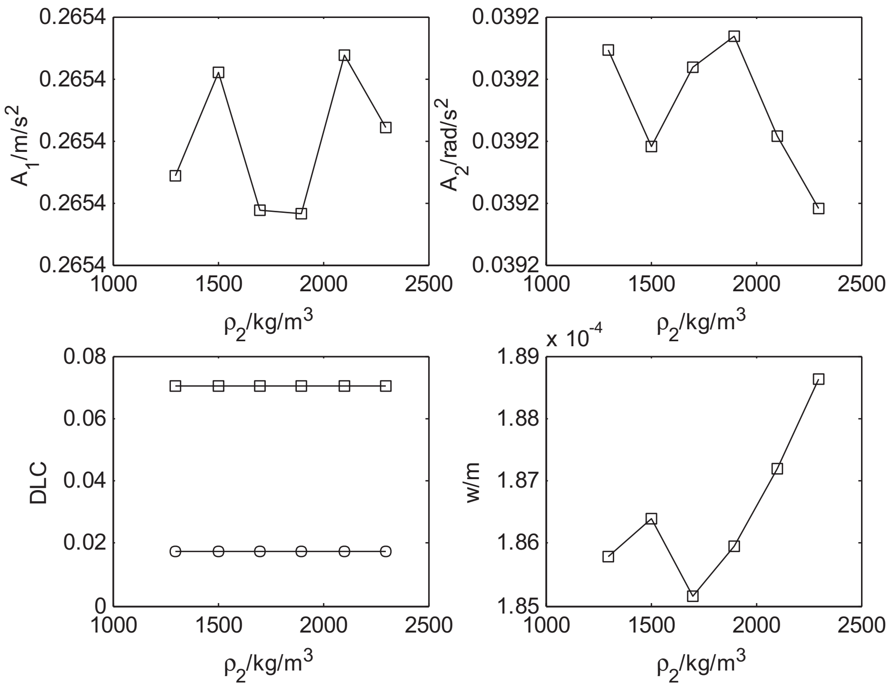

Fig. 8.17 The effect of the base course density. Reprinted from ref. [1], with kind permission from Inderscience Enterprises Limited

Thus, a large topping or base course height contributes to a decrease in road damage but does harm to riding comfort.

8.4.3 The Effects of Elastic Modulus

Figures 8.20 and 8.21 show the effects of the pavement elastic modulus. From these two figures, it can be noted that

1. With an increase in the topping or base course elastic modulus, the vertical acceleration of the vehicle body increases. But the effect of these two parameters on the pitching acceleration of the vehicle body is slight.
2. With an increase in the topping or base course elastic modulus, the DLC of the front wheel increases and the DLC of the rear wheel decreases slightly.
3. An increase in the topping or base course elastic modulus leads to a decrease in the pavement displacement.

Taking the pavement displacement as a criterion, a large topping or base course elastic modulus will improve road fatigue life but do harm to riding comfort.

