INTRODUCTION

Road accidents and their consequences due to technical progress show a decreasing tendency. Even unfavorable figures do not discourage us from driving motor vehicles [11]. There are also drivers who drive in high speed on the problematic road section where was a serious accident in the past, thinking they can always avoid an accident because of their experience[12]. Many of them, however, do not realize that the driving characteristics of the vehicle in operation are changed [9]. Surface quality of the road that the vehicle is moving along, ambient temperature, or technical condition of the vehicle have an impact on changing the vehicle driving characteristics[25]. The vehicle load and load distribution have significant influence because they change the center of gravity towards individual axles and its height above the road surface [6]. With wheel load the angle of directional deviation changes as well having a significant impact on the driving characteristics of the vehicle [7].

INFLUENCE OF HEIGHT OF THE CENTRE OF GRAVITY ABOVE THE ROAD SURFACE

The centre of gravity position affects the distribution of weight between the individual wheels when cornering. It also significantly affects the magnitude of the heeling moment caused by centrifugal force [24]. The maximum safe speed can be estimated based on simplifying assumptions [14]. Let’s assume that the vehicle is cornering at a constant speed. The effects of rolling and wind resistance are neglected as their magnitude is small compared to the mag-
nitude of the centrifugal force. A common pas-

cenger car of a weight of 1200 kg, when pass-
ing curves with the radius of 100 m at a speed of
90 kmph, reaches the centrifugal force of 7500
N, where the rolling resistance is 130 N and wind
resistance 255 N. For simplification, let’s assume
that lateral wheel deformation does not occur [1].
At this moment, it is possible to determine the
maximum safe speed for cornering. In the vehicle
centre of gravity dextral coordinates system will
be placed and individual forces applied on the ve-
hicle will be marked (see Figure 1).

There are two situations compared:
The vehicle is sufficiently overturning resis-
tant; therefore only the sum of the forces acting in
the axial direction Y [23], (see Figure 1). For this
case, the following equation must be valid:

\[ F'_Y + F''_Y = F_o \cdot \cos \alpha - G \cdot \sin \alpha \]  \hspace{1cm} (1)

By solving this equation, the equation for
determining the maximum speed of the vehicle
when passing the curve at the skid speed limit
[20] will arise:

\[ V = 3.6 \cdot \sqrt{R \cdot g \cdot \frac{\mu + \tan \alpha}{1 - \mu \cdot \tan \alpha}} \]  \hspace{1cm} (2)

The speed thus calculated is subsequently
compared with the speed calculated regarding
that the road grip of the wheels is so high that as
a result of the forces acting in the axial direction
Y, the vehicle will not get into skid, but will tend
to overturn around the point 1 [23]. In that case,
the following equation must be valid:

\[ G \cdot \sin \alpha \cdot h + G \cdot \cos \alpha \cdot \frac{B}{2} - \]
\[ - F_o \cdot \cos \alpha \cdot h + F_o \cdot \frac{B}{2} \cdot \sin \alpha = 0 \]  \hspace{1cm} (3)

By solving this equation, the equation for cal-
culating the maximum speed of the vehicle when
passing the curve at the overturning speed limit
according to [10]:

\[ V = 3.6 \cdot \sqrt{R \cdot g \cdot \frac{2 \cdot h \cdot \tan \alpha + B}{2 \cdot h - B \cdot \tan \alpha}} \]  \hspace{1cm} (4)

where:  \( V \) is speed limit [kmph],
\( R \) is curve radius [m],
\( g \) is acceleration due to the gravity [m.s\(^{-2}\)],
\( \mu \) is adhesion coefficient [-],
\( \alpha \) is the road slope in the curve [°], trans-
verse gradient of the road,
\( h \) is the height of the centre of gravity [m],
\( B \) is the vehicle wheel track [m].

