

Dynamic simulation of a virtual prototype of a one-track vehicle in motion on uneven ground conditions

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Abstract. This article presents the procedure of designing and testing the virtual prototype of the one-track vehicle using the Autodesk Inventor Professional software. A multi-stage process of preparing the virtual prototype and the results of selected simulation tests were presented. During the first stage of work, a digital geometric model of the vehicle was created. The second stage includes placing the model in the dynamic simulation environment and defining the testing conditions corresponding to the actual vehicle operation conditions. The next phase relates to the realization of virtual model tests in the Autodesk Inventor dynamic simulation environment. The model was subjected to tests using the multibody systems method (MBS) to determine the forces and displacements in selected structural nodes of the vehicle, in motion on uneven ground conditions. The obtained simulation results in the form of force values over time and displacements were analyzed and conclusions were formulated. The test results can be used to conduct a more detailed endurance analysis of individual construction elements, model optimization and impact on the driver's body. It was stated that the used method allows for a more efficient process of creating a new product and more efficient evaluation of the impact of the conditions in which it will be used.

Keywords: virtual prototype, multibody systems method, dynamic simulation

1 Introduction

It has been reported that modern-day businesses, operating under strong pressure of market forces, are often forced to an instant reaction to the market's needs. Additionally, changing trends and various consumer wealth create the need for many variants of a product to exist

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in the market, which are tailored to the individual users' needs as much as possible. There is a common belief [1-3], that the creation of a prototype is a crucial stage of the process of creation of a new product and is a certain verification of the design stage, happening before the implementation stage. It needs to be noted that the designed products need to comply with many detailed criteria of construction assessment. The fulfilment of all those criteria, which can often be contradictory, is very difficult. There is a constant search for alternative, in relation to the currently used, methods of implementing new products into production. One such method is the process using numerical methods, known as virtual prototyping. It is based on the creation of a numerical model (most often of a machine, device or a technological process) and the consecutive performance of multi-variant simulations of the object's behavior under different conditions, aiming at reaching the optimal solution in relation to the required functions of the object. This allows to lower the cost of research and the analysis of multiple solutions. This modern method of designing allows to efficiently fulfill the majority of time-consuming and currently expensive stages which together form the process of the creation of a new product [4-10]. It may be used both in relation to the whole construction, its subgroups, or individual components [11-13]. Fig. 1 presents a general overview of the elements of the computer-aided design and production process.

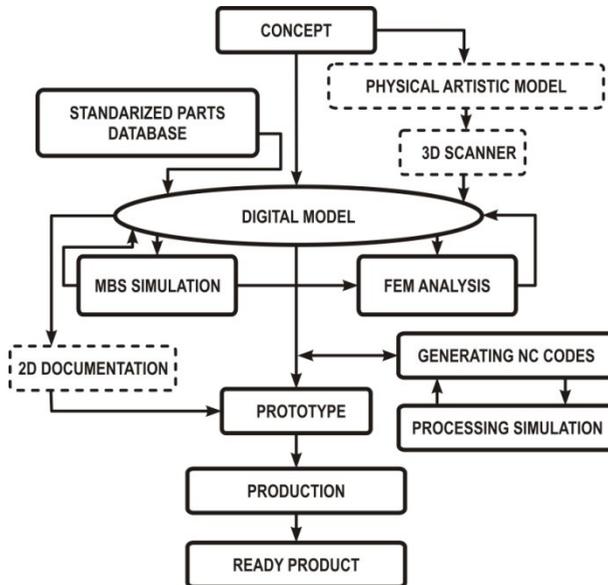


Fig. 1. Computer-aided design and production processes

The traditional process of product development in comparison to virtual prototyping is expensive and time-consuming, as it requires the construction and testing of a physical model. The physical prototype undergoes verification analyses, based on which the required changes are introduced, at which point the entire process is repeated. Before a satisfactory result is obtained, more than a dozen of such design iterations are sometimes performed. Such design cycle makes the development process more expensive and delays the moment of the product's entry into the market, especially in the case of complex mechanism structures. It needs to be noted that products designed using the traditional method are often different from the optimal solutions. The lack of precise identification of the load values and deformations of individual elements in turn leads to their frequent over dimensioning, which influences the weight and size of the product.

In the area of prototype assessment there is often the necessity of performing a kinetic and dynamic analysis of systems consisting of many elements moving in relation to each other and their surroundings. Such systems are often very complex, which causes the notation of equations, which describe their movement, and their analysis, to be a complicated and time-consuming task.

