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INVESTIGATION OF DRIVING STABILITY OF A VEHICLE–TRAILER COMBINATION DEPENDING ON THE LOAD'S POSITION WITHIN THE TRAILER

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Abstract: Passenger cars are a means of transportation used widely for various purposes. The category that a vehicle belongs to is largely responsible for determining its size and storage capacity. There are situations when the capacity of a passenger vehicle is not sufficient. On the one hand, this insufficient capacity is related to a paucity in the space needed for stowing luggage. It is possible to mount a rooftop cargo carrier or a roof basket on the roof of a vehicle. If a vehicle is equipped with a towbar, a towbar cargo carrier can be used for improving its space capacity. These accessories, however, offer limited additional space, and the maximal load is determined by the maximal payload of the concerned vehicle. If, on the other hand, there is a requirement for transporting a load with a mass or dimensions that are greater than what could be supported using these accessories, then, provided the vehicle is equipped with a towbar, a trailer represents an elegant solution for such demanding requirements. A standard flat trailer allows the transportation of goods of various characters, such as goods on pallets, bulk material, etc. However, the towing of a trailer changes the distribution of the loads, together with changes of loads of individual axes of the vehicle–trailer axles. The distribution of the loads is one of the key factors affecting the driving properties of a vehicle–trailer combination in terms of driving stability, which is mainly a function of the distribution of the load on the trailer. This research introduces a study into how the distribution of the load on a trailer influences the driving stability of a vehicle–trailer combination. The research activities are based on simulation computations performed in a commercial multibody software. While the results presented in the article are reached for a particular vehicle–trailer combination as well as for a particular set of driving conditions, the applicability of the findings can also be extended more generally to the impact that the load distributions corresponding to various vehicle–trailer combinations have on the related parameters and other driving properties.

Key words: driving stability, vehicle–trailer combination, multibody simulation

1. INTRODUCTION

Trailers are used for transport of goods for shorter as well as longer distances. An important reason why trailers were developed and why their use still finds widespread prevalence is the steadily increasing need for transport, specifically the transport of cargo whose volume and weight exceed what could possibly be supported by the transport capacities typically associated with the engines of road vehicles.

Modelling and simulation is very important for science and research. Mechanical engineers use virtual models and software for modelling of road vehicles every day and these constitute an inseparable part of their work activities. These models allow the investigation of reactions and responses of road vehicles or road vehicle–trailer combinations to changes of input parameters, their driving properties and other factors, and additionally allow researchers to ascertain various means by which a reduction can be achieved in the cost associated with development and testing [1–3]. It is possible to obtain valuable information about an investigated subject in relatively short time. In this work, the investigation undertaken concerns the driving stability of a vehicle–trailer combination that is exposed to various effects, such as different roadway surface qualities, load distributions, driving speeds and other parameters [1, 4].

The main objective of this research is to analyse the driving properties of a vehicle with a trailer depending on a position of the load on a trailer loading area. The research is performed using a commercial multibody software, Simpack. It has been necessary to input to this software the researchers' own model of a vehicle and a trailer.

Although a number of studies have been conducted with regard to the influence that the driving properties of vehicle–trailer combinations exert on these vehicles in a state of motion, some characteristics, such as the dimensions, weight and occasionally other parameters, are specific for a particular combination.

There are various scientific works focussing on the investigation of the driving properties of vehicle–trailer combinations. They are aimed at assessing the manoeuvrability, handling, braking properties and behaviour of vehicle–trailer combinations. These researches are performed in various ways, such as by means of simulation computations, experimental tests, analytical models and other similar methods [5–8]. As the mentioned studies have shown, the driving properties of vehicle–trailer combinations are often and also significantly influenced by braking during driving manoeuvres [9–12]. However, in our research, the effects of braking during a movement of a vehicle–trailer combination are not investigated. This is because our research aims to ascertain the exact moment when, given that it is travelling at a constant driving speed, a vehicle–trailer combination comes into an unstable movement. On one hand, the multibody model allows the definition of a braking of the combination; however, on the other hand, the authors of the present study do not have access to the representative data, which would enable a driver's behaviour to be simulated as part of the overall simulated operational situations [10, 13, 14]. This matter can be a subject of study for future research. Further, the investigated vehicle–trailer combination is not equipped with a braking system (i.e. it does not have an overrun brake) [9, 15–17], and therefore, the braking operation has not been considered at all during simulated manoeuvres comprising the present study.