For determining the maximum speed at which
the vehicle can pass the curve with a specific radi-
us, it is necessary to determine the maximum speed
at the overturning speed limit and subsequently the
skid speed limit. The lower value becomes a con-
straining factor [7]. Table 1 shows the maximum
speed when passing curves with different radius
for a vehicle with the following parameters:

| Height of centre of gravity \( h \) = 0.7 m, trans-
|verse gradient of the road \( \alpha = 3 \) %, vehicle wheel track \( B = 1.45 \) m, lateral adhesion of wheels \( \mu = 0.8 \). The question is show theses values change
| for a vehicle of a weight of 1200 kg with a 70-kg
| roof rack, with a centre of gravity at the height of
| 1600 mm above the road surface. For a vehicle
| with such load, the height of the centre of gravity
| above the road surface will increase from 0.7 m
| to 0.75 m. The new values of the maximum speed
| for cornering are showed in Table 2.

As seen from Table 2, the maximum speed
values at a limit of overturning approaches to
the values at the limit of skid. The change of the
position of the centre of gravity for trucks/goods
vehicles will show higher dependency on the
load, since their payload is comparable or higher
than the weight of the vehicle [26]. This naturally
causes that the overturning speed limit can be
lower than the skid speed limit [11]. A compari-
son was carried out for a vehicle of the weight of
\( m_v = 8000 \) kg, the load capacity of the vehicle \( m_u = 8000 \) kg and the following parameters:
The height of the centre of gravity of an empty vehicle $h_t = 1.0$ m, the height of the centre of gravity of loaded vehicle $h_{tN} = 1.5$ m, road slope in the curve $\alpha = 3\%$, vehicle wheel track $a_B = 2.1$ m, adhesion coefficient $\mu = 0.8$. The results are showed in Table 3.

### TURNING CIRCLE RADIUS

According to Ackerman’s theory (see Figure 2), assuming that the vehicle passes through a curve with a large radius at a low speed, so the vehicle is not affected by centrifugal forces and the vehicle wheels show no directional deviation, the axes of wheels rotation intersect at one point at the axis of the rear axle. This is a condition for the vehicle wheels to roll on the road surface and do not show any lateral shift [9]. With a rotation of the outside front wheel by angle $\beta_1 = 2.934^\circ$ the vehicle turning radius is 50 m.

When passing the curve, the vehicle will be under the influence of centrifugal forces [17]. This causes different wheel load. The real wheels with lateral load show a specific directional deviation [8]. In such case, the condition for the validity of Ackerman’s theory is not fulfilled and the actual turning radius of the vehicle will be different. The actual turning radius of the vehicle can be calculated using the following equation [5]:

$$ R_z = \frac{L - \frac{B}{2} \cdot \tan(\beta_1 - \alpha_1)}{\tan(\beta_1 - \alpha_1) + \tan \alpha z} $$  \hspace{1cm} (5)

where $L$ is the distance of axles [m], $\beta_1$ is the steering angle of the outside front wheel [$^\circ$], $\alpha_1$ is the directional deviation angle of the outside front wheels [$^\circ$], $\alpha_z$ is an average value of the directional deviation angle of the outside rear wheels [$^\circ$].

To compare the theoretical and actual turning radius, the steering angle of the outside wheel will be $\beta_1 = 2.934^\circ$. Theoretically, the vehicle passes the curve with the radius of 50 m. Now the directional deviation angles of individual wheels need to be determined. These change according to the wheel load $F_z$ lateral force $F_y$ [9] (see Figure 3).

The distance between the centre of gravity and the front axle $L_1 = 1.2$ m and between the centre of gravity and the rear axle $L_2 = 1.4$ m. The maximum safety speed of a passenger car for passing the curve at the skid speed limit is 73.5 kmph according to Table 1.

With some safety reserve, drivers are recommended to pass the curve at the speed of 40 kmph [15]. The magnitude of centrifugal force acting at the centre of gravity of the vehicle $F_o$ is calculated as follows:

$$ F_o = \frac{m \cdot V^2}{3.6^2 \cdot R} $$  \hspace{1cm} (6)

where: $m$ is the weight of the vehicle [1200 kg], $V$ is the vehicle speed [kmph], $R$ is the curve radius [m].

