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Research on dynamical properties of a three-wheeled electric vehicle from the point of view of driving safety

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Abstract: Many vehicles in urban and suburban environment are occupied just by one passenger, i.e. by a driver. Therefore, it is worth to think about vehicles, which would be smaller and lighter and which would include environmental-friendly power source. One such vehicle is the presented three-wheeled electric vehicle. This vehicle is designed for one passenger and it is powered by an ecologic electric powertrain. Therefore, it is necessary to research its driving properties. There are two types of vehicle designs, an original design and a modified design with a reworked body. Both are characterised by the symmetrical distribution of the mass to the longitudinal axis. In terms of driving properties of the vehicle, overturning stability during cornering and vertical dynamics in terms of safety are assessed for both original and modified designs. The article presents the main description of the original and modified designs of the three-wheeled vehicle and results from simulation computations focused on analysis of the over-turning stability. It has been revealed that the original vehicle, which is lighter, has better dynamical properties in curves with regards to driving and the higher total weight of the modified vehicle is safer in terms of vertical dynamics.

Keywords: three-wheeled vehicle, dynamical properties, multibody model, numerical simulations, driving stability

1 Introduction

Currently, vehicles with an electric powertrain are coming to the forefront. Bicycles, cars, as well as bigger vehicles like buses and lorries are among them. As currently many sources of electric energy are available, it turns out that the electric power could be the future of transport and electric vehicles could replace common vehicles with combustion engines.

Electric vehicles are most often used in cities, because they have shorter range. Thanks to this, it creates a space for other types of cheaper vehicles, such as tricycles, because there is no emphasis on high driving speeds [1–3]. In many cities, the maximal speed is from 50 to 80 km/h (in case of multiple line roads) [4]. Therefore, requirements for aerodynamics or soundproofing are not so strict in comparison to driving at the motorway speeds. On the contrary, the emphasis is on the total weight and compactness of the vehicles. In this term, two- and three-wheeled vehicles are more advantageous [5–7].

As time and development went forward, the design of these vehicles has become much simpler, thanks to 3D programs, in which, it is possible to design such a vehicle relatively quickly and easily. The proposed solution can be used again over time for new types of vehicles or some parts of the vehicle can be modified without the need for a lot of completely new documentation. However, the design of the model does not end there, it is necessary to perform various tests on these vehicles, for which we use simulation programs. Today, there are a number of simulation programs that allow to investigate a vehicle in many points of view, e.g. to evaluate vertical dynamics,
driving properties and others. These simulations replace real tests, which can lead to complete destruction of the vehicle in many cases, or even to personal injury. This method of testing can save a lot of money as well as time [8–10].

This work is focused on investigation of driving properties of a three-wheeled electric vehicle (a tricycle). The tricycle has been designed to provide a small city electric vehicle with low noise, low operational cost and improved driving stability by implementing a special steering mechanism. The vehicle is equipped with the electric powertrain providing zero-emission operation [11]. The detailed description of the designed steering mechanism as well as the results of simulation computations of its stability during driving in curves can be found in the literature [12,13].

The current design of the vehicle (Figure 1) is without a roof and other elements are missing (e.g. lighting).

Although such a vehicle is light in weight, its operation is limited by weather conditions. Therefore, the research team is continuing to work on the universal usage of the three-wheeled vehicle for any weather conditions, to improve its active and passive safety and its utility properties.

The goal of this work is to present the results of the research focused on changing the design of the tricycle and to present a comparison of the achieved dynamic properties of the original (a basic design) and modified tricycle (a modified design).

Section 2 contains theoretical background of the designs of the three-wheeled vehicles. A description of the modified design is given in Section 3, an analysis of overturning stability is included in Section 4 and an assessment of the vertical dynamics of the vehicles is provided in Section 5. Discussion is provided in Section 6 while conclusion of the research is given in Section 7.

2 Materials and methods

A tricycle is a three-wheeled vehicle, which is intended to transport people or material. This type of vehicle has certain advantages and disadvantages compared to the concept of two- and four-wheeled vehicles.

2.1 Basic types of three-wheeled vehicles

There are two types of three-wheeled vehicles (Figure 2): Delta version (Figure 2a), which has two rear wheels and one front wheel and Tadpole version (Figure 2b) with two front wheels and one rear wheel.