2. SIMULATION COMPUTATION OF A VEHICLE–TRAILER COMBINATION

A simulation involves experimentation with a virtual computation model, which represents a real vehicle. The goal is to optimise its properties before the final production. A simulation is widely accepted as a scientific method, and it is an apparatus of almost every scientific activity. While the accuracy obtained as a result of performing experimentation under actual real-world conditions is certainly desirable, the particular circumstances under which experiments are performed may not in themselves be adequately representative of the real-world conditions prevailing for the duration of time to which the research findings are sought to be extrapolated. For this reason, real-world experimentation may fail to manifest findings representing true, exact, structured and systematic facts, which necessities the use of simulations. A simulation works with a certain model of a vehicle, i.e. with an idealised form of a real vehicle. It can be understood that a simulation is an experiment with a model.

In the present study, simulation computation has been performed using Simpack software. It is a multibody software that enables virtual models of vehicles and vehicle combinations to be set-up, including nonlinearities [18–20]. A created MBS (multibody system) model of a vehicle and a trailer consists of rigid bodies interconnected by force elements. These force elements include massless components of a model, such as coil springs, hydraulic dampers, further torsion bars, components of wheels' suspension systems and others. Moreover, in the case of road vehicles, the Simpack software offers special force elements, which include models for tyre–road contact.

3. RESEARCH OF DRIVING OF A VEHICLE WITH A TRAILER WITH VARIOUS POSITIONS OF A LOAD

In practice, many accidents happen because a driver does not distribute a load on a loading area of a trailer to a proper position. These accidents are observed mostly in the case of passenger cars to which a single-axle trailer has been attached. In the case of single-axle trailers, drivers should ensure that a proper load will act upon a towbar. This maximal load is defined in a road law [21]. However, many drivers are not able to estimate this load, which leads either to an overload of a towbar in a vertical direction or to a towbar load that is too small [22–24]. A towbar overload can cause problems with the suspension system of a tow vehicle's rear axle. However, an even bigger problem can occur, if the centre of gravity (CoG) of the load, or of the entire trailer, is situated behind the trailer axle. Depending of the total weight of the trailer, this can cause the load distribution to become precariously skewed in such a way that the rear axle of the vehicle bears the least load, which can seriously compromise the steerability of the vehicle; this phenomenon is indeed the result of several serious road accidents. In particular, some instances of particular vulnerability for the loss of steerability to take place are driving in a curve and driving over road irregularities; and other circumstances, such as taking a sharp turn, could also be responsible for loss of vehicle control while attempting steering [25–28]. Accordingly, using simulation with the Simpack software, the present research introduces the results of analyses of various driving situations of a vehicle–trailer combination.

During investigation of the dynamics of vehicles or vehicle–trailer combinations, various output quantities are evaluated. From the dynamics point of view, acceleration signals are the most important. These signals pertain to accelerations in various locations of a vehicle [29]. These locations are chosen in such a way that the driving comfort can be evaluated [30–33]. Other quantities are forces, which most often pertain to the driving safety. In the presented research, the signals of accelerations would not find a direct application to the investigated phenomenon, i.e. the driving safety and driving stability of the vehicle–trailer combination [34–36]. Therefore, the wheel forces have been chosen as the main output parameters. In mentioning these forces, we refer to the lateral wheel forces between the trailer tyre and the roadway surface. In principle, either a left or a right wheel can be evaluated. In our case, we have decided to evaluate the lateral forces of the left wheel.

It is important to estimate the limit value of these forces. It can be assessed from multiple points of view. The limit value of the lateral wheel force has been estimated as the zero value of this force. This stance is an outcome of the fact that zero lateral force means slipping a wheel on the roadway surface, i.e. the danger of an accident. There has not been estimated any other limit value for the lateral wheel force.

3.1. An MBS model of a vehicle–trailer combination

A road model has been selected from the Simpack model database. Subsequently, CAD (computer-aided design) models of individual bodies of the passenger car and the single-axle trailer, such as car bodywork, wheels, the trailer frame and others have been imported to a model. Mechanical and kinematic joints have been defined between:
– a trailer towing bar and a trailer frame;
– a vehicle bodywork and a suspension system;
– a suspension system and a wheel; and
– a wheel and a roadway surface.