One of the commonly used methods is the so called multibody system method (MBS), which is the generally used name for modelling methods, analysis and synthesis of real systems, treated as multibody systems. The MBS theory is widely described and discussed by many researchers, e.g. [14-17].

Due to a complicated mathematical mechanism used to solve problems related to kinetics and dynamics of multibody systems, numerical methods are widely used. Software emulation of the designed objects enables to conduct a wide array of simulations, including multiple variants, which is a desirable function for designers. The usage of such prototyping method reduces the amount of tests on real models, shortens the time of implementation and lowers the development costs.

Currently there is an observable interest among designers in software which allows to realize kinetic and dynamic simulations, often referred to as mechanical system simulation (MSS). Typical work in a mechanical simulation system starts with the construction of a geometric model of the device. The option of importing geometry from a CAD system is often used at this point. The individual parts making up the model of the device are connected using joints taken from a bond library. The next step is the introduction of movement generators (e.g. actuators, motors) and loads. Next, the software solves the equations of mechanical structure movement and calculates the displacement, speed, acceleration and reaction force value in the analyzed places. The results of the calculations can be presented on charts or presented as realistic animations. The designed model can be modified and through consecutive simulations try to create an optimal solution [18]. Very often mechanical simulation systems are equipped with modules enabling strength calculations for load statics, or calculations of the natural frequency. Another very popular solution is the possibility of inputting the results of calculations from MSS systems as input data for MES software, in which loads, deformations, etc. are determined. The need for such software means that the leading CAD systems are equipped with calculation environments integrating geometric modelling, MES analysis and simulation modules.

There are many CAD systems available on the market. Due to their functions, they can be divided into:

- advanced (e.g.: Catia, NX, Pro/Engineer),
- intermediate (e.g.: Autodesk Inventor, Solid Edge, SolidWorks),
- basic (e.g.: Autocad, LibreCad, Megacad).

This work focuses on the software from the intermediate group, due to their large popularity in the industry. This popularity is mainly the result of large possibilities of the software combined with relatively low cost of purchase and usage. Using an intermediate system, one can design virtual models of advanced mechanical structures [4, 19, 20].

The aim of this work is an attempt to design a virtual prototype of a single-track vehicle and conducting initial tests in a dynamic simulation environment in Autodesk Inventor, enabling the designation of loads and displacements at selected joints of the vehicle in motion on uneven ground conditions. The detailed aim of these tests is the analysis of the viability of using spring load regulation of front suspension.

2 Designing the geometric model of the vehicle

The virtual 3D model of the vehicle was designed based on the Hanzz Fritzz 160 HPA [21] bicycle manufactured by Cube. The bike falls into the category of full-suspension mountain bikes, which is suited for riding on various types of surfaces such as typical hard roads or trails with roots, rocks, bumps and larger drops of approximately 0.5 m. The model was chosen due to high complexity of its construction, for which the classic methods of multi body element dynamics are characterized by a high level of complexity and a time-consuming design process.

The model of the vehicle with all of its components was created in the Autodesk Inventor Professional 2018 software environment. While designing the virtual model of the vehicle, the following assumptions of general bicycle construction were made:

- type of bicycle – mountain bike,
- vehicle weight – 13.8 kg,
- wheel diameter – 27”,
- wheel base – approx. 1200 mm,
- frame material – aluminum alloy,
- type of suspension – full suspension.

The individual parts of the vehicle have been joined together by using appropriate joints in the system environment. In order to optimize the work in this environment, the entire bicycle model was divided into smaller elements, such as front tire, rear tire, handlebar, frame etc. In order to properly place the components and correctly define their movement, appropriate joints or connections between individual parts had to be considered. The dimensions of the bicycle including the location of the center of mass are presented in Fig. 2. The joint command available in the software, directly defined the type of joint, movement and orientation. Elements responsible for the movement of mechanisms were inserted into the main system individually, as the inserted systems at this level form static groups, which means they are fused together. Fig. 3 shows isometric view of the designed geometric model of the single-track vehicle.