The Tadpole type allows better stability in curves at higher speeds; however, it has usually larger turning radius, which is not so suitable for crowded cities. In both technical solutions, one wheel is placed in the axis of symmetry of the vehicle.

The Delta type brings better versatility and manoeuvrability, as the front wheel can rotate to larger angles.

Figure 1: Current design of the three-wheeled electric vehicle.
in comparison with the Tadpole. Theoretically, this design allows us to reach a turning radius equal to the vehicle length; however, in practice, this is not possible to fulfill.

The disadvantage of the Delta type is its lower stability during driving in curves (moreover, in combination with braking) [15–17].

The turning stability condition of the Delta type comes from Figure 3a and b, where \( F_0 \) (m) is the centripetal force and it represents a hypotenuse. Then, the force \( F_0 \) is the needed component of the centripetal force \( F_0 \) and it equals to the value \( F_0 = F_0 \cdot \cos \phi \) and it is a leg. Hence, the turning stability condition of the Delta type is given by the following formula:

\[
\frac{F_0}{G} \leq \frac{B}{2 \cdot L} \cdot \frac{L_p}{h}.
\]

(1)

The centrifugal force of the vehicle is calculated based on the known formula.

\[
F_0 = m \cdot a_0,
\]

(2)

where \( m \) (kg) is the weight of the vehicle, \( a_0 \) (m/s\(^2\)) is the centripetal acceleration and \( G \) (N) is the gravitational force of the vehicle and it is calculated by the known formula as follows:

\[
G = m \cdot g,
\]

(3)

where \( g \) (m/s\(^2\)) is the gravitational acceleration.

After substituting equations (2) and (3) in equation (1) and subsequent elimination of the vehicle weight \( m \), the stability condition is as follows:

\[
\frac{a_0}{g} \leq \frac{B}{2 \cdot L} \cdot \frac{L_p}{h},
\]

(4)

where \( a_0 \) (m/s\(^2\)) is the centripetal acceleration, \( g \) (m/s\(^2\)) is the gravitational acceleration, \( B \) (m) is the rear wheel-base, \( L \) (m) is the track width, \( L_p \) (m) is the position of the centre of gravity from the front wheel and \( h \) (m) is the vertical position of the centre of gravity. These parameters are depicted in Figure 3.

Figure 2: Basic types of the three-wheeled vehicles: (a) Delta version and (b) Tadpole version [14].

Figure 3: A modified design of the three-wheeled electric vehicle: (a) ground plan and (b) rear plan.
Centripetal acceleration $a_O$ is calculated as follows:

$$a_O = \frac{v^2}{R},$$  \hspace{1cm} (5)

where $v$ (m/s) is the vehicle speed and $R$ (m) is a curve radius.

The resulting condition for the limit speed of overturning stability of the Delta type is as follows:

$$v_{\text{max}} \leq \sqrt{\frac{B}{2 \cdot h} \cdot \frac{l_p}{L} \cdot R \cdot g},$$  \hspace{1cm} (6)

where $v_{\text{max}}$ (m/s) is the maximal speed of the vehicle and $R$ (m) is the curve radius. As it can be identified, the maximal speed in terms of the overturning stability of a Delta three-wheeled vehicle proportionally depends on the wheelbase $B$, the position of the centre of gravity $l_p$, the curve radius $R$ and disproportionally on the height of the centre of gravity $h$ and the track width $L$. The weight of a vehicle is not critical, because it influences both gravitational force (the stability moment) and the centrifugal force (the tilting moment) equation (1).

### 2.2 Steering of three-wheeled vehicles

Obviously, the design of the front wheel is much simpler for the Delta type. The best is to choose a telescopic front fork. The rear axle is more complicated, because there are many types of wheel suspensions and it is necessary to investigate the best option for a particular vehicle.

The Tadpole design has the opposite situation. The rear wheel is usually suspended by a swinging arm and front wheels are suspended on a more complicated front axle. The Tadpole must include a steering mechanism and all needed components to reach an Ackermann steering geometry (Figure 4).