A vehicle–trailer combination model is shown in Fig. 1.

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Fig. 2 depicts selected dimensions of the vehicle–trailer combination, and the basic parameters of the towing vehicle are listed in Tab. 1.

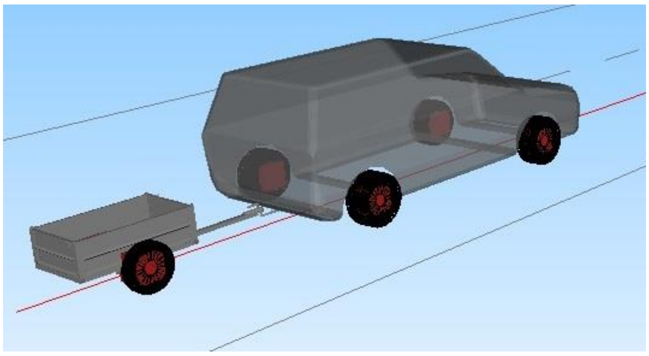

Fig. 1. A vehicle–trailer combination model

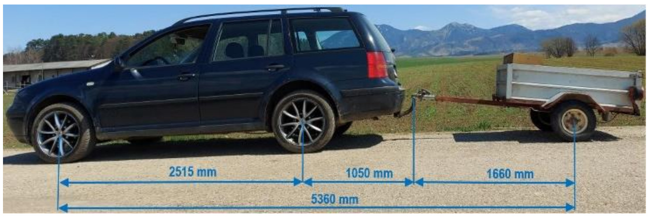

Fig. 2. Dimensions of the vehicle–trailer combination

Tab. 1. Parameters of the towing vehicle

Parameter	Value (mm)
Length	4,397
Height	1,473
Width	1,735
Wheelbase	2,515

The superstructure of the trailer has dimensions of 1,300 mm (the length) and 1,000 mm (the width).

Within the research, various driving situations have been evaluated. These have been observed with reference to the output parameters total vertical force and lateral force. Further, the research has investigated a situation of driving in a curve when a load with the total weight of 220 kg has been placed on the trailer loading area. The vehicle–trailer combination has been driving on the road at the speed of 55 km/h and the load has been positioned in such a way that the CoG of the load is located:

- in the front part of the trailer;
- in the rear part of the trailer; or
- behind the trailer.

Moreover, the research investigates a maximal speed, at which a vehicle–trailer combination is able to drive in a curve safely. The vehicle–trailer combination has been driving on a road with a specified geometry. The road geometry has been created based on experiences of researchers and it has not corresponded to any real road. The road profile has been chosen in such a manner that the equanimity or steadiness of the movement of the vehicle–trailer combination would be disturbed even under optimal driving conditions. The road geometry in the horizontal plane is shown in Figs. 3 and 4; from these images, we infer the road curvatures in the corresponding locations. Additionally, the road tracking in the Simpack software is depicted in Fig. 5.

The modelled road profile is comprised of several sections, which are the following: a straight section of 20 m, a right-handed curve with a radius of 30 m, a left-handed curve with a radius of 20 m, a straight section of 10 m and finally two curves – firstly a left-handed curve and then a right-handed one, each with the radius of 20 m. Fig. 3 provides the view from below to the road profile (as the software renders it).

