

Impact of Road Conditions on the Normal Reaction Forces on the Wheels of a Motor Vehicle Performing a Straightforward Braking Maneuver

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Abstract. In the paper analysis is presented, which concerns the impact of both the road surface condition and the change in a vehicle model center of mass location on the course of the normal reaction forces, acting on the wheels versus the distance travelled during the braking maneuver. The road was flat in one case, and randomly uneven in the other.

Research was based on the simulation of a motor vehicle model in MSC Adams/Car, for two different road conditions, with braking starting from the speed of 100 km/h. Such attempt enabled analysis of the influence of both mass – inertia and road condition on the wheel normal forces. The results may as well serve as a cognitive element, showing the specifics and the range of changes in the derived parameters.

Keywords: Normal reaction forces · Brake maneuver · Road conditions

1 Introduction

The aspect of motor vehicle safety seem to be an important issue in research on dynamics of the means of transport, particularly considering the motion in difficult road conditions. From the point of view of different types of road users the motor vehicle safety seems to be a key element in terms of traffic disturbances.

One of the issues often analysed is the problem of the contact between the wheels and a road surface. In the papers devoted to it the following aspects, among others, were distinguished:

- the problem of radial elasticity of tires rolling on flat and uneven surfaces (e.g. [1, 10, 12]);
- normal (perpendicular to the road surface) reaction forces of the road surface on the wheels (e.g. [6, 7, 9]);
- forces occurring in the contact plane between the wheel and the road (e.g. [2, 5, 8]), causing e.g. the lateral drift or slip.

In this paper attention was paid to the issue of changes in the values of the normal reaction forces on the wheels of a sports vehicle model, which rode along a straight line, realising the braking maneuver. In relation to that, analysis was conducted on the

influence of road conditions and load of the selected motor vehicle model on the course of the normal reaction forces on the wheels as a function of distance traveled during the completion of the braking maneuver along a straight line. Such research can be carried out on real objects, however it generates additional logistical problems, simultaneously extending time and increasing costs.

In further parts of the paper, by mentioning the normal reaction forces, the author means the resultant forces in the area of contact between road and tire, perpendicular to the road surface.

2 The Assumptions for the Simulation

In order to determine the changes in the road surface normal reaction forces on the wheels of a braking vehicle a simulation was conducted in the MSC Adams/Car environment. The following assumptions were taken:

- the vehicle model has nonlinear characteristics of spring - damping suspension elements, as in [12], and its body is treated as a quasi-rigid solid;
- vehicle model starts braking at the speed of 100 km/h on the fifth gear;
- the motion during braking is rectilinear;
- the brake value was set at 10, which is relevant to the vertical pressure on the brake pedal, and the time of reaching that value was set at 1 s;
- the weight distribution in the vehicle body is illustrated in Figs. 1 and 2.

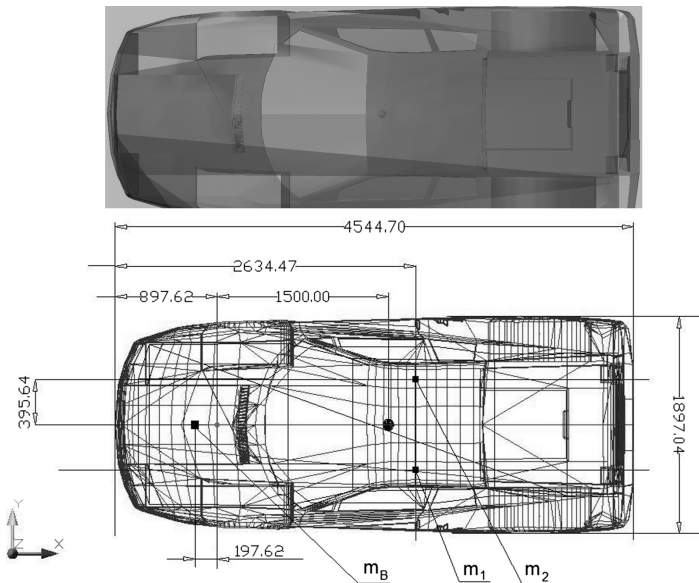


Fig. 1. Projection of the sports vehicle model body from the top along with the dimensions and location of the driver, passenger and baggage [own study]