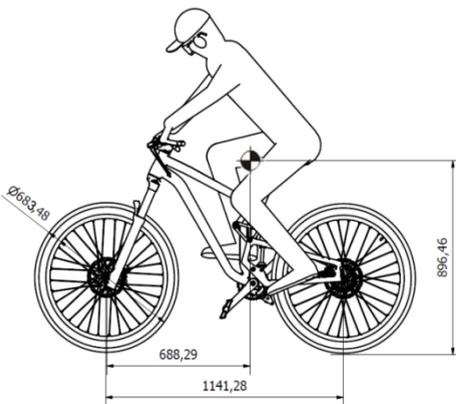


Fig. 2. Dimensions of the bicycle including center of mass



Fig. 3. A view of the geometric model of the vehicle

The Autodesk Inventor software has modules which allow to generate various types of mechanisms. These include the so called Compression Spring Generator. Using the above mentioned tool, springs for the front and rear suspension were generated.

A model of a rider was added to the 3d model of the vehicle in order to recreate real conditions of bicycle movement as precisely as possible. The geometry of the rider’s model corresponds to an adult person of an approximate weight of 85 kg.

3 Designing the virtual model in a dynamic simulation environment

3.1 Description of research conditions

In this work, the behaviour of the vehicle for variable parameters listed in Table 1 is tested. The dynamic simulation environment of the software is used for this purpose, and the simulation was realised in conditions of the vehicle model moving on various road profiles, whose parameters are shown in Table 2.

Table 1. Assigned research parameters

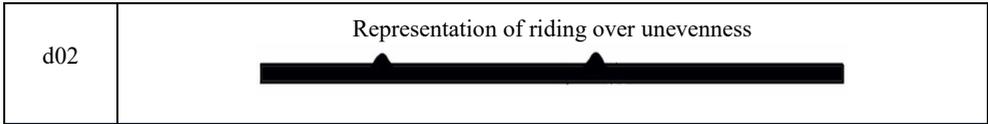
Parameter	Symbol
Vehicle speed	
Front wheel spring tension	
Rear shock damping	
Rear wheel spring tension	
Tyre rigidity	

The following values of parameters determining the research conditions have been assumed:

- vehicle speed: 8 km/h, 9.5 km/h, 10 km/h,
- rear wheel spring tension: 32 N/mm, 64 N/mm, 128 N/mm,
- rear shock damping: 0.5 Ns/mm, 1 Ns/mm, 10 Ns/mm,
- front wheel spring tension: 11 N/mm, 22 N/mm, 44 N/mm,
- tyre rigidity: 50 N/mm, 100 N/mm, 1000 N/mm.

Table 2. Road profiles used during research

Name	Profile
d01	Sinusoidal profile with an amplitude of 10 mm and unevenness spacing of 50 mm 



The directions of the axes and the places of measurement are presented in Fig. 4. After each simulation the results were observed in the software window, and then exported to MS Excel. The Output Grapher of the software made it possible to generate individual reports, create charts and observe and analyze them. Table 3 presents the output value symbols from the analysis.

Table 3. Observed parameters

Parameter	Symbol
Front wheel spring compression (mm)	
Rear wheel spring compression (mm)	
Measurement point displacement at front wheel hub in the direction of the Z axis (mm)	
Measurement point displacement at the handlebar in the direction of Z axis (mm)	
Measurement point displacement at the handlebar in the direction of Y axis (mm)	
Forces at the headset (N)	

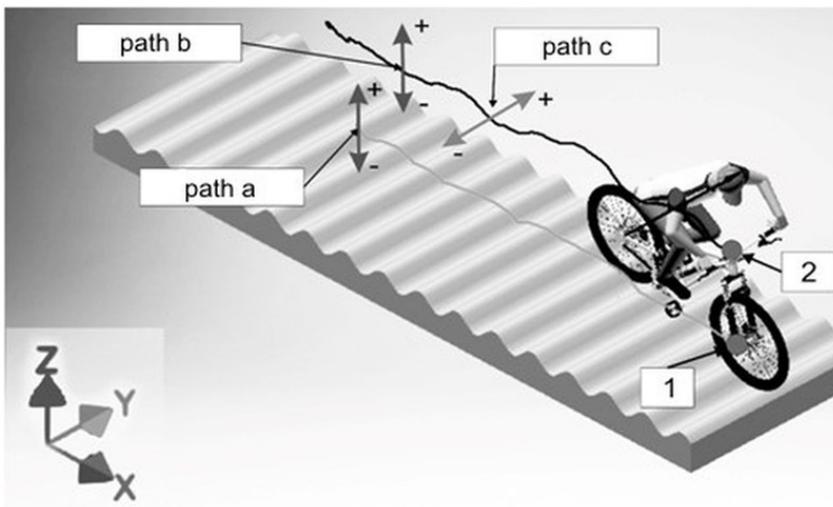


Fig. 4. Symbols used in dynamic simulation: 1 – measurement point at front wheel hub, 2 – measurement point at handlebar

The following names for measurement points were used (Fig. 4):

- measurement point displacement at front wheel hub in the direction of Z axis – path *a*,
- measurement point displacement at handlebar in the direction of Z axis – path *b*,
- measurement point displacement at handlebar in the direction of Y axis – path *c*.