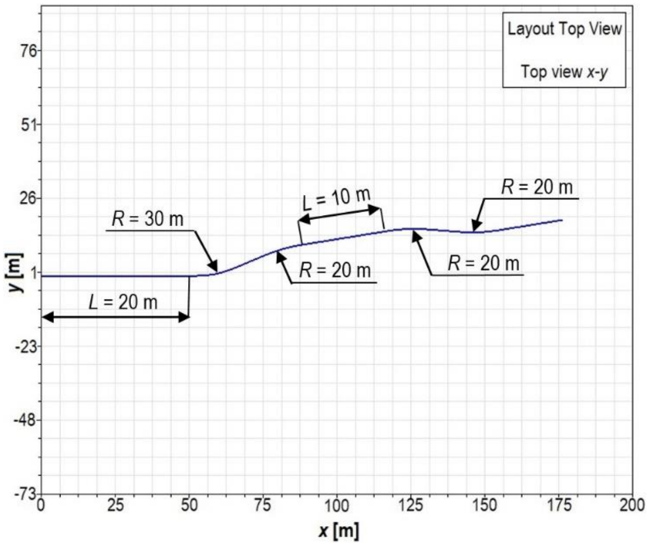

Fig. 3. Road geometry shown in a horizontal plane

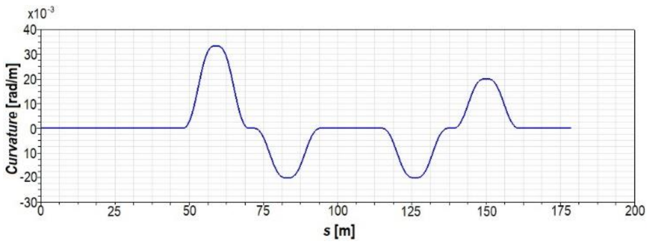

Fig. 4. The curvature of the created road

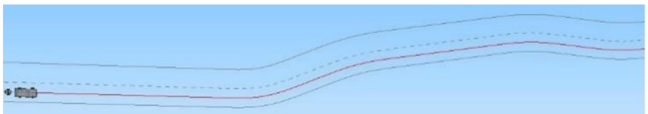

Fig. 5. A testing road in the Simpack software

An important element of simulation-based computations of movement of a vehicle (or an entire vehicle–trailer combination) is a model of tyre–road contact. There are several models of tyre–road contacts that are available for researchers to study, as well as available in the used Simpack software. In our case, a tyre–road model called the Pajecka contact model has been used [37, 38]. The parameters are defined through a text file, which has been used in conjunction with a setting win-dow applicable to this modelling element

The defined tyre–road model includes parameters for dimensions of tyres, vertical and lateral stiffness of tyres, damping coefficients, roadway surface coefficients and others. In the created vehicle–trailer combination, three different tyre–road models have been applied, namely for the front wheels of the vehicle, for the rear wheels of the vehicle and for the trailer wheels. While the tyre model of the trailer wheels has been very different in comparison with the tyre models of the vehicle, the tyre models of the front and rear wheels have differed only in having stiffness values and damping coefficients that are slightly different from each other, and this minute difference was caused by variations in the tyres' air pressure values. The friction coefficient has been set to the value of 0.75 for all tyre–road contacts [37–40].

3.2. The CoG of the load located in the front part of the trailer

The trailer has been loaded with a load of 220 kg. The curb weight of the trailer is 180 kg, and together with the load, this gives a total weight of 400 kg. The driving speed of the vehicle–trailer combination has been set to a value of 55 km/h. The load has been deposited in the front part of the trailer. A comparison between an actual vehicle–trailer combination operating under real-world conditions, and the same combination according to the MBS model employed in the present research, is shown in Figs. 6 and 7.

Fig. 6. A real vehicle–trailer combination with the load deposited in the front part of the trailer

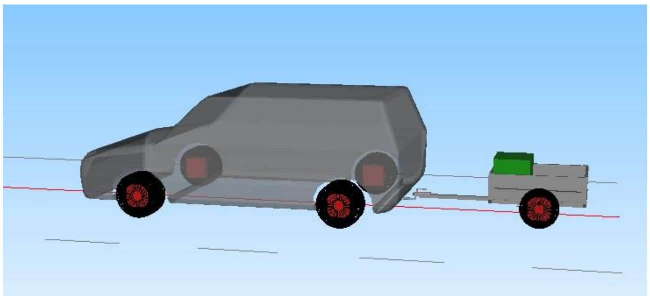

Fig. 7. An MBS model of a vehicle–trailer combination with the load deposited in the front part of the trailer

In this case, in order to determine the optimal position within the trailer in which the load may be de-posited, it is first necessary to obtain the maximum permissible load that can be borne by the towing ball of the vehicle. For the chosen vehicle, 75 kg is pre-scribed as the maximal permissible vertical load. The same load can be represented as 735.75 N in terms of force (together with the gravitational acceler-ation being considered at g = 9.81 m/s2). The CoG of the trailer is given by its design, and it is located 115 mm in front of the axle (in the driving direction). If the dimensions of the trailer and the vehicle–trailer combination (Fig. 2) were considered, then, for our particular case corresponding to a load of 220 kg, the maximum allowable distance within which the CoG needs to be located would be 471.82 mm in front of the trailer axle. The internal length of the superstructure of the trailer and the dimensions of the designed load allow the load to be placed in such a position that the CoG of the trailer is located 400 mm in front of the trailer axle. This is depicted in Figs. 6 and 7. It means that the permissible vertical load of the towing ball of the vehicle of 735.75 N is not exceeded.