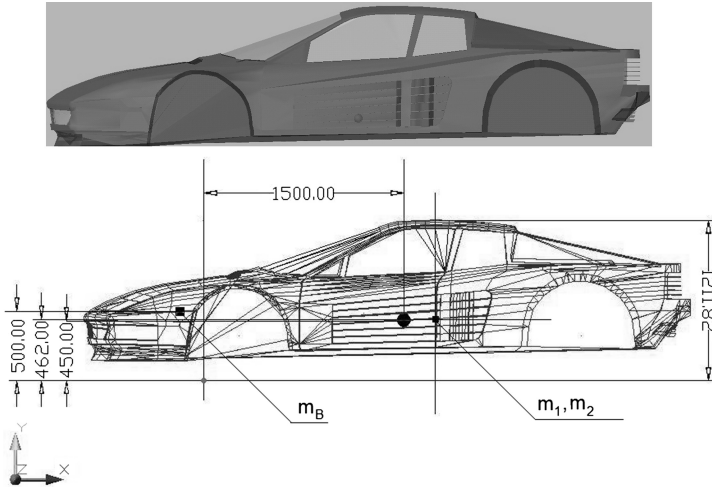


Fig. 2. Projection of the sports vehicle model body from the left side [own study]

The simulation was prepared for four configurations:

- unladen vehicle on a dry, flat road surface with a coefficient of friction between wheels and road $\mu = 0.8$;
- unladen vehicle on a dry and uneven road surface ($\mu = 0.8$), where the surface irregularities occur randomly;
- vehicle laden with a driver, a passenger and a baggage (Figs. 1 and 2) on a dry, flat road surface with a coefficient of friction $\mu = 0.8$;
- vehicle laden as above, moving on a dry and uneven road surface ($\mu = 0.8$) also with randomly occurring inequalities;

3 Selected Model of the Motor Vehicle

The motor vehicle model used in the simulation was previously described e.g. in [12]. It is a model of a two-seater sports vehicle with the drive unit located above the rear axle. The model is available in the database of the MSC Adams/Car software. The load consisted of three masses representing the driver (m_1), the passenger (m_2) and the baggage (m_B), distributed in the vehicle as shown in Figs. 1 and 2. The mass-inertia disturbances were derived according to the so-called “origo” [12], which represents the origin of a coordinate system associated with the road, but moving along with the vehicle during motion. The coordinates of the center of mass is also relative to the point “origo”.

Selected parameters of the vehicle body and the vehicle as a whole before adding the load are as follows:

- total mass of the vehicle body $m_{VB} = 995\text{kg}$ and of the whole vehicle $m_V = 1528\text{kg}$;

- coordinates of the center of mass of the vehicle body relative to the point “origo”:
 $x_c = 1,5 m$, $y_c = 0$, $z_c = 0,45 m$;
- coordinates of the center of mass of the vehicle relative to the point “origo”:
 $x_c = 1,75 m$, $y_c = -0,001 m$, $z_c = 0,43 m$;
- moments of inertia of the vehicle body relative to the axes passing through the “origo”: $I_{xx} = 401 kg \cdot m^2$, $I_{yy} = 2940 kg \cdot m^2$, $I_{zz} = 2838 kg \cdot m^2$;
- moments of inertia of the vehicle relative to the axes passing through the “origo”:
 $I_{xx} = 583 kg \cdot m^2$, $I_{yy} = 6129 kg \cdot m^2$, $I_{zz} = 6022 kg \cdot m^2$;
- moments of deviation of the vehicle body relative to the axes passing through the “origo”: $I_{xy} = 0$, $I_{zx} = 671 kg \cdot m^2$, $I_{yz} = 0$;
- moments of deviation of the vehicle relative to the axes passing through the “origo”:
 $I_{xy} = -1,9 kg \cdot m^2$, $I_{zx} = 1160 kg \cdot m^2$, $I_{yz} = -1,3 kg \cdot m^2$.