At the front wheel hub and at the handlebar, measurement points were defined using the Track tool. Due to this measurement data could be obtained for these measurement points, as well as movement trajectories.

3.2 Preparation of simulation

The initially prepared geometric model of the vehicle served as the basis for the designing of a virtual model in the dynamic simulation environment, which is one of the modules of Autodesk Inventor software. The software has a sizeable library of movement joints. For each joint an appropriate amount of degrees of freedom is added. This allows to impose limitations on individual elements during motion. The software enables to define forced movement on each joint, using speed, displacement or acceleration, as well as to load each element with force values and torque. Thanks to the tools available in the software the user has the possibility to test the designed mechanism in motion and determine the value of forces and torque created during the mechanism's operation. It is possible to automatically convert the joints in the system to movement joints available in the dynamic simulation. The prepared models, however, were characterized by a high level of complexity which is why it was necessary to define the movement joints manually. In order to obtain the proper operation of individual pairs of kinetic models it was necessary to define appropriate movement joints which varied from each other in the amount of degrees of freedom. Another very important condition for the proper performance of the simulation was the appropriate definition of the orientation of the coordinate system of the components. To this purpose points, axes and surfaces of individual parts of the model were used.

During the process of creation the simulation a few types of movement joints were used. The base element (immobile part) in relation to which the vehicle was moving was the virtual road model. The elements of suspension always take part in the transfer of load. These have to be taken account of in the model, if it is intended to recreate the loads on the frame [4, 18]. Between the road surface and the wheels, rolling joints were introduced. Damping elements in the vehicle were defined using spring-damper type force joints.

4 Results of prototype tests in a dynamic simulation environment

Dynamic simulations were conducted for each combination of parameters presented in Table 1 and Table 2. As a result of these tests, time courses of displacements, speed and acceleration were obtained, as well as forces and torques in joints. This work presents the selected, most characteristic results of the dynamic simulation.

4.1 Road profile d01

Profile d01 (Fig. 5) was described using a sinusoidal curve $z(x) = 10 \sin(1 \cdot x/50)$. Fig. 6, Fig. 7 and Fig. 8 present sample results of the dynamic simulation for this road profile.

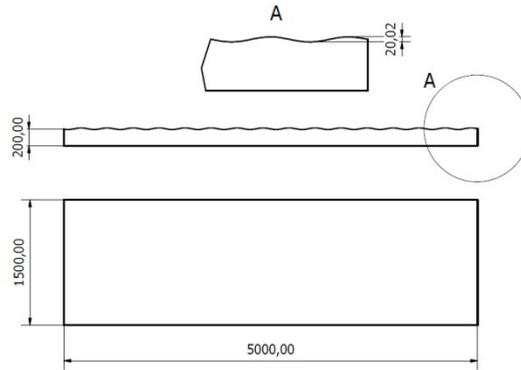


Fig. 5. Road profile d01

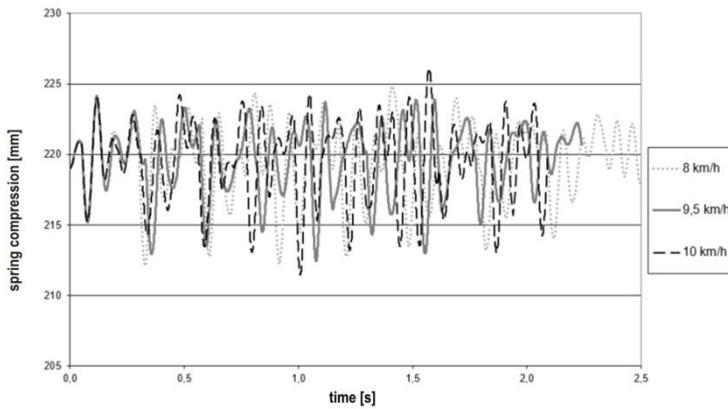


Fig. 6. Observed spring compression of the front wheel in time functions for 3 different speeds (profile d01)