It follows that the Tadpole is more expensive type in terms of design and production and it is necessary to think about the requirements of the particular three-wheeled vehicle [12,13].

### 3 Modification of the tricycle

The modified design of the solved three-wheeled vehicle (Figure 5) comes from the original design of the vehicle (Figure 1). The main goal of the three-wheeled vehicle modification is to improve driving safety, driving comfort, protection against negative weather conditions as well as to improve the utility of the vehicle.

#### 3.1 Components of driving safety

A roof serves as the main safety element. It protects the driver against injury in case of overturning of the vehicle. It is composed of a frame, which is welded by means of hollow square profiles and thin metal sheets. A windscreen is also located on this frame and it protects passengers against wind and flying objects from the vehicle driving in front of it. The modified model is equipped with complex lighting technology, i.e. front lights, rear lights, a fog light and others (Figure 5). It is proposed to be made of LED technology to save electric energy and to warrant a life as long as possible.

Furthermore, the front part of the vehicle includes a covering of the special steering mechanism [19,20]. It will ensure a protection against dirt and it will significantly improve the passive safety of the vehicle in case of an accident (pedestrians, other vehicles, etc.) (Figure 6).

#### 3.2 Utility of the vehicle

The utility of the vehicle helps to improve a box mounted on the rear part of the vehicle on two holders. The box can serve as a luggage compartment, or it can be replaced by a bicycle carrier and others. The box is made of plastic material, which allows us to reduce the total weight at sufficient strength together with corrosion resistivity (Figure 5b).

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![Figure 4: Ackermann steering geometry of two types of three-wheeled vehicles: (a) Delta version and (b) Tadpole version.](image-url)
The interior of the vehicle is equipped with a dashboard to display the required indicators, e.g. for lights, direction indicators, parameters of electrical powertrain and others. Further, it serves as a cover of a steering mechanism and it also actuates devices for lights, starting up, etc.

All these modifications of the vehicles have led mainly to change the total weight and position of the centre of gravity, which affect the dynamic properties of the vehicle. The position of the centre of gravity has been considered symmetrical to the longitudinal axis of the vehicle in both cases. Section 4 gives the results of simulation computations and comparison of the main parameters of the vehicle for the original design (Figure 1) and modified design (Figure 5).

To summarise, the description of the modified vehicle includes elements of active safety, which are mainly front and rear lights, indicators, mirrors, special steering mechanism for increasing overturning stability and others. The main element of passive safety is the frame, which prevents a passenger against injuries in case of an accident.
4 Simulation computations of driving overturing stability when driving in curves

Knowledge of theoretical parameters is necessary to compare the results of simulation computations. The theoretical parameters are obtained by means of analytical calculations. Calculations are performed for both original and modified designs of the three-wheeled vehicle and for various curve radii.

Basic parameters of the three-wheeled vehicle are listed in Table 1, where \( B (\text{m}) \) is the wheelbase, \( h (\text{m}) \) is the vertical position of the centre of gravity, \( L (\text{m}) \) is the track width, \( l_P (\text{m}) \) is the position of the centre of gravity from the front wheel and \( g (\text{m/s}^2) \) is the gravitational acceleration. The original design of the three-wheeled vehicle does not have a roof (Figure 1), while the modified design includes a roof (Figure 5).

Calculation of the maximal driving speed \( v_{\text{max}} (\text{m/s}) \) for cornering is obtained by substituting parameters from Table 1 in the following formula:

\[
v_{\text{max}} = \frac{0.775 \cdot 0.798 \cdot 10 \cdot 9.81}{2 \cdot 0.210 \cdot 1.650} = 33.68 \text{ km/h}. \tag{7}
\]

The introduced calculation serves as an example and parameters are chosen for the original design of the vehicle and the curve radius \( R = 10 \text{ m} \). Maximal driving speeds have been calculated for the driving speed range from 0 to 100 km/h. Table 2 contains results for five selected curve radii.

These results indicate the stability of the vehicles for cornering. It can be understood from this kind of stability that a vehicle can drive through a curve at the maximal speed corresponding to the situation, when all wheels are still in contact with the road.

The position of the centre of gravity affects most significantly the stability for cornering. It is obvious from Figure 7 that the vertical position of the centre of gravity is higher for the modified vehicle (Figure 7b) in comparison to the original one (Figure 7a).