The following configuration of the vehicle body load was adopted. It was assumed that the body is loaded with the masses representing the driver ($m_1 = 70 kg$), the passenger ($m_2 = 70 kg$) and the baggage ($m_B = 50 kg$). Selected parameters of the vehicle body after loading were as follows:

- total mass of the vehicle body $m'_{VB} = 1185 kg$ and of the vehicle $m'_V = 1718 kg$;
- coordinates of the center of mass of the vehicle body relative to the point “origo”:
 $x'_c = 1,456 m$, $y'_c = 0$, $z'_c = 0,454 m$;
- coordinates of the center of mass of the vehicle relative to the point of “origo”:
 $x'_c = 1,69 m$, $y'_c = 0$, $z'_c = 0,43 m$;
- moments of inertia of the vehicle body relative to the axes passing through the “origo”: $I'_{xx} = 444 kg \cdot m^2$, $I'_{yy} = 3256 kg \cdot m^2$, $I'_{zz} = 3112 kg \cdot m^2$;
- moments of inertia of the vehicle relative to the axes passing through the “origo”:
 $I'_{xx} = 626 kg \cdot m^2$, $I'_{yy} = 6445 kg \cdot m^2$, $I'_{zz} = 6295 kg \cdot m^2$;
- moments of deviation of the vehicle body relative to the axes passing through the “origo”: $I'_{xy} = 0$, $I'_{zx} = 783 kg \cdot m^2$, $I'_{yz} = 0$;
- moments of deviation of the vehicle relative to the axes passing through the “origo”:
 $I'_{xy} = -1,9 kg \cdot m^2$, $I'_{zx} = 1272 kg \cdot m^2$, $I'_{yz} = -1,3 kg \cdot m^2$.

4 Disturbances Coming from the Road Surface

Braking examination of a vehicle model from a speed of 100 km/h was carried out for the road with both a flat and dry, and an uneven (the irregularities occurred randomly) and dry surface. Disturbances coming from the road were realised using the “2d_stochastic_uneven.rdf” file, which describes the random surface irregularities using the function described in Adams/Car as ARC 901 [11].

Randomly occurring road irregularities are obtained as follows. First, white noise signals are generated on the basis of random variables with almost uniform distribution. Two of those variables are assigned to the road at a distance of every 10 mm. The obtained values are integrated over the road length, using the time-discrete filter, whose independent variable is the road. The result of this operation is the obtaining of two

approximated realisations of the white noise velocity. Signals of such properties make the road profiles having the waviness equal to 2 (waviness for the measured wave spectral density of the roads is in the range between 1.8 and 2.2 [4]).

Then the two realisations $z_1(s)$, $z_2(s)$ are correlated in order to obtain a profile of the road for the left and right wheels $z_l(s)$, $z_r(s)$ (1). The correlation coefficient is 0 for two different profiles, and 1 for the same. In the file defining the road profile with random irregularities the value of the correlation coefficient was assumed equal to 1.

$$\begin{aligned} z_l(s) &= z_1(s) + \frac{corr_{rl}}{2}(z_2(s) - z_1(s)) \\ z_r(s) &= z_2(s) + \frac{corr_{rl}}{2}(z_2(s) - z_1(s)), \end{aligned} \quad (1)$$

where: $corr_{rl}$ - correlation coefficient between the road profiles for the realisation of the signals $z_1(s)$, $z_2(s)$.

As it can be seen, random irregularities of the road are described as realisations of the white noise velocity, which is a stochastic process. In order to be used in the simulation of motion, where the expected result is a trajectory, those realisations must be a stochastic process with the properties: stationary in a broader sense and globally ergodic. Both of these characteristics are satisfied here, because each of the realisations is a signal representing the road profile for the left and right wheels. In addition, these signals have a length of the road as a specificity domain, which made it necessary to take the stochastic process into account as a component describing unevenness of the roads [3].

In the described vehicle model, the default model of tires, PAC89, was removed, because it was unable to cooperate with the road surface, for which the wavelength of the irregularities is smaller than the radius of the rolling wheel [11]. Instead the FTIRE model (flexible structure tire model), consisting of panels connected to each other with the deformable spring elements, was used. The panels may deform in three mutually perpendicular direction (Fig. 3).