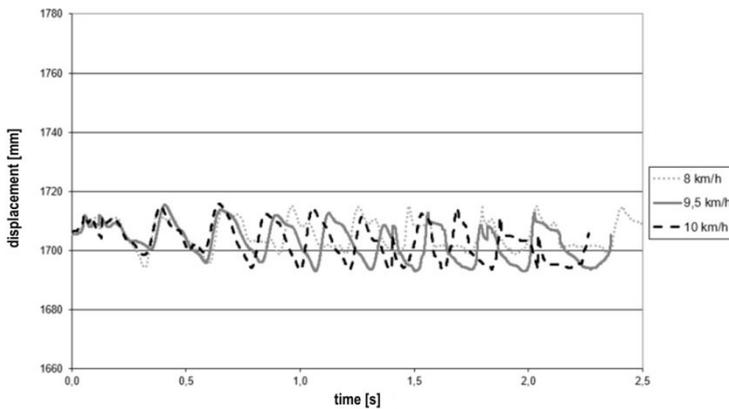


Fig. 7. Observed displacements for the measurement point on the handlebar in the direction of Y axis in a time function for 3 different speeds (profile d01)

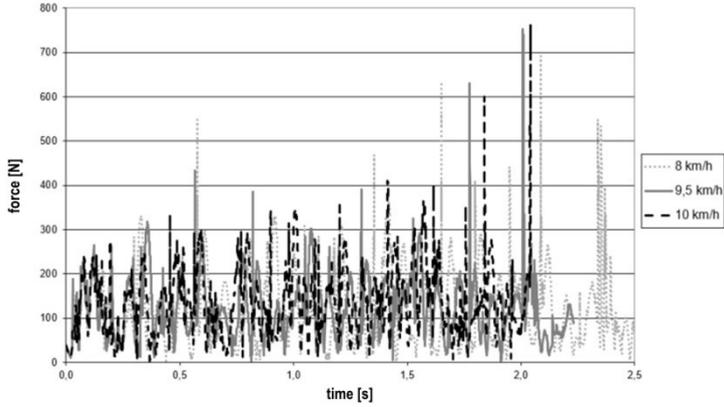


Fig. 8. Observed forces in the headset in a time function for 3 different speeds (profile d01)

4.2 Road profile d02

Profile d02 (Fig. 9) presents riding over uneven bumps of the height of 50 mm. Fig. 10, Fig. 11 and Fig. 12 present sample results of the dynamic simulation for this profile.

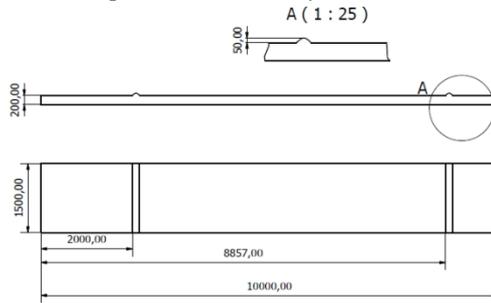


Fig. 9. Road profile d02

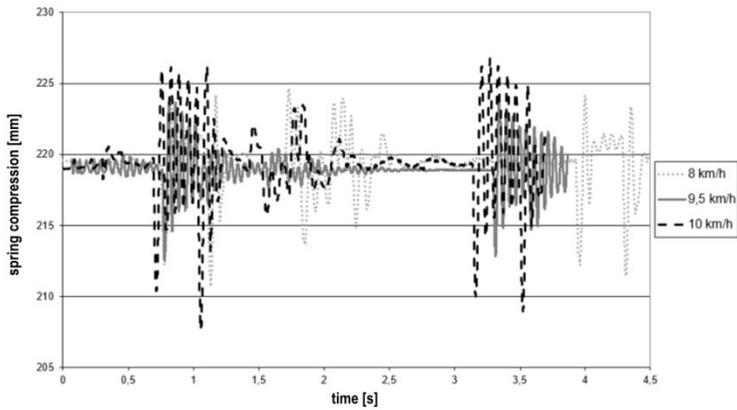


Fig. 10. Observed spring compression of the front wheel in time functions for 3 different speeds (profile d02)