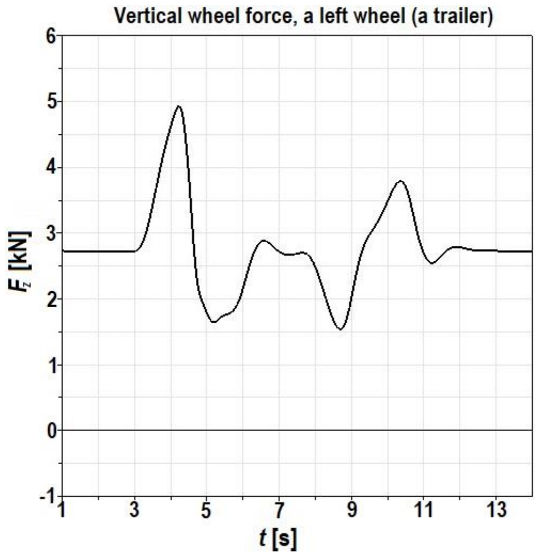

Fig. 8. A waveform of the total vertical wheel force of the trailer (a left wheel), with the load located in the front part of the trailer

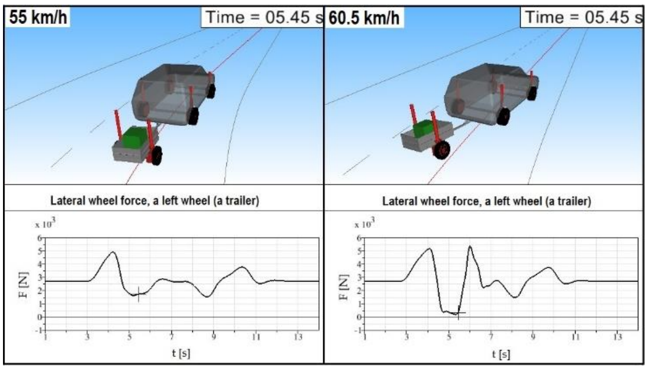

Fig. 9. A comparison of situations for the driving speeds of 55 km/h and 60.5 km/h

The results of a waveform of the vertical wheel force of the left wheel of the trailer (shown in Fig. 8) demonstrate that a vehicle–trailer combination has been able to safety drive in the curve. Further, 60.5 km/h has been identified as the maximal speed at which a vehicle–trailer combination with the described configura-tion is able to safely drive along the given curve. The speed of 61 km/h leads to the loss of wheel–road contact and skid occurs. A comparison of the total vertical force of the trailer wheel for two different speeds is shown in Fig. 9.

3.3. The CoG of the load located in the rear part of the trailer

For investigating the driving properties of the vehicle–trailer combination, this time with the load placed in the rear, a load

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quantity was chosen such that the total weight amounted to the same 220 kg, and the chosen driving speed also remained the same at 55 km/h. Again, the driving of the vehicle–trailer combination on the same road and with the same curves' radii has been investigated. Figs. 10 and 11 illustrate a comparison of a real vehicle–trailer combination with an MBS model, with the load deposited in the rear part of the trailer.

Fig. 10. A real vehicle–trailer combination with the load deposited in the rear part of the trailer

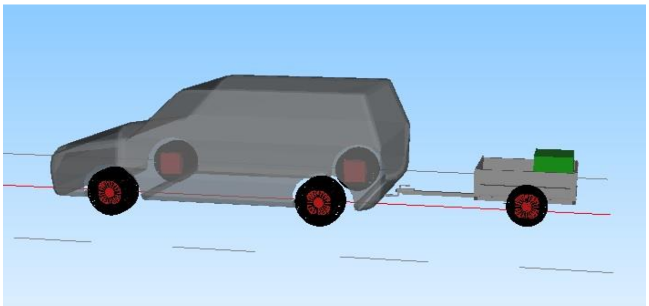

Fig. 11. An MBS model of a vehicle–trailer combination with the load deposited in the rear part of the trailer

Based on the calculated output parameters, it is ascertained that the vehicle–trailer combination is able to drive through the curve safely. On the one hand, the trailer was moving in a slight oscillating movement in the horizontal plane; however, on the other hand, after overcoming the curve, the drive of the vehicle–trailer combination was stabilised.