5 Simulation of the Brake Maneuver

Simulation of the brake maneuver was carried out at an initial speed of 100 km/h for each configuration described in p. 2. For each configuration four trajectories were obtained, which are presented in Figs. 4, 5, 6 and 7. The MSC Adams/Car 2005r2 software was used, however without the built-in solvers to solve the sets of equations of motion for the presented vehicle model and its components. Instead, an external solver assigned to Adams, but not embedded in the package was used, making it possible to perform calculations in the ordinary command window, rather than directly in the Adams/Car interface, which reduced the use of the operative memory. Of course, in this case it is necessary to generate certain executable files that enable calculation somewhat outside of the program. These files are obviously generated in the Adams/Car environment.

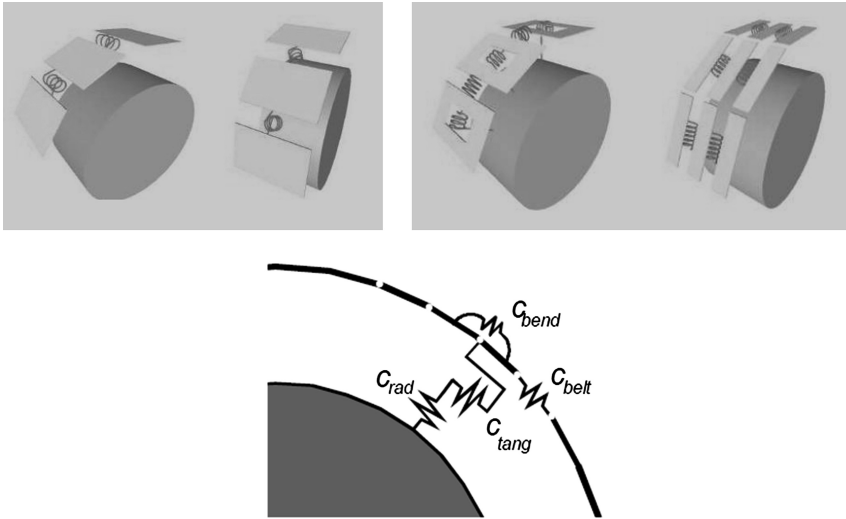


Fig. 3. Scheme of the FTIRE model for the deformation in radial, transverse and circumferential direction [13]

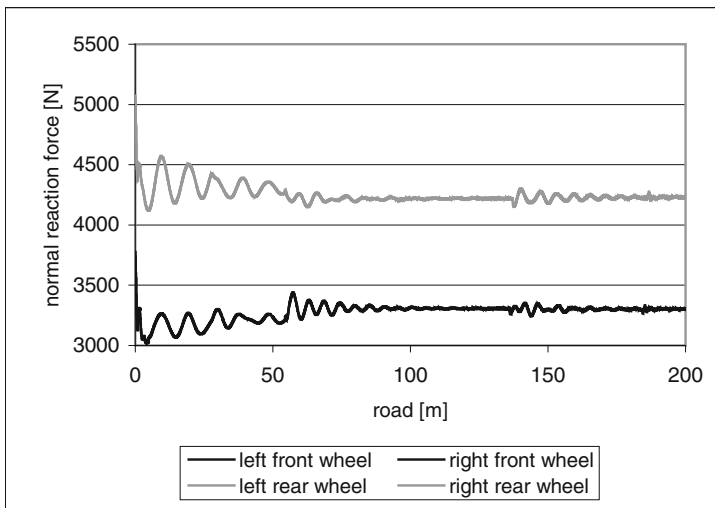


Fig. 4. The normal reaction forces on wheels of the unladen vehicle model as a function of distance traveled during braking on a flat, dry road surface [own study]

In all configurations the vehicle model has traveled for about 200 m during the simulation, which lasted 10 s. The road length resulted from the low pressure on the brake pedal of the vehicle model. In this case more important was to track changes in the normal reaction forces for each wheel than the braking effectiveness. Another important issue was the time of increasing the pressure on the brake pedal to its

