Simulation of a vehicle movement on a roadway with stochastic irregularities prescribed by the power spectral density

J Dižo¹, M Blatnický¹, O Kravchenko², V Mamrai², D Barta¹ and P Gasper¹

¹ University of Žilina, Univerzitná 8215/1, 010 26 Žilina, Slovakia
² Zhytomyr Polytechnic State University, 103, Chudnivska str., 10005 Zhytomyr, Ukraine

E-mail: jan.dizo@fstroj.uniza.sk

Abstract. A vehicle represents a mechanical system, which consists of bodies interconnected by joints, force elements, constraints and other coupling elements. When a vehicle moves on a roadway, it is excited due to roadway surface irregularities. It results to vibration of the vehicle mainly in the vertical direction. These vertical movements are known as a vertical dynamics of vehicles. The level of vibrations characterized by their frequency and amplitudes considerably effects two main phenomena, i.e. driving safety and ride comfort for passengers. Therefore, it is necessary to investigate and analyse response of vehicles to the vertical excitations. This article is aimed at evaluation and research of driving properties of a vehicle by means of simulation computations. In case of analysing vehicle’s mechanical system using a virtual model, it is necessary to define in a proper way not only parameters of an investigated vehicle, but also parameters of the excitations due to a roadway surface irregularities. In the reality, roadway surface irregularities have a stochastic behaviour. These fact is processed using statistical methods and it results to the power spectral density of the roadway surface irregularities. A presented research is focused on evaluation of selected output quantities of a vehicle, which moves on the road at various speeds and on various road qualities. An evaluated vehicle uses independent front wheels suspension, which design comes from the utility model. The rear axle is a rigid axle. Dynamic analyses and assessment of the resulting parameters were performed in the Simpack multibody software package. Based on reached results it is obvious, that vertical dynamics of the vehicle is affected by road quality and driving speed. Moreover, the performed analyses have proven, that the used independent front wheels suspension improves driving properties of the vehicle, contributes to better ride comfort and ensures required driving safety.

1. Introduction
The content of the paper is focused on investigation of a vehicle movement on a roadway, at which, an analysed vehicle is equipped by an independent wheel suspension system of the front axle. The rear axle uses a rigid wheel suspension. It is an off-road vehicle, however, it can operate not only in heavy off-road conditions, but, it can drive also on an even road [1]. The design of the front independent suspension system comes from an utility model [2]. The main objective of investigation of a vehicle with the given suspension system is to improve driving properties of off-road vehicles.

Improvement of wheels suspension systems is still a topical issue. In the past, not only off-road vehicles used rigid axles. Such an axle does not meet requirements regarding to driving comfort on an even road. Therefore, several systems of independently suspended wheels were developed. Newly
developed types of independently suspended wheels really reach better driving characteristics in comparison with the rigid axle [3-7]. However, these systems also relate with certain disadvantages, such as higher production costs, more difficult maintenance and also they are not so suitable for operation in heavy off-road conditions. Currently, off-road vehicle producers accepted a compromise and they produce off-road vehicles, which combine the independently suspended wheels on the front axle and rigid rear axle.

The article presents description of the design of an independent suspension system for an off-road vehicle. There are listed parameters of the analysed vehicle. As analyses of the vehicle were performed by means of a computational software, there are described parameters of used road surfaces including irregularities. In the further section of the article, waveforms of investigated quantities and their consequences are concluded.

2. Description of the used vehicle suspension system
A vehicle suspension system is its part, which interconnects a vehicle frame (or a chassis) which wheels. Thus, it includes several components, such as wheels (in a case of a passenger car, there are usually two wheels), a subframe, hubs, driveshafts (in case of a driving axle), and also components of a steering system, a braking system and other components. Individual components of a vehicle axle ensure various functionalities [8-10]. They allow to transmit vehicle weight to wheels, a wheel/road contact as well as transmission of lateral (centrifugal), braking, steering, driving, inertial and other forces [11-15].