### Table 1. Influence of the curve radius on the passing speed

<table>
<thead>
<tr>
<th>Curve radius [m]</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{skid}$ [kmph]</td>
<td>73.5</td>
<td>104.0</td>
<td>127.3</td>
<td>147.0</td>
<td>164.4</td>
<td>180.1</td>
</tr>
<tr>
<td>$V_{overturning}$ [kmph]</td>
<td>83.6</td>
<td>118.2</td>
<td>144.8</td>
<td>167.2</td>
<td>186.9</td>
<td>204.8</td>
</tr>
</tbody>
</table>

### Table 2. Influence of the curve radius on the passing speed

<table>
<thead>
<tr>
<th>Curve radius [m]</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
</tr>
</thead>
<tbody>
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<td>127.3</td>
<td>147.0</td>
<td>164.4</td>
<td>180.1</td>
</tr>
<tr>
<td>$V_{overturning}$ [kmph]</td>
<td>80.8</td>
<td>114.2</td>
<td>139.9</td>
<td>161.5</td>
<td>180.6</td>
<td>197.8</td>
</tr>
</tbody>
</table>

### Table 3. Influence of the curve radius on the passing speed for a goods vehicle

<table>
<thead>
<tr>
<th>Curve radius [m]</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{skid}$ [kmph]</td>
<td>73.5</td>
<td>104.0</td>
<td>127.3</td>
<td>147.0</td>
<td>164.4</td>
<td>180.1</td>
</tr>
<tr>
<td>$V_{overturning}$ pre $h_t = 1$ m [kmph]</td>
<td>84.8</td>
<td>119.9</td>
<td>146.9</td>
<td>169.6</td>
<td>189.6</td>
<td>207.7</td>
</tr>
<tr>
<td>$V_{overturning}$ pre $h_t = 1.5$ m [kmph]</td>
<td>69.3</td>
<td>98.0</td>
<td>120.1</td>
<td>138.6</td>
<td>155.0</td>
<td>169.8</td>
</tr>
</tbody>
</table>
Magnitude of centrifugal force is:

\[ F_o = \frac{1200 \cdot 40^2}{3.6^2 \cdot 50} = 2962.9 \, N \]

Forces acting on individual axles can be calculated by application of sine law for non-right-angled triangles [11] (see Figure 3). The individual angles are determined according to Figure 3:

\[ \tan \delta = \frac{L}{R} = \frac{2.6}{50} = 0.052 \Rightarrow \delta = 2.977^\circ \]

\[ \tan \gamma = \frac{L}{R} = \frac{1.4}{50} = 0.028 \Rightarrow \gamma = 1.604^\circ \]

\[ \varepsilon = \delta - \gamma = 2.977 - 1.604 = 1.373^\circ \]

\[ \eta = 180 - \varepsilon - \gamma = 180 - 1.373 - 1.604 = 177.023^\circ \]

By application of the sine law, for calculating \( F_1 \) force is valid that:

\[ F_1 = \frac{F_o \cdot \sin \gamma}{\sin \eta} = \frac{2962.9 \cdot \sin(1.602^\circ)}{\sin(177.023^\circ)} = 1594.9 \, N \]

whereas for calculating \( F_2 \) force, it holds true that:

\[ F_2 = \frac{F_o \cdot \sin \varepsilon}{\sin \eta} = \frac{2962.9 \cdot \sin(1.373^\circ)}{\sin(177.023^\circ)} = 1367.0 \, N \]

For determining the wheels load for the front axle it is assumed that the centre of mass \( m_1 = 646 \, kg \), which falls on the front axle, is at the same height above the road surface as the centre of gravity of the vehicle and is located in the centre of the axle. The same assumption will apply for \( m_2 = 554 \, kg \), which is the weight falling on the rear axle. The subscripts 1 are assigned to the front axle, subscript 2 to the rear axle. Superscripts 1 signify the outside wheel, P means inside wheel.