These obtained results of analytical calculations have been compared with the results of the simulation computations performed in the Simpack software package. In principle, the results of simulation computations correspond to the results of analytical calculations. Slight differences are caused by the fact that simulation software better simulates a real situation, i.e. the centre of gravity moves during cornering in the direction of the vehicle movement. Tilting of the vehicle is not considered in analytical calculations. Therefore, the maximal driving speeds from simulation computations are little lower (Table 3).

The maximal driving speeds have been identified in the multibody simulation by evaluating the value of the vertical wheel force of the inner wheel during cornering (Note: an inner wheel during driving in a counter-clockwise curve is the left wheel, while an inner wheel during

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**Table 1**: Basic parameters of the three-wheeled vehicle

<table>
<thead>
<tr>
<th>Type of the vehicle</th>
<th>( B (\text{m}) )</th>
<th>( h (\text{m}) )</th>
<th>( l_P (\text{m}) )</th>
<th>( L (\text{m}) )</th>
<th>( g (\text{m/s}^2) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original design</td>
<td>0.775</td>
<td>0.210</td>
<td>0.798</td>
<td>1.650</td>
<td>9.81</td>
</tr>
<tr>
<td>Modified design</td>
<td>0.775</td>
<td>0.470</td>
<td>0.855</td>
<td>1.650</td>
<td>9.81</td>
</tr>
</tbody>
</table>

**Table 2**: Calculated maximal driving speeds during cornering for the original and modified vehicles

<table>
<thead>
<tr>
<th>( R (\text{m}) )</th>
<th>Original vehicle ( v_{\text{max}} (\text{km/h}) )</th>
<th>Modified vehicle ( v_{\text{max}} (\text{km/h}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>33.68</td>
<td>23.31</td>
</tr>
<tr>
<td>25</td>
<td>53.26</td>
<td>36.85</td>
</tr>
<tr>
<td>50</td>
<td>75.32</td>
<td>52.11</td>
</tr>
<tr>
<td>75</td>
<td>92.25</td>
<td>63.83</td>
</tr>
<tr>
<td>100</td>
<td>106.52</td>
<td>73.70</td>
</tr>
</tbody>
</table>

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**Figure 7**: Position of the centre of gravity: (a) the original design and (b) the modified design [18].
driving in a clockwise curve is the right wheel). The limit case is when the reaction between an inner wheel and the road equals to zero, i.e. the vertical reaction \(F_R = 0\) N.

Further, Figure 8 shows the waveforms of vertical wheel forces of the rear wheels of the original vehicle (left) and of the modified vehicle (right). This figure depicts how the vertical wheel forces are being changed during driving in curves with various radii. As it can be seen, the vertical wheel forces of the original vehicle are smaller due to lower total weight of the vehicle. Lower total weight is reflected by lower amplitudes of these forces in curves.

On the other hand, the heavier vehicle has higher values of the vertical wheel forces as well as higher amplitudes of these forces in curves.

Figure 9 shows a comparison of additional kinematic parameters, the angle of tilting of the bodyworks of both the original and modified vehicle designs. As it can be recognised, the tilting of the bodywork of the modified vehicle is higher than the tilting of the original vehicle.

### Table 3: Results of the contact of individual wheel and road surface with various surface qualities during driving for the original vehicle design

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>Wheel</th>
<th>Very good cement concrete</th>
<th>Good asphalt concrete</th>
<th>Good macadam</th>
<th>Medium pavement</th>
<th>Bad pavement</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Front</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Rear right</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Rear left</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>20</td>
<td>Front</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Rear right</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Rear left</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>30</td>
<td>Front</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Rear right</td>
<td>x</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Rear left</td>
<td>x</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
<td>x</td>
</tr>
</tbody>
</table>

Note: The road surface qualities and driving speeds are listed, wherein signs “✓” and “✗” in the columns indicate whether the individual wheel is still in contact with the roadway (“✓”) or it has lost contact (“✗”). Once any wheel has lost contact with the road surface during simulation, the driving is evaluated as unacceptable and the corresponding box is marked with the sign “✗.”