2.1. Construction of the front axle suspension system
The analyzed off-road vehicle is equipped with front axle suspension system, which design comes from the utility model [2] designed at the Department of Transport and Handling Machines. This design represents an experimental solution. This design reflects effort to improve a double wishbone suspension system, which would have more advantageous properties during operation in off-road conditions.

This design (Fig. 1) consists of an upper swinging arm (1) and a bottom swinging arm (2), which are bases and they are swinging mounted to a subframe (3) and they are inclined backwards by an angle of $\alpha = 15^\circ$ to $50^\circ$. A steering knuckle (4) is rotating mounted on extended ends of the upper (1) and bottom swinging arms. The extended end of the bottom swinging arm (2) is connected with the subframe (3) by means of a spring and a damper (5).

![Figure 1. Mounting of the front wheels according to the utility model](xx)
The disadvantage of a double wishbone suspension system is a hard wheel impact on an obstacle during driving in off-road conditions. It is caused by a vertical attachment of a spring and a damper, because of what the direction of a swing of arms is also vertical. In order to overcome an obstacle, a vehicle has to sharply accelerate. It leads to lower life-time of the wheel and higher loading of the spring-damper system. The design of wheels suspension (Fig. 1) could solve this problem.

2.2. Construction of the rear axle suspension system
In contrast with the front wheel suspension system, the analyzed off-road vehicle uses a rigid rear axle. Both wheels of the rear axle are connected rigidly on the common subframe. During driving in a terrain, the wheel gauge is not changed. Suspension process needs more space, therefore, a vehicle has a higher ground clearance and higher position of a center of gravity. It is typical for off-road vehicles [16-19]. The rigid axle is connected with the vehicle chassis by means of a leaf springs. The example of the rear rigid axle is shown in Fig. 2.

![Figure 2. A rigid rear axle with leaf spring system (xx).](image1)

The leaf spring is advantageous, because it guides the axle in the longitudinal direction. The analyzed vehicle uses so-called the Panhard rod for lateral guidance of the rear axle. It interconnected the subframe of the axle and the vehicle frame.

3. A computational model of an analysed vehicle
A computational model of the analysed off-road vehicle comes from the commercially produced vehicle Lada 4x4 (older known as Lada Niva or also as VAZ 2121) (Fig. 3), which has favourable driving properties in off-road terrain.

![Figure 3. A Lada 4x4 vehicle (xx).](image2)
An original front double wishbone axle was replaced by the newly designed axle according to the utility model \[2\]. The rear axle was used the original one, i.e. the rigid axle. Selected parameters of the analysed vehicle are listed in Tab. 1.

| Parameter                  | Designation | Value       | Unit |
|----------------------------|-------------|-------------|------|
| Wheelbase                  | L           | 2200        | mm   |
| Maximal engine power       | $P$         | 61/5000 rpm | kW   |
| Maximal engine torque      | $M_t$       | 129/4000 rpm| Nm   |
| Engine displacement        | $V_{el}$    | 1690        | cm$^3$|
| Ground clearance           | $A$         | 205         | mm   |
| Curb weight                | $m_p$       | 1265        | kg   |
| Total weight               | $m_c$       | 1606        | kg   |
| Tyre parameters            |             | 185/75 R16  | mm   |

The vehicle model and dynamic analyses of its driving on a roadway surface with various irregularities have been carried out in Simpack software package \[20,21\]. It is one of the most widely used a multibody software. It allows to create complex virtual models of vehicle and their subsystems and to analyse wide range of phenomena regarding to kinematic and dynamic behaviours.

The procedure of the setting up of the analysed vehicle has included modelling of geometries of essential components of the vehicle. There were mainly components of front and rear axles and a bodywork. The CAD models were created in Catia software. These bodies have been imported in the corresponding format into the Simpack software. Subsequently, there was necessary to set up the MBS vehicle model itself. It included definition of construction points, so-called markers, further joints, couplings, force elements, wheel/road contacts of individual wheels etc. This process also included prescribed basic mass and inertia parameters of individual bodies. Figure 4 shows a view to a final model of the front axle model.