According to the figures above it was possible to determine the wheel load for the front inside wheel:

\[ R_{z1}^p = \frac{G_2 \cdot \frac{B}{2} - F_2 \cdot h_i}{B} = \frac{554 \cdot 9.81 \cdot 1.45 - 1367 \cdot 0.7}{2 \cdot 1.45} = 2057.4 \, N \]

As well as for the front outside wheel:

\[ R_{z1}^l = G_1 - R_{z1}^p = 3938.4N \]

Similar procedure will be applied in case of the rear axe:

\[ R_{z2}^l = G_2 - R_{z2}^p = 3377.3N \]

It should be also supposed that the transmission of the lateral force will be ensured by wheels proportionately to their weight. The individual wheels will then capture the following force:

\[ F_{y1}^p = \frac{F_1}{G_1} \cdot R_{z1}^p = \frac{1594.5}{646 \cdot 9.81} \cdot 2398.9 = 603.6 \, N \]

\[ F_{y1}^l = F_1 - F_{y1}^p = 1594.5 - 603.6 = 990.9 \, N \]

\[ F_{y2}^p = \frac{F_2}{G_2} \cdot R_{z2}^p = \frac{1367}{554 \cdot 9.81} \cdot 2057.4 = 517.5 \, N \]

\[ F_{y2}^l = F_2 - F_{y2}^p = 1367 - 517.5 = 849.5 \, N \]

Based on the load and the magnitude of the lateral force it is possible to identify the angle of the directional deviation of the individual wheels [23]:

\[ \beta_1 \]

\[ \beta_2 \]
At this moment, it is possible to determine / calculate the actual turning ratio of the vehicle:

\[
R_s = \frac{L - \frac{B}{2} \cdot \tan(\beta_i - \alpha_i)}{\tan(\beta_i - \alpha_i) + \tan(\alpha_z)} = \frac{2.6 - \frac{1.45}{2} \cdot \tan(2.934 - 2.965)}{\tan(2.934 - 2.965) + \tan 2.149} = 70.3 \text{ m}
\]

The vehicle is understeered.

Change of the position of the center of gravity has caused deterioration of vehicle understeer and the actual turning circle radius has increased.

**BRAKING PROCESS**

CG position also affects the axle load and hence the magnitude of braking forces that are transmitted by the wheels on each axle [15]. According to Mockor [19], it is possible to calculate the percentage share of the braking forces on the axles using the following equation:
\[
\frac{K_{b1}}{K_{b2}} = \frac{\lambda_2 + \lambda_1 \cdot (\mu_x + f)}{\lambda_2 - \lambda_1 \cdot (\mu_x + f)}
\]  
(7)

where 
\(K_{b1}, K_{b2}\) is braking force percentage out of total braking force (front and rear axles), 
\(\lambda_1\) is calculated as a quotient of the distance of the CG from the front axle and Wheel Base, 
\(\lambda_2\) is calculated as a quotient of the distance of the CG from the rear axle and Wheel Base, 
\(\lambda_t\) is calculated as a quotient of the height of the CG above a flat surface from the Wheel Base, 
\(f\) is the coefficient of rolling resistance, 
\(\mu_x\) is the coefficient of adhesion between tires and road surface in the direction of the X axis.

The height of center of gravity above the flat road surface affects the distribution of braking forces as well [3]. Table 5 provides an overview of changes in the proportion of the braking forces at a constant distance of the center of gravity from each axle depending on the height of the center of gravity changes.

Again, it can be assumed that there will be significant impact on trucks, because the center of gravity of the laden vehicle will be significantly higher than the CG of the empty vehicle [2].

The braking forces are affected by the adhesion coefficient between tires and road surface as well [9]. Typical values of adhesion coefficient \(\mu\) for different surfaces are shown in Table 6.

The effect of the adhesion coefficient of tires on the distribution of the braking forces is demonstrated in Table 7. The change is calculated for a constant distance of center of gravity from axles \(L_1 = 1.2\, \text{m}, L_2 = 1.4\, \text{m}\) and for the height of the CG \(h_t = 0.7\).

As shown in Table 7, the value of the adhesion coefficient has a significant impact on the distribution of the braking forces as well [18]. The individual results show that there is an advantage in using such braking systems, which can affect the braking forces depending on the load [10], or which can use brake possibilities independently on each wheel [13].