Figure 8: Waveforms of vertical wheel forces for rear wheels, the original design (left), the modified design (right).
Again, it is caused by the position of the centre of gravity, namely, its height. It also means that a passenger feels lower ride comfort level [20–23].

It can be concluded from the achieved results that modified vehicle can drive in curves at lower driving speeds than the original vehicle. The higher position of the centre of gravity leads to lower stability in curves.

5 Simulation computations of driving safety when driving on different road surfaces

From the driving safety point of view, the vertical force between the tyre and road surface is necessary to be investigated. When a vehicle is driven on a roadway with stochastic irregularities, the time response of the vertical loading of a wheel $F_w(t)$ is stochastic as well [23] (Figure 10).

The force $F_W$ varies about a certain average value $F_\text{Wstat}$, which is equal to the static load of a wheel $F_\text{Wstat}$ (N).

$$F_\text{W}(t) = F_\text{Wstat}. \quad (8)$$

Then, the total vertical load of a wheel is given by the sum of the static vertical load of a wheel $F_\text{Wstat}$ (N) and the dynamic vertical loading of a wheel $F_\text{Wdyn}$ (N).

$$F_W(t) = F_\text{Wstat} \pm F_\text{Wdyn}(t). \quad (9)$$

If equations (5) and (6) are considered, the variance in the vertical load of a wheel during the vehicle driving is defined as follows [23]:

$$\sigma_{F_W}^2 = (F_W(t) - F_{\text{Wstat}})^2 = (F_{\text{Wstat}} \pm F_{\text{Wdyn}}(t) - F_{\text{Wstat}})^2 = F_{\text{Wdyn}}^2(t). \quad (10)$$

The formulation (9) expresses the quadrature of the root means square of the vertical dynamic load of a wheel during driving on road irregularities. In the driving safety point of view, the standard deviation of the vertical dynamic load of a wheel $\sigma_{F_\text{Wdyn}}$ has to be as small as possible.

Figure 9: Waveforms of tilting angle of the bodywork, the original design (a black solid curve), the modified design (a red dash curve).

Figure 10: Response of the vertical load of a wheel with respect to time [23].
Table 4: Results of the contact of individual wheel and road surface with various surface qualities during driving for the modified vehicle design

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>Wheel</th>
<th>Very good cement concrete</th>
<th>Good asphalt concrete</th>
<th>Good macadam</th>
<th>Medium pavement</th>
<th>Bad pavement</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Front</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Rear right</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Rear left</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>20</td>
<td>Front</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Rear right</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<td>✓</td>
</tr>
<tr>
<td></td>
<td>Rear left</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>30</td>
<td>Front</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Rear right</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td></td>
<td>Rear left</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Note: The road surface qualities and driving speeds are listed, wherein signs “✓” and “✗” in the columns indicate whether the individual wheel is still in contact with the roadway (“✓”) or it has lost contact (“✗”). Once any wheel has lost contact with the road surface during simulation, the driving is evaluated as unacceptable and the corresponding box is marked with the sign “✗.”

It is possible to determine the vertical static wheel force relatively easily, i.e. it is calculated from the total weight of the vehicle and the position of the centre of gravity in longitudinal and lateral directions. However, determining the vertical dynamic load of a wheel is more difficult. It is because the dynamic vertical load depends on vibrational properties of a vehicle, driving speed and roadway irregularities. These factors affect the total phenomenon called as the vertical dynamics of a vehicle. In terms of driving safety of a vehicle, reducing a wheel loading with respect to its static load is important. Smaller values of the vertical wheel force decrease the transmittable tangential forces, among which are the driving force, braking force and radial force, which are very important for steering of a vehicle. In limit cases, when a wheel jumps off the roadway, the vertical load of the wheel equals to zero \( F_{W_{dyn}} = 0 \text{ N} \). When this case appears on the steering axle, the vehicle is uncontrollable in this moment [24,25].

Simulation computations were performed for driving on a roadway with different surface qualities. Road surface irregularities have been modelled by means of the power spectral density (PSD). The PSD is a mathematical description of road surface irregularities and it allows us to input into a road surface model such data, which represent typical road surface qualities [26,27]. Hence, the mechanical system of the investigated vehicle is excited by the kinematic excitations.