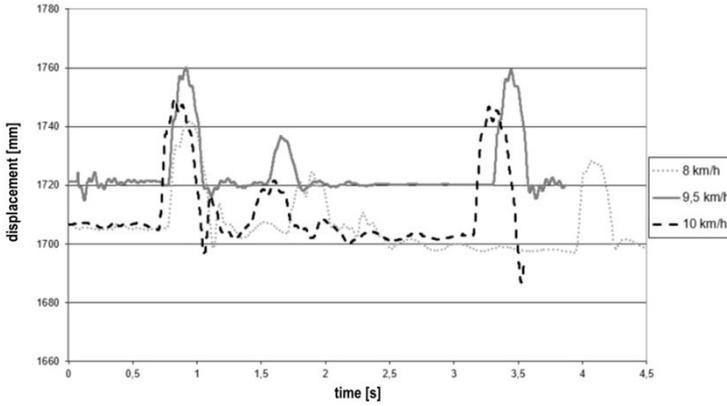


Fig. 11. Observed displacements for the measurement point on the handlebar in the direction of Y axis in a time function for 3 different speeds (profile d02)

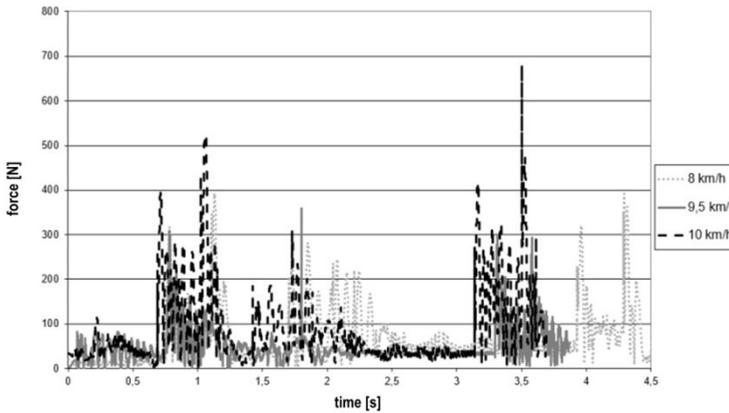


Fig. 12. Observed forces in the headset in a time function for 3 different speeds (profile d02)

4.3 Analysis of results

Based on the obtained simulation results it can be stated that the average range of compression of a front wheel spring and the maximum amplitude of vibrations are most influenced by the value of front wheel spring tension and speed.

At higher tension there are visible higher forces affecting the handlebar. The value of the force in the headset increases together with speed of the vehicle, front wheel spring tension and the damping of the rear damper. It was observed that smaller displacements of the handlebar, in the case of analysed roads, occur at a value of damping for the rear damper of 10-20 Ns/mm. A higher value of damping in the rear damper cause the decrease of the average range of compression of the spring and the increase of the maximum vibration amplitude.

Higher speed causes the decrease of the average compression range of the spring and a decrease of the maximum vibration amplitude, while, however, the load on the suspension elements increases significantly.

Higher tyre rigidity causes the decrease of the average compression range of the spring, but it increases the maximum vibration amplitude.

The stability of the movement of the model is significantly influenced by the vibrating vertical components along the Z axis, which changed depending on the rigidity, damping and speed. An increase in rigidity limited the vibration amplitude, but influenced the vibration frequency negatively, which increased as a result of the road bumps. The increased damping values caused a beneficial lowering of vibration amplitude. In cases of strong damping it was noted that the vibration movement was highly aperiodical.

5 Conclusions

Owing to the included analytic tools, the Autodesk Inventor software enables the analysis of a model in relation to stress analysis and model behaviour in motion. The integration of all tools used in the process of designing with the virtual prototyping method in one software package creates the possibility of fast and cheap adjustment of the designed product to the conditions, in which it will be used as well as verification of the influence of changes in these conditions on the designed product. Virtual prototyping provides the possibility to verify the solutions designed with various technical requirements in mind.

The conducted simulation attempt of the motion of a single-track vehicle on an uneven surface yielded many interesting results. It was observed that many different parameters influence the behaviour of the bicycle and its components. The force value noted in the headset, which in motion is transferred directly onto the handlebar and the arms of the cyclist increased with speed of the vehicle and the unevenness of the road. The rigidity of the shock absorber also played a key role. Higher rigidity caused higher force values affecting the handlebar. The negative effect of road unevenness on the cyclist can be reduced using low spring tension and moderate damping.

The dynamic simulation is a helpful tool in virtual prototyping. It is a cheaper albeit time-consuming method, requiring good mastery of the software. The results obtained based on the simulation can be used for further research such as stress analysis, which can be helpful in determining the sense, direction and value of forces affecting the model, including the rider's body.

This work is just a fragment of a much broader analysis of the issue of vehicle motion under conditions other than those presented here. The created model can be used to study other behaviours of the vehicle such as while in motion on a curved road section, or with taking acceleration into account.

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