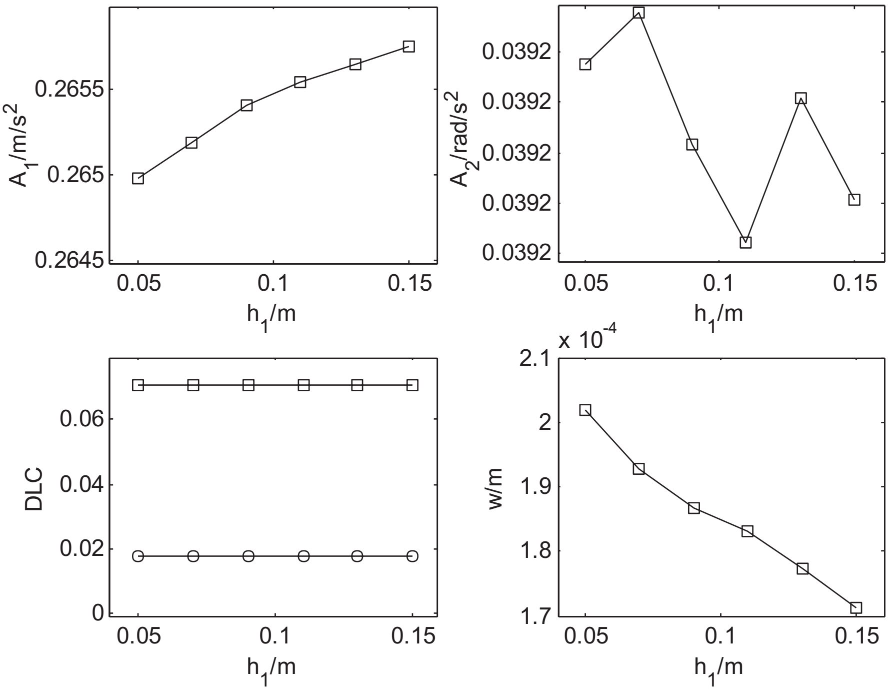

Fig. 8.18 The effect of the topping course height

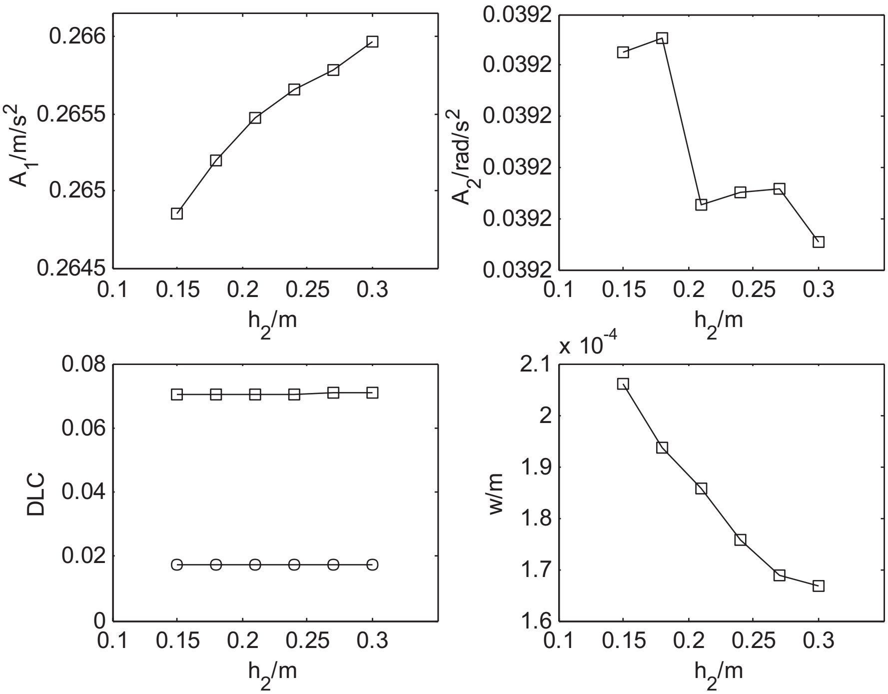

Fig. 8.19 The effect of the base course height

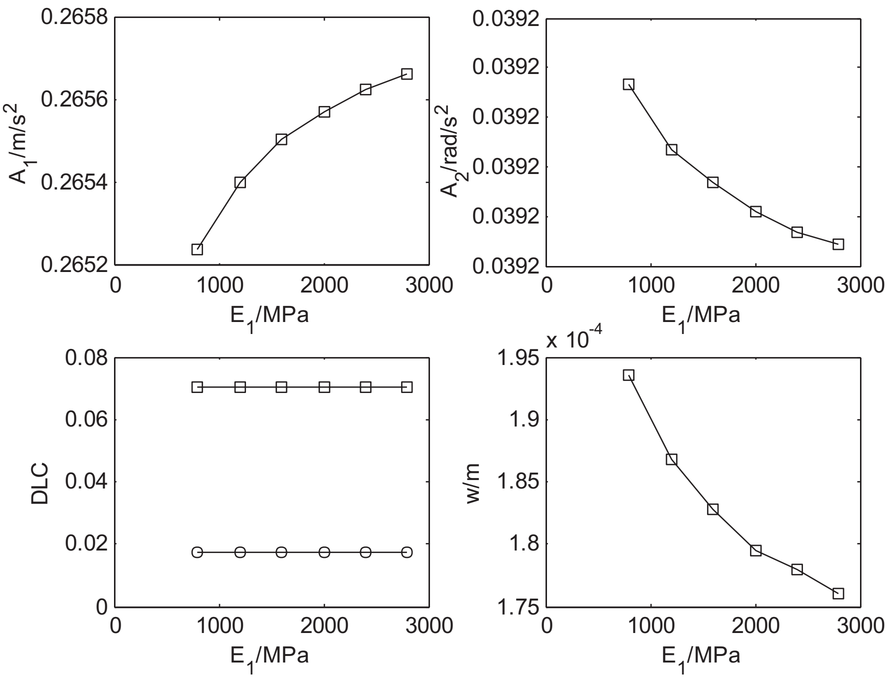

Fig. 8.20 The effect of the topping course elastic modulus

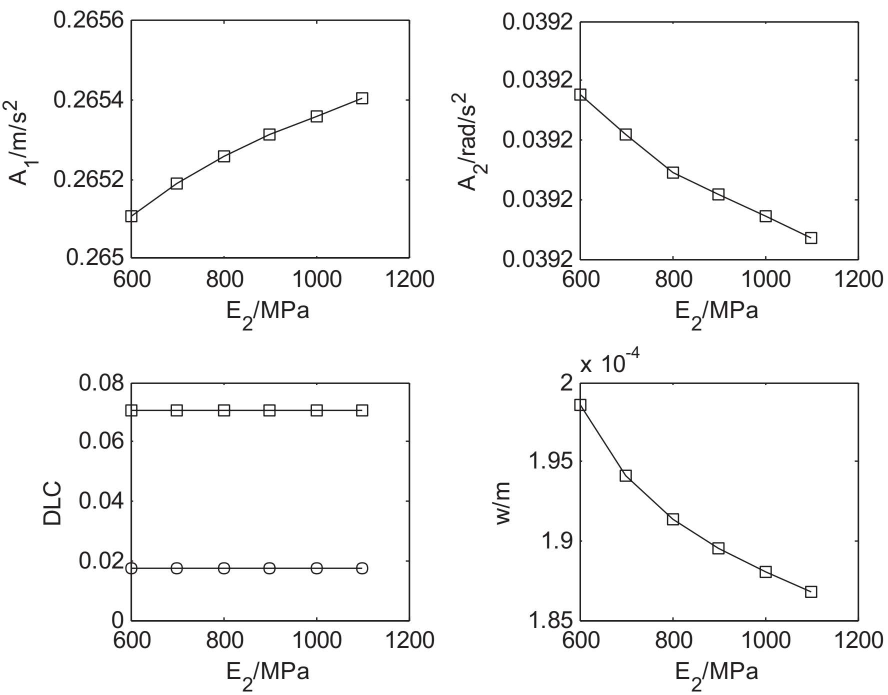

Fig. 8.21 The effect of the base course elastic modulus

8.4.4 The Effects of the Pavement Poisson Ratio

Figures 8.22 and 8.23 show the effects of the pavement Poisson ratio. From these two figures, it can be found that

1. With an increase in the topping or base course Poisson ratio, the vertical acceleration of the vehicle body increases. But the effect of these two parameters on the pitching acceleration of the vehicle body is slight.
2. With an increase in the topping or base course elastic modulus, the DLC of the front wheel increases and the DLC of the rear wheel decreases slightly.
3. An increase in the topping or base course elastic modulus leads to a decrease in the pavement displacement.

Taking the pavement displacement as a criterion, a large topping or base course Poisson ratio will improve road fatigue life but do harm to riding comfort.

8.4.5 The Effect of the Foundation Response Modulus

The effect of the foundation response modulus is shown in Fig. 8.24. It can be seen that