In our research, a number of simulations have been performed for various types of road surface irregularities. As a representative example, results for five selected road surface irregularities are evaluated, in which, an adhesion coefficient \( f \) defined for individual road surfaces is indicated.

- Very good cement concrete \( (f = 0.75) \);
- Good asphalt concrete \( (f = 0.75) \);
- Good macadam \( (f = 0.65) \);
- Medium pavement \( (f = 0.65) \);
- Bad pavement \( (f = 0.65) \).

All road surfaces were supposedly dry. Driving safety of the investigated three-wheeled vehicle was assessed for several driving scenarios. The vehicle was tested with a variety of simulations and the vehicle was driven on the road with irregularities described above and at various speeds. The results presented below include only selected interesting results, namely, for the driving speed of 10, 20 and 30 km/h. In our tests, a straight track section has been chosen for avoiding negative effects to the monitored quantities, e.g. driving in curves, climbing, downhill, etc.

Table 3 shows the total overview of the results of simulation analyses for the original three-wheeled vehicle design. Results for the modified three-wheeled vehicle analysed in a similar manner are displayed in Table 4.

The achieved results show that the original three-wheeled vehicle drive is still safe for speeds of 10 and 20 km/h (Table 3). All wheels were still in contact with the road and it does not depend on whether the three-wheeled vehicle is driven on very good quality road or a road with medium pavement surface quality. Once the original vehicle is driven at the speed of 30 km/h, the driving is not safe either for low road quality or for very
good road quality. Despite the front wheel of the vehicle being in contact with the road for four out of five road qualities, the other wheels jumped off the road, therefore, the driving must not be evaluated as safe.

On the other hand, the driving of the modified three-wheeled vehicle seems to be safer for investigated driving conditions (Table 4). All wheels are in contact with the road for speeds of 10, 20 km/h as well as 30 km/h for very good cement concrete, good asphalt concrete and good macadam. Driving on the medium pavement represents not completely safe driving, because the rear left wheel jumped off the road. Despite the centre of gravity being located in the longitudinal plane of the symmetry, rear right wheel is still in contact with the road. However, driving the modified vehicle on the bad pavement quality at the speed of 30 km/h is not safe.

As it can be seen from the presented results in terms of vertical dynamics, higher total weight of the vehicle has led to better driving safety with regards to driving on the road with irregularities. The modified vehicle has higher total weight, but the stiffness-damping parameters of the suspension system correspond to the original one.

6 Discussion

Achieved results of simulation computations for defined driving conditions have revealed important findings.

In terms of overturning stability of the vehicle during cornering, the original design of the vehicle with lower position of the centre of gravity is more appropriate and this type of vehicle is able to overcome curves at higher driving speeds. On the other hand, the modified vehicle (with a roof and additional accessories) has higher total weight, which contributes to decreased vertical vibrations of the vehicle during driving on a rough road, mainly at higher driving speeds.

The driving speeds of both vehicles (original and modified) for analysis of overturning stability have been chosen much higher than the driving speeds were for analysis of the driving safety on various road surfaces. The achieved results lead to the motivation to perform further research activities with the vehicle, such as additional modification and investigation of the vehicle. All activities should lead to optimal technical solutions, which will make use of favourable parameters of the vehicle, such as the position of the centre of gravity, wheelbase, track width and others for safe driving in curves. The vertical dynamics of the vehicle is affected mainly by the parameters of the used springs and dampers. These components should be modified to achieve the acceptable vibrational properties for driving on various road surface qualities, which can occur in urban environment.

7 Conclusion

Using small urban vehicles with an electric powertrain will be still up to date. They provide relatively rational solution not only for overcrowded agglomerations, but also for smaller cities, which want to retain a clean environment. The presented three-wheeled vehicle is one of the transport means. As the vehicle is just a prototype, it is necessary to investigate its driving properties. The presented research provided the view for development process. The original vehicle was modified to improve its utility for universal operation. The performed simulation calculations revealed that the overturning stability of the original vehicle is more favourable in comparison to the heavier modified design. In contrast, the higher total weight of the vehicle has certain advantages with respect to the vertical dynamics.

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