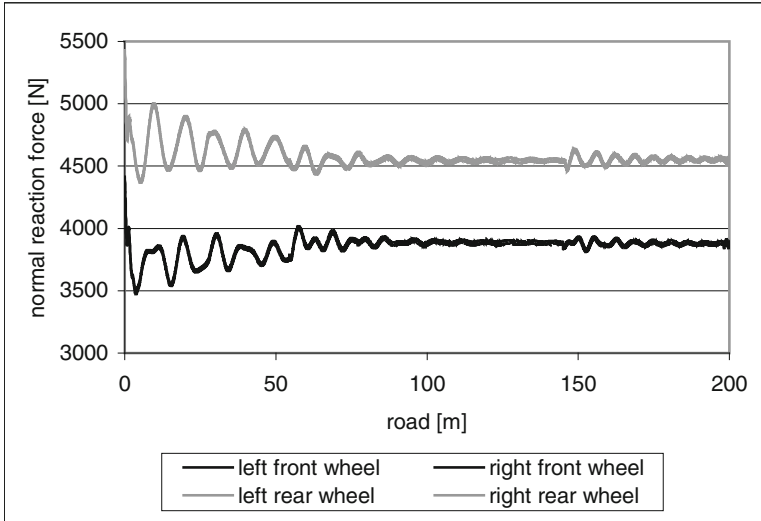


Fig. 5. The normal reaction forces on wheels of the laden vehicle model as a function of distance traveled during braking on a flat, dry road surface [own study]

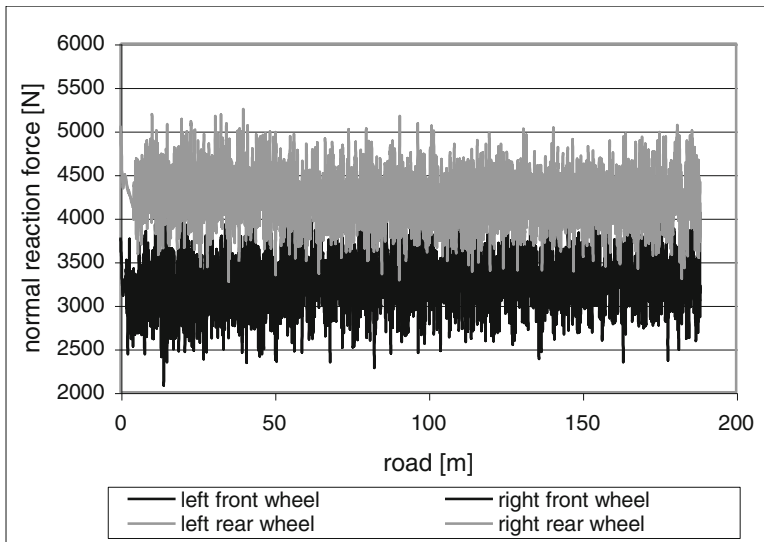


Fig. 6. The normal reaction forces on wheels of the unladen vehicle model as a function of distance traveled during braking on an uneven, dry road surface. [own study]

maximum value, which lasted 1 s. In the simulation of the laden vehicle, with random disturbances coming from the uneven road, braking distance was shorter by about 10 m due to an error in calculations for low speed motion at the end of the maneuver, when the laden vehicle model travelled at low speed.

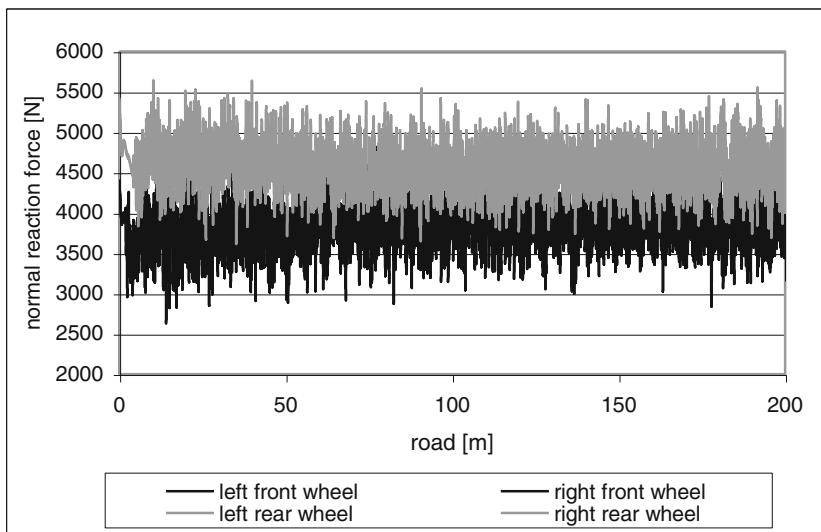


Fig. 7. The normal reaction forces on wheels of the laden vehicle model as a function of distance traveled during braking on an uneven, dry road surface [own study]