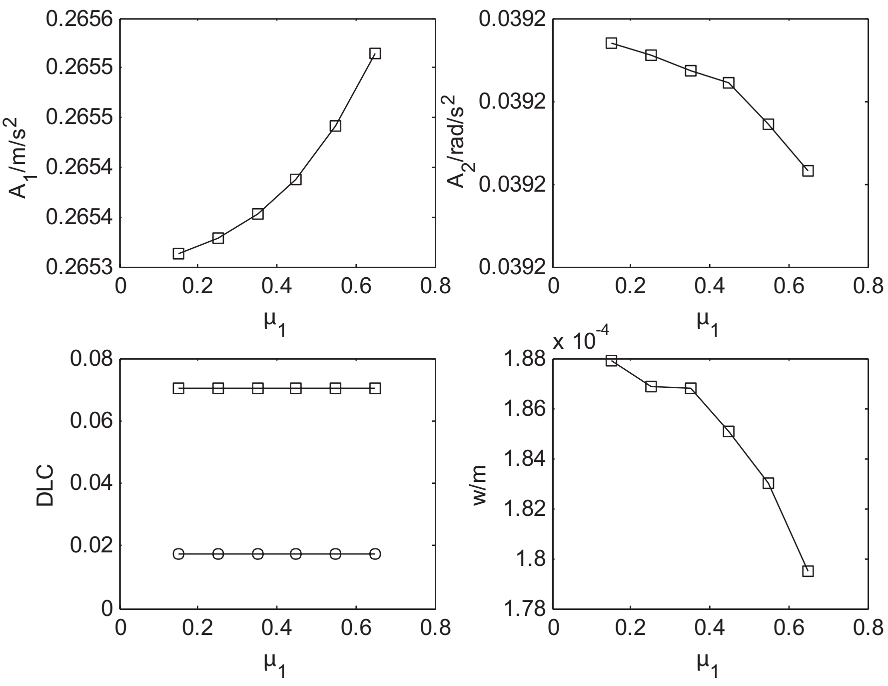

Fig. 8.22 The effect of the topping course Poisson ratio

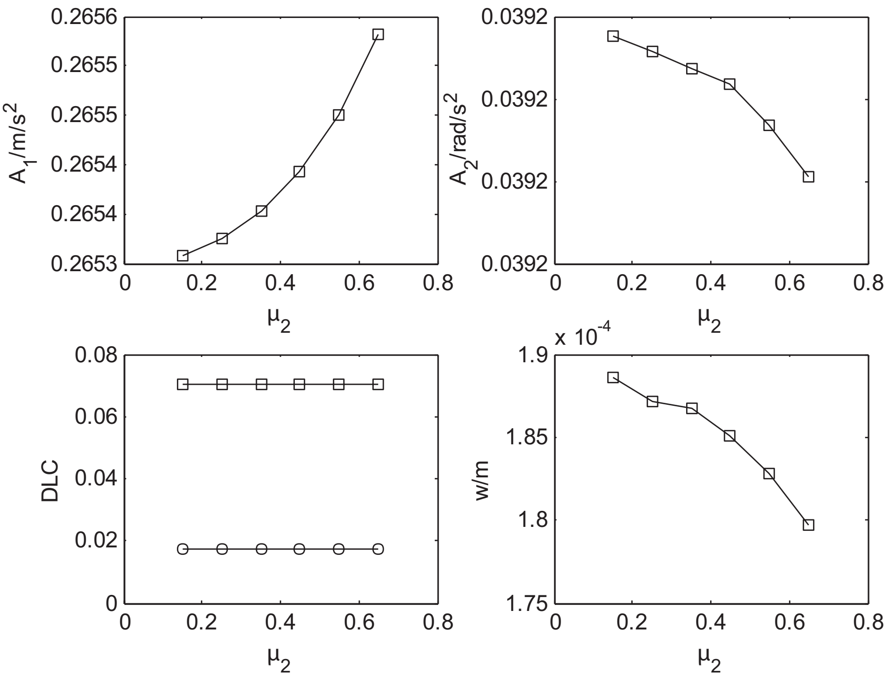

Fig. 8.23 The effect of the base course Poisson ratio

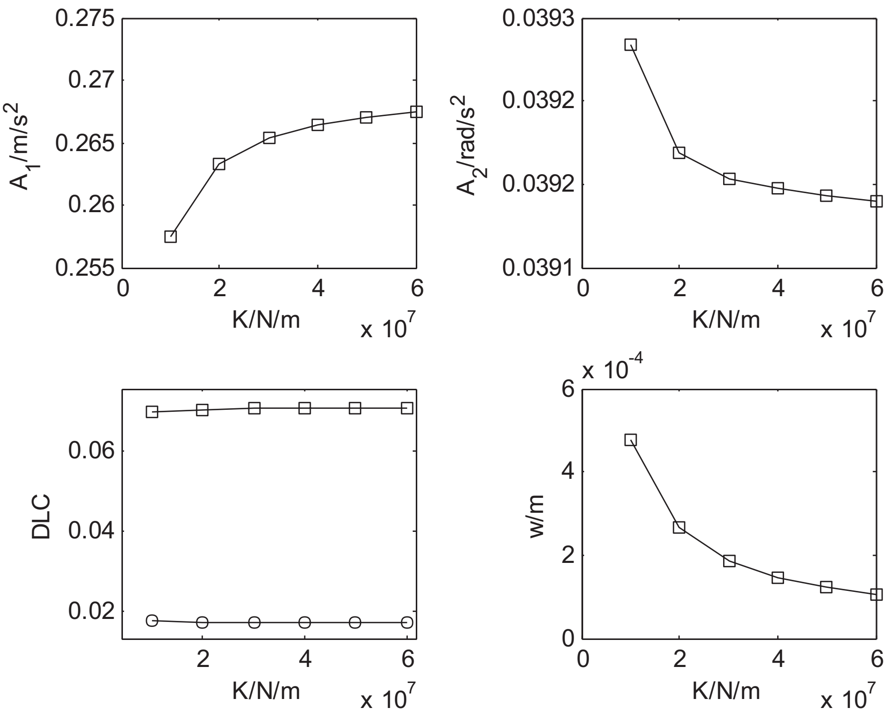

Fig. 8.24 The effect of the foundation response modulus

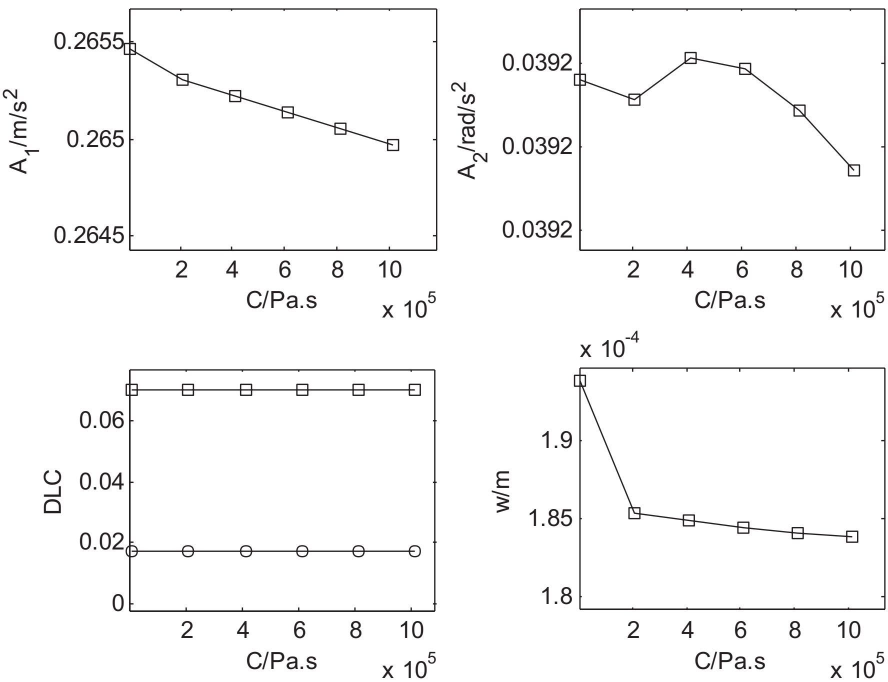

Fig. 8.25 The effect of the foundation damping coefficient

1. With an increase in the foundation response modulus, the vertical acceleration of the vehicle body increases, but the pitching acceleration of the vehicle body decreases.
2. With an increase in the foundation response modulus, the DLC of the front wheel increases and the DLC of the rear wheel decreases slightly.
3. An increase in the foundation response modulus results in a reduction of the pavement displacement.

Taking the pavement displacement as a criterion, a large foundation response modulus is beneficial to road fatigue life but harmful to riding comfort.

8.4.6 The Effect of the Foundation Damping coefficient

The effect of the foundation damping coefficient is shown in Fig. 8.25. It can be seen that

1. With an increase in the foundation damping coefficient, the vertical acceleration of the vehicle body decreases, but the pitching acceleration of the vehicle body only varies slightly.

2. With an increase in the foundation damping coefficient, the DLC of the front and rear wheel decreases slightly, and the pavement displacement also decreases.

Hence, a large foundation damping coefficient is beneficial to both road fatigue life and riding comfort.

8.5 Chapter Summary