Further, a special marker for a steering and other markers in steering knuckles were defined. These markers and kinematic couplings allow to steer a vehicle model during driving in curves. Steering of the vehicle and controlling also ensure other modelling elements, such as control elements, sensors etc.

Table 2 includes mass and inertia parameters of the bodywork, which if one of the most dominant body of the vehicle model.
Springs and dampers have had defined linear characteristics, i.e. it was sufficient to prescribe their parameters by one number. Some parameters of suspension systems of the vehicle are written in Table 3.

Table 2. Mass and inertia parameters of the vehicle bodywork.

| Parameter                        | Designation | Value  | Unit     |
|----------------------------------|-------------|--------|----------|
| Mass                             | $m_k$       | 1122   | kg       |
| Moment of inertia about $x$ axis | $I_x$       | 278.22 | kg·m²    |
| Moment of inertia about $y$ axis | $I_y$       | 733.73 | kg·m²    |
| Moment of inertia about $z$ axis | $I_z$       | 829.84 | kg·m²    |

Table 3. Selected parameters of the front and rear suspension systems.

| Parameter                          | Designation | Value  | Unit  |
|------------------------------------|-------------|--------|-------|
| Front spring stiffness ($z$ axis)  | $k_F$       | 145000 | N·m·l  |
| Rear spring stiffness ($z$ axis)   | $k_R$       | 135000 | N·m·l  |
| Damping coefficient - front        | $b_F$       | 2250   | N·s·m·l|
| Damping coefficient - rear         | $b_R$       | 2000   | N·s·m·l|

In our case, the Pacejka similarity tyre model was defined in the vehicle model. This is a wide used model for modelling and computations of needed parameters in the wheel/road contact. As there is a four wheel vehicle, the vehicle model also comprises four individual force elements with prescribed tyre model. It is necessary to define in the related file tyre dimensions and some other parameters, such as vertical and lateral stiffness, damping coefficients etc. Figure 5 shows the final multibody model of the analysed off-road vehicle in the Simpack software.

Figure 5. A multibody model of the analysed vehicle in the Simpack software.

4. A computational model of a road with stochastic irregularities
Simulations of the vehicle were performed for various road surface qualities. The software allows to define several types of road irregularities, from the simplest, i.e. individual obstacle in the form of a sinusoidal function, through multiply harmonic irregularities (also by sinusoidal function or other) up to more complicated irregularities. These more complicated irregularities can be input from real...
experimental measurements (including corresponding statistical processing) or they can be prescribed by the power spectral density (PSD). The standard ISO 8608 [22] includes certain standardized types of stochastic road irregularities, from the very good cement concrete to very bad unfortified road [23-26].

The Simpack software includes ten road surfaces quality as following (Fig. 6):

- Very good cement concrete.
- Good cement concrete.
- Good asphalt concrete.
- Good macadam.
- Medium asphalt concrete.
- Medium pavement.
- Bad pavement.
- Very bad macadam.
- Bad unfortified road.
- Very bad unfortified road.

The power spectral density is determined according to the ISO 8608 standard [17] and the road surface qualities is classified by the formulation:

\[ G_d(\Omega) = G_d(\Omega_0) \left( \frac{\Omega}{\Omega_0} \right)^{-n} \]  \hspace{1cm} (1)

where \( G_d(\Omega) \) is the power spectral density for a particular surface \([m^3]\), \( G_d(\Omega_0) \) is the reference power spectral density \([m^3]\), \( \Omega \) is the particular distance angular frequency \([m^1]\), \( \Omega_0 \) is the reference distance angular frequency \([m^1]\) and \( n \) is the road surface wave rate.
The PSD is determined experimentally. Measured values are written in a table and a graph is estimated. The PSD waveform is in logarithmic coordinates linear with a good approach. An illustrative example of such waveforms for various road surface qualities is shown in Fig. 7.