Table 4. Change in the magnitude of braking forces (in percentage) at the front and rear axles depending on the distance between the center of gravity and the front axle.

<table>
<thead>
<tr>
<th>Distance of center of gravity [m]</th>
<th>from the front axle (L_1)</th>
<th>1.1</th>
<th>1.2</th>
<th>1.3</th>
<th>1.4</th>
<th>1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>from the rear axle (L_2)</td>
<td>1.5</td>
<td>1.4</td>
<td>1.3</td>
<td>1.2</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>above the flat road surface (h_t)</td>
<td>0.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percentage from the total braking force [%]</td>
<td>for front axle (K_{b1})</td>
<td>72.6</td>
<td>68.2</td>
<td>64.4</td>
<td>60.6</td>
<td>56.7</td>
</tr>
<tr>
<td>for rear axle (K_{b2})</td>
<td>27.4</td>
<td>31.8</td>
<td>35.6</td>
<td>39.4</td>
<td>43.3</td>
<td></td>
</tr>
</tbody>
</table>

Table 5. Change in the magnitude of the braking force (in percentage) at the front and rear axles depending on the height of the CG above the flat road surface using \(\mu_x = 0.8\) and \(f = 0.011\)

<table>
<thead>
<tr>
<th>Distance of center of gravity [m]</th>
<th>from the front axle (L_1)</th>
<th>1.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>from the rear axle (L_2)</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>above the flat road surface (h_t)</td>
<td>0.6</td>
<td>0.65</td>
</tr>
<tr>
<td>Percentage from the total braking force [%]</td>
<td>for front axle (K_{b1})</td>
<td>72.6</td>
</tr>
<tr>
<td>for rear axle (K_{b2})</td>
<td>27.4</td>
<td>25.9</td>
</tr>
</tbody>
</table>

Table 6. Typical values of the adhesion coefficient of automobile tire depending on the surface

<table>
<thead>
<tr>
<th>Surface</th>
<th>Dry concrete</th>
<th>Dry asphalt</th>
<th>Wet concrete</th>
<th>Wet asphalt</th>
<th>Dry pavement</th>
<th>Wet pavement</th>
<th>Muddy surface</th>
<th>Packed snow</th>
<th>Melting ice</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mu)</td>
<td>1.0</td>
<td>0.9</td>
<td>0.7</td>
<td>0.6</td>
<td>0.5</td>
<td>0.4</td>
<td>0.3</td>
<td>0.3</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 4 gives an overview of changes in the magnitude of the braking force depending on the distance between the center of gravity and the front axle.

A significant impact of the distance of the center of gravity from each axle is evident from the table. Trucks are significantly much more susceptible to changes of CG position [5] because their payload is comparable with a curb weight of the vehicle and the cargo is placed over the rear axle [4].

Table 5 provides an overview of changes in the proportion of the braking forces at a constant distance of the center of gravity from each axle depending on the height of the center of gravity changes.

Table 7 demonstrates the significant impact on trucks, because the center of gravity of the laden vehicle will be significantly higher than the CG of the empty vehicle [2].
CONCLUSIONS

Vehicle load causes changes in the center of gravity position. Displacement of the center of gravity affects the driving characteristics of the vehicle. The increase in the height of the center of gravity is reflected in the reduction of the maximum speed when cornering or in the need of increasing the road curve radius. Load of the passenger vehicle reduces the maximum speed by an average of 5 kmph when passing the road curve section. In case of a truck the vehicle payload is comparable to the vehicle weight, which causes a significant increase in height of the center of gravity when loaded in comparison with a passenger vehicle. The average reduction of speed rate needed for safe cornering achieves in this case the value of 27.9 kmph.

Displacement of the CG of vehicle has an effect on vehicle axles load distribution as well. Axle load determines the maximum of braking force as well as the adhesion coefficient of tires. In modern vehicles an adverse effect of different axle loads and thus the individual wheels is eliminated by electronic brakeforce distribution system (EBD).

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