The acting of the total vertical wheel force between a wheel of the trailer and the road is depicted in Fig. 12.

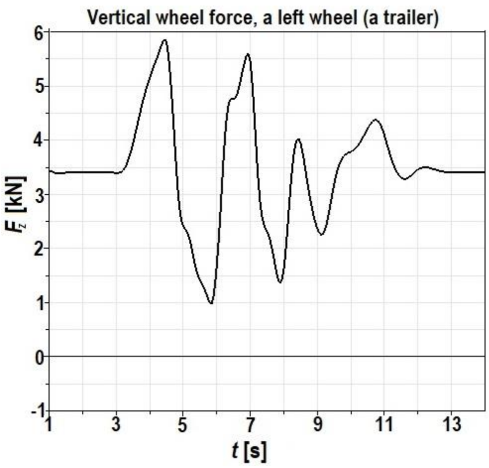

Fig. 12. A waveform of the total vertical wheel force of the trailer, with the load located in the rear part of the trailer.

3.4. The CoG of the load located behind the trailer

This is a case of load-carrying involving a trailer, wherein the driver uses the trailer to transport lengthy items, such as wooden beams, metal plates or rods or other similar objects. In such a case, the CoG of the load is usually located behind the trailer, as can be seen in Fig. 13. A multibody model of the vehicle–trailer combination with the load situated behind the trailer is depicted in Fig. 14.

Fig. 13. A real vehicle–trailer combination with the CoG of the load situated behind the trailer

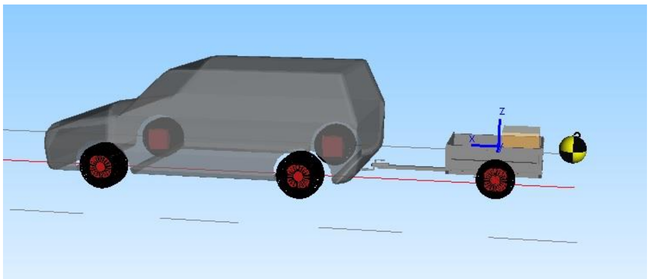

Fig. 14. An MBS model of a vehicle–trailer combination with the CoG load situated behind the trailer

The parameters of the load and the inputs for the simulation have again been the same, i.e. the total weight (the sum of the curb and load weights) has been set as 220 kg and the driving speed has been set as 55 km/h. The CoG of the load located behind the trailer is marked by a black-yellow sphere (Fig. 14).

The passage of the vehicle–trailer combination along the same path as in the previous cases has been examined.

The vehicle–trailer combination has not passed the test of driving in curves. When it was moving along the first curve, a skid occurred and the vehicle–trailer combination was ejected out of the road (Fig. 15). A waveform of the total vertical force on the left wheel of the trailer is shown in Fig. 15. As can be seen, the vertical wheel force in the time interval 6.5–8 s equals 0, which means that no lateral force could be generated, resultant to which the trailer slides to the side.

For this case, a waveform of the lateral wheel force of the left rear wheel of the vehicle is shown in Fig. 16. This waveform reveals that the rear part of the vehicle oscillates around a mean value. Practically, this corresponds to the oscillating movement of the rear part of the vehicle, and this movement of the vehicle is uncontrolled. Due to the described facts (trailer dimensions, load dimension, the permissible vertical load of the towing ball and the load value), the position of the load presented in Section 3.2 is recommended for these particular conditions.