5. Results and findings
This section contains waveforms of observed output quantities, namely waveforms of vertical wheel forces. These forces are important in term of driving safety, because they express, if the driving of the vehicle is still safe or not anymore. The vertical wheel force composed from the static load of a wheel $F_{stat}$ and from the dynamic load of the wheel $F_{dyn}$. For the safe driving it is necessary to keep a constant contact of a wheel with the road. Lower value of the vertical wheel leads to a worse ability of transmission of driving, braking and steering forces and in the extreme case, a wheel can jump off the road and the driving is dangerous.

In our case, we investigate a vehicle driving on a road with selected surface qualities, namely very good cement concrete, good macadam, very bad macadam, bad unfortified road and very bad unfortified road. There were performed several driving manoeuvres, at which, the vehicle has been always moving at the speed $v = 60$ km/h. This speed correspond to the vehicle purpose (off-road vehicle) and general instruction of the producer for using in terrain. Road irregularities begin, when the vehicle has overcome the distance $s_1 = 176$ m and they and at the distance $s_2 = 220$ m. Thus, the vehicle has overcome the total distance $s = 44$ m on road irregularities within the time $t = 2.75$ s. For purposes of this work, graphs of three sets of results for various driving manoeuvres were chosen.

Figure 8 shows comparison of the vertical wheel force for the front left wheel for four road irregularities. We can compare the waveforms of the vertical wheel forces for good bad unfortified road, very bad unfortified road, good macadam and very bad macadam. These surface qualities represent assumed road, on which, the analysed vehicle could be operated.

![Figure 8](image)
Figure 8. A comparison of values of the vertical wheel force of the front left wheel in the time domain at the speed of $v = 60$ km/h during driving on various road irregularities (bad unfortified road, very bad unfortified road, good macadam, very bad macadam).
According to graphs shown in Fig. 8, individual results for various surfaces and maximal values of the vertical wheel force can be compared. It is found out, that the vertical wheel force $F_k$ has very different maximal values.

In the case, when the vehicle moves on the very bad unfortified road, the vertical wheel force reaches very high maximal values. In the case of vehicle driving on the bad unfortified road as well as on the very bad unfortified road, the vertical wheel forces reaches zero values, it means, this wheel jumps off the road and the driving is for these cases dangerous. The case of driving on good macadam and very bad macadam surfaces, values of the vertical wheel force oscillate with quite large amplitude around the value of the static wheel load, however, the forces are large sufficiently to transmit needed forces.

The next figure (Fig. 9) contains comparison of waveforms of the vertical wheel forces for all four wheels, when the vehicle drives on the very bad unfortified road. It is the worst observed road surface quality. The main purpose of these results is to identify, if the different constructions of front and rear axle influence the driving safety. It can be seen, that the very bad unfortified road is such a poor road surface, that dynamic response of the front and rear wheels almost not differ. Waveforms show, that the vehicle driving at the speed $v = 60 \text{ km/h}$ on this surface leads to lots of wheel/road contact. In this case, the independent suspension of the front wheels does make better driving characteristics in comparison with the rear rigid axle.

As the last manoeuvre, the following drive has been performed. In order to identify an influence of the various constructions of the front and rear axle, the analysed vehicle has been driving on two various road qualities and that so the left side of the vehicle has been moving on the very bad unfortified road and the right side has been moving on the very good cement concrete as the best road surface, which can be prescribed in the used software by means of the PSD definition. Results of this driving manoeuvre are shown in Fig. 10. The driving speed has been again chosen $v = 60 \text{ km/h}$.

As it can be assumed, different road surface qualities lead to different dynamic response of individual wheels on the left and right side of the vehicle. According to an assumption, the very bad unfortified
road, as the worst investigated road surface, causes the high maximal values of the wheel forces. And, it does not matter, if it is the independent suspension of the front wheel or the rigid rear axle. This driving manoeuvre results to the wheel/road contact loss and the driving is dangerous.