6 Analysis of the Obtained Results

By analysing the results a qualitative assessment of the received trajectories has been made. It shows that during braking on a flat road the normal reaction force values stabilize after driving a particular part of the road, and the deflection of the mean value in the second half of the braking distance is negligible. Regarding the impact of random road surface irregularities the amplitudes of normal reaction force search the peak values over the entire length of the braking road. Note, however, that for uniform loading of the vehicle the course of road surface reaction as a functions of the distance covered is moderately uniform.

A quantitative assessment of the values of the road surface normal reaction forces on the wheels was also prepared. In tab. 1 the mean values of reaction forces for each wheel are shown, as well as the maximum amplitude of these values for each wheel in the presented road conditions and for the laden and unladen vehicle model.

From the values presented in Table 1 it can be seen that when braking the unladen vehicle with the drive unit in the rear, both on the flat and uneven road the rear axle was burdened. That is also confirmed by the fact of the occurrence of the normal reaction force amplitudes acting on the wheels, which, especially in case of motion on uneven roads, are about 1000 N higher than the average. In case of motion of the laden vehicle model the rear axle is also more burdened. However, the differences between the maximum amplitude and the mean value of the normal reaction forces do not seem to be as great as for the unladen vehicle, especially for the front wheels.

As it can be observed from the prepared analysis, the disturbance of the center of mass location in connection with the poor condition of the road may affect both the

Table 1. Mean values of the normal reaction forces for each wheel and their maximal amplitudes during the brake maneuver [own study]

Wheel	unladen vehicle				laden vehicle			
	Flat road		Uneven road		Flat road		Uneven road	
	normal reaction force mean value [N]	amplitude [N]	normal reaction force mean value [N]	amplitude [N]	normal reaction force mean value [N]	amplitude [N]	normal reaction force mean value [N]	amplitude [N]
Left front	3280	3780	3280	4300	3870	4420	3870	4900
Right front	3270	3770	3270	4270	3850	4400	3850	4870
Left rear	4230	5060	4240	5190	4580	5430	4580	5640
Right rear	4220	5040	4220	5250	4560	5410	4560	5640

average values of the normal reactions on the wheels, as well as the maximum amplitudes of these reactions, particularly on a certain road section, on which a specified maneuver takes place. Such approach seems important both for reconstruction of accidents and as a part of infrastructure improvement connected with road vehicle dynamics.

7 Conclusion

Based on the simulation of motion of the unladen and laden vehicle model in Adams/Car software the courses of the normal reaction forces on wheels for two different road conditions were obtained. Taking into account the results, the following conclusions can be reached.

The mean values of reaction forces differ in each case by 10 to 20 N, which, considering that these are mean values, and the vehicle is braking, do not seem of great importance. The changes may occur due to the momentary roll of the vehicle body on the suspension and temporary, minor burden or relief on either left or the right pair of wheels. It is true that the motion was straightforward, but in such case as vehicle ride, minor movements in other directions than longitudinal should be expected.

When laden vehicle motion is considered, the differences in normal reaction forces on the wheels of the same axle were also between 10 and 20 N. The existence of larger forces and amplitudes in case of the laden vehicle can be explained by the better contact between the wheels and the road surface (coefficient of friction remains the same, but the area of contact between the wheel and the road may be greater). It is understood that the wheels rolling along the uneven surface may temporarily lose contact with the road, or their burden could be even momentarily relieved. Additional masses (driver, passenger and baggage) can compensate vibrations occurring in the suspension. If the oscillating system increase sits mass, than at the same driven force the expected response may be of the lesser value than for the smaller mass.

The simulation results can be used to determine the location of the center of mass on the basis of normal reaction forces with which the road affects the wheels. Also the nature and dynamics of these changes can be presented on the basis of the instantaneous normal reaction forces and investigate their influence on motion of the vehicle as a mechanical system.

Further research will provide analysis of the impact of non-uniform load on the normal and contact forces within the area of contact between the road and wheels, basing on computer simulations.

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