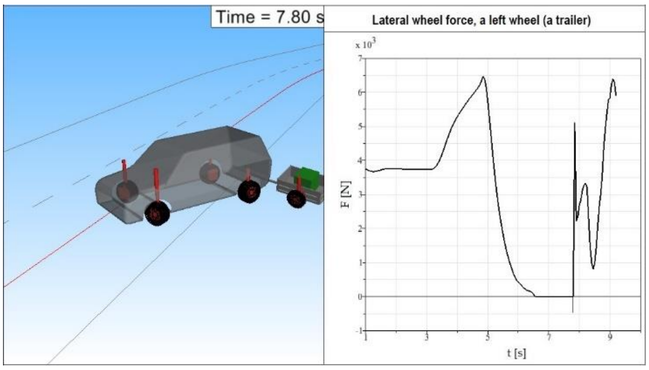

Fig. 15. A waveform of the wheel force of the trailer, a left wheel

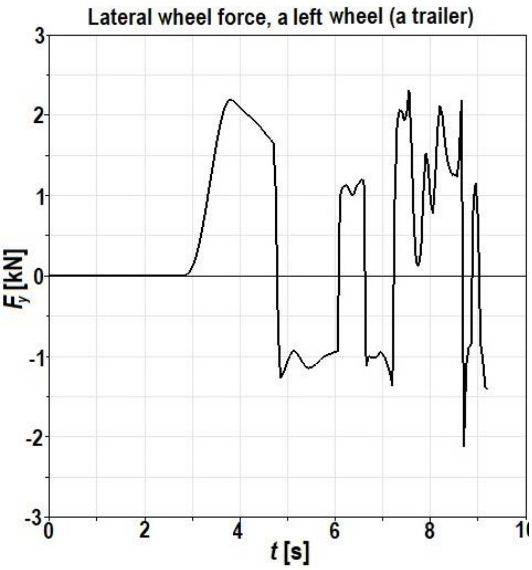

Fig. 16. A waveform of the lateral wheel force of the trailer, with the CoG of the load located behind the trailer

The future research in this field will be focussed on performing simulations with vehicle–trailer combinations with different parameters, i.e. for vehicles and trailers of different categories. Further, the multibody model can be improved by implementation of flexible bodies. Such a multibody model will better represent some structural properties of a vehicle, a trailer or even both.

As is obvious, the presented results are obtained from simulation-based computations. The credibility of simulation-based computations should be verified through comparisons with the results of experimental tests [9, 29]. Such tests can be performed using a real vehicle–trailer combination or, alternatively, using a scale model [41]. Each of these approaches has its own advantages and disadvantages depending on the point of view. While experiments deploying a real vehicle-and-trailer pair provide actual results, results derived from tests performed using a scale model need to undergo a certain process of conversion before they can be compared with parameters pertaining to real vehicles. In terms of safety and financial costs, scale models appear more advantageous, because an expensive infrastructure would be required for conducting tests with real vehicles (a road without public traffic, a vehicle and trailer with a safety system in a case of overturning, etc.) [42].

4. CONCLUSIONS

The main goal of the paper was to investigate the dependence of the driving properties of a vehicle–trailer combination on the load positions. The work consisted in creating the CAD models of a vehicle and a trailer. Subsequently, these CAD models of vehicles were implemented within the framework of the MBS software Simpack. After defining the mass and inertia parameters of the vehicles, various simulation computations were performed.

Three possibilities of depositing a load on the loading area of a trailer were compared. It has been discovered during the research that a small change in driving speed and in the position of the load can cause a deterioration of driving properties in terms of driving stability, i.e. can result in the vehicle–trailer combination sliding off the road or even overturning.

Using an MBS software such as Simpack, it is possible to relatively easily introduce changes in the various driving situations and parameters concerning the investigated vehicles. Such an exercise is helpful for evaluating and assessing the driving properties of vehicles without calling forth the risk that would be involved in performing dangerous driving manoeuvres with a real vehicle–trailer combination.

The simulations demonstrated in the present study, performed with the use of MBS software, have revealed the most dangerous position that can be used for depositing a load on a trailer, together with more favourable positions. The obtained results and findings introduce a more general benefit, in that it can be assumed that vehicle–trailer combinations with different parameters (with regard to vehicle and a trailer dimensions) will also behave in a similar way. A driver must avoid a situation wherein the CoG of the load on the trailer is situated behind the trailer axle, even behind the trailer itself. Such a position of the load leads to a considerable lightening of the weight-burden of the rear axle of the towing vehicle, and driving at a higher speed in this condition can thus result in a dangerous accident.

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