In this chapter, vehicle–road coupled system is compared with the finite element model first so as to verify the validity of this coupled system. Then the effects of the vehicle–road coupling and system parameters on vehicle riding comfort and road fatigue damage were analyzed. Some rules of choosing parameters for low dynamic action can be suggested that

1. The effect of vehicle running velocity on vehicle riding comfort and pavement damage is fluctuant. Thus, those velocities inducing the maximum of vehicle body acceleration or pavement displacement should be calculated beforehand and drivers should be informed the risk of these velocities.
2. Increase of the vehicle load may further intensify road damage. However, there exists an unreasonable load value near to half gauge load which will induce resonance of vehicle body and be harmful to riding comfort.
3. It is favorable to decrease tire stiffness or suspension stiffness for controlling road damage. Increase of wheel track or wheelbase also leads to the decrease of road damage.
4. In order to improve riding comfort, the suspension stiffness should be decreased and the tire damping increased. Effects of wheel track, wheelbase, and tire stiffness on vertical acceleration of vehicle body contradict with that on pitching acceleration of vehicle body. Thus, the effect of these three parameters on ride comfort is complex.
5. Increase of topping height, base course height, topping density, base course density, topping Poisson ratio, base course Poisson ratio, or foundation response modulus is favorable to both improving ride comfort and decreasing road fatigue damage.

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