On the other hand, the left side of the vehicle has been moving on the much better road surface quality, namely on the good asphalt concrete. From Fig. 10, there are recognizable difference of the dynamic response. The vertical wheel force of the front right wheel has significantly lower amplitude and also the oscillation frequency is considerably lower. Although the rear right wheel oscillates with higher frequency than the left wheel, also in this case, we can observe certain improvement in comparison with the left rear wheel.

![Figure 10. A comparison of vertical wheel forces of all four wheels of the analysed vehicle, when left wheels move on the very bad unfortified road and right wheels move on the good asphalt concrete, driving speed $v = 60$ km/h.](image)

From the results presented by means of the Fig. 10, we can recognize certain findings. Let’s compare the dynamic response of the front wheels. The independent suspension system of the front wheels (upper part of Fig. 10) has more favourable driving properties in comparison with the rigid rear axle. The independent wheel suspension system has an advantage, that oscillation of one wheel is not transmitted to the opposite side of a vehicle. This can be also observe for our investigated case. The left wheel has obviously lower values of the vertical wheel force. Theoretically, the right side of the vehicle should not be affected by the left side at all. However, dampers used as well as a stabilizer bar, which is a standard component of an independent suspension system, cause a partial transmission of the oscillation of the opposite side of the vehicle.

A rigid axle has more negative effect for dynamic properties of vehicles. A rigid coupling between opposite wheels does not allow to absorb vibration of the wheel on the one side of the vehicle. Therefore, vibration are transmitted to the opposite wheel. This fact can be observed in a lower part of Fig. 10. Rigid axles are also equipped by a stabilizer bar, however, it is not a necessary accessory.

Performed analyses represent initial activities in the research of the properties of the designed front independent axle suspension. There is necessary to continue in these activities. The future research in
this field will be focused on investigation of the driving properties of the vehicle on other driving conditions including various driving speed, optimization of parameters of suspension system (parameters of springs, dampers, a stabilizer bar). Further, there will be investigated possibility of usage this axle also on other types of off-road vehicle, i.e. on different categories regarding to the weight and dimensions of vehicles. For these purposes, it will be necessary to know all needed parameters.

As the next level in computational modelling and simulation will be implementation of a flexible body into the multibody model of the vehicle. Such an approach will allow to simulate more realistic loading of the vehicle components under the defined operational conditions [27-30].

6. Conclusions
Vehicle suspension systems are one of the most important component of vehicles, which ensure driving safety and comfort. These construction units are being still developed. The presented research contained a description of a newly developed independent suspension system of a front axle. Possibility of its using were investigated by means of simulation computations, at which, a multibody computational model of a vehicle corresponded with an off-road vehicle.

Simulations of vehicle driving were performed for a chosen speed of 60 km/h on a road with irregularities prescribed by means of the power spectral density. There were investigated three different driving manoeuvres for various road irregularities. Simulation computation showed, that the independent suspension of the front wheels lead to better driving safety in comparison with the rigid rear axle. For more detailed assessment of the vehicle driving properties, there are planned to perform further simulations.

Future research activities in this field will be focused on improving the current MBS model of the off-road vehicle. This will be realized by implementation of a flexible model of one or more component of the front wheels suspension system to the created MBS model of the vehicle. Such a model will better represent a real vehicle, it will be possible to make more realistic simulation with the car under the rough driving conditions and it will be possible to reveal the most exposed components of the front wheels suspension system during operation. In addition, the presented process of modelling the off-road vehicle will allow to create another models coming from the multibody system principles, at which, dynamic responses could be investigated due to various vehicles parameters.

Acknowledgments
This work was supported by the Cultural and Educational Grant Agency of the Ministry of Education of the Slovak Republic in the project No. KEGA 023ŽU-4/2020: Development of advanced virtual models for studying and investigation of transport means operation characteristics.

References
[1] Chudzikiewicz A and Melnik R 2012 Proc. of the Mini Conf. on Vehicle System Dynamics, Identif. and Anomalies vol 13, ed I Zobory (Budapest: Hungary) p 149–155
[2] Dobrodenka P et al 2017 Attachement of front axle wheels of off-road vehicles Utility model.
[3] Saga M, Vasko M, Handrik M and Kopas P 2019 Scientific J. of Silesian University of Technol. 103 143–154
[4] Leitner B 2010 Proc. Int. Conf. Transport Means vol 14, ed V Ostasevicius (Kaunas: Lithuania) p 21-24
[5] Cerskus A et al 2020 Symmetry 13 1149-1149.
[6] Davis BR and Thompson AG 2001 Vehicle System Dynamics 35 409-415
[7] Marczuk A, Caban J, Aleshkin AV, Savinykh PA, Isupov AY and Ivanov II 2018 Sustainability 11
[8] Lack J and Gerlici J 2017 Proc. 23rd Int. Conf.: Current Problems in Rail Vehicles vol 23, ed BV Michalkova (Ceska Trebova: Czech Republic) p 217-234
[9] Fomin O, Lovska A, Radkevych V, Horban A, Skliarenko I and Gurenkova O 2019 ARPN J. of Eng. and Appl. Sciences 14 3747–3752
[10] Leitner B, Decky M and Kovac M 2019 Transport 34 195–203
[11] Harusinec J, Maňurová M and Suchánek A 2016 Manufacturing Technology 16 917–923
[12] Mucka P, Stein GJ and Tobolka P 2019 Vehicle System Dynamics 58 630-656
[13] Harusinec J, Suchanek A, Loulova M and Kurcik P 2019 MATEC Web of Conferences 254
[14] Leitner B and Figuli L 2018 MATEC Web of Conferences 157
[15] Dharankar CS, Hada MK and Chandel S 2017 J. of Brazilian Soc. of Mechanical Sciences and Eng. 39 1957-1967
[16] Hauser V, Nozhenko OS, Kravchenko KO, Loulová M, Gerlici J and Lack T 2017 Manufacturing Technol. 17 306–312
[17] Baran P, Šťastniak P, Kukuča P and Brezáni M 2018 MATEC Web of Conferences 157
[18] Gerlici J and Lack T 2008 Komunikacie 10 26–32
[19] Howe JG et al 2004 Int. J. of Vehicle Design 36 248-269
[20] Stastniak P and Smetanka L 2019 Proc. Int. Conf: 24th Medzinarodna konferencia Sucasne problemy v kolajovych vozidloch Part 2 vol 24, ed D Kalincak (Zilina: Slovakia) p 319-328
[21] Rabinovich E et al. 2018 SAE Technical Papers 2018 1–12
[22] ISO 8608: 2016 Mechanical vibration – Road surface profiles – Reporting of measured data
[23] Li J et al 2018 Int. J. of Vehicle Design 77 247-271
[24] Turkay S and Akcay H 2016 Proc. Int. Conf: 20th International Conference on Syst. Theory, Control and Computing vol 20, ed E Petre and M Brezovan (Sinaia: Romania) p 567-572
[25] Chomphan S 2021 Int. J. of Geomat 20 29-35
[26] Prznowski K, Mamala J, Smieja M and Kupina M 2020 Sensors 20 5987-5987
[27] Lack T and Gerlici J 2008 Komunikacie 10 10–18
[28] Saga M and Jakubovicova L 2014 Scientific J. of Silesian University of Technol. 84 113–118
[29] Parczewski K and Wnek H 2018 Proc. Int. Conf Transport Means vol 22, ed Kaunas Univ Technol (Trakai: Lithuania) p 321-326
[30] O. Fomin, A. Lovska, Engineering Science and Technology 23, 6 (2020)