Investigation of the Influence of the Centre of Gravity Position on the Course of Vehicle Rollover

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ABSTRACT

Rollover crashes belong to the most danger type of road accidents. Particularly vehicles with a high situated center of gravity are exposed to this type of accidents. The basic measure of vehicle resistance to rollover is Static Stability Factor SST, i.e. the ratio of half the track width to the height of the center of gravity. In the quasi-static rollover limit it is assumed that the SST should not be less than the tire-to-road friction coefficient. This follows from the assumption that the side skid is less dangerous than the rollover. Most of the passenger cars are designed in order to prevent the rollover on flat surface with normal friction. However from several reports it is known that the quasi-static rollover limit can be not met in the case of vehicles with the high center of gravity position (in relation to the tread): heavy trucks, delivery vans or busses, especially high-floor coaches and double-deckers. Also other cars especially, very trendy at present, SUVs and trucks could also undergo the rolling over when the tire-to-road friction coefficient would be extremely high, namely its value would exceed 1 or more. The rollover can happen on a flat surface also when the height of the centre of gravity is higher then the height assumed by the designers.

In the paper the method of calculation of the course of rollover in time domain is described and it is investigated the influence of the height the centre of gravity on the increase of the rollover angle velocity. The conducted calculations show that during rollover the rotation angle of the vehicle increases progressively. It can be noted that the higher the vehicle centre of gravity is located, the faster the rotation angle increases.

On the basis of calculation results it is discussed whether the drive has a chance to counteract the rollover of the vehicle. It is shown, that in a few first tenth parts of the second the angle of the rotation is small enough that it gives the driver a chance to correct the movement of the car using the steering wheel or by reducing speed, even when the rollover process has already begun.

INTRODUCTION

Rollover crashes belong to the most danger type of road accidents. Admittedly accidents of this type constitute only 3% of all accidents; fatalities of these accidents constitute is as many as 33% of all fatalities [3] . It is the reason why the problem of rollover accidents is discussed in many papers, e.g.: [10], [5], [11], [6]. Particularly vehicles with high situated centre of gravity are exposed to this type of accidents. Most dangerous are accidents with buses, especially with double-decker and high-floor buses [4].

In the vehicle dynamics the rolling over is treated as the case of loss of stability, which is one of the most important problems of lateral vehicle dynamics. The loss of stability consists on a rapid, uncontrolled by the driver, increase of vehicle deviance from its assumed trajectory. The loss of stability is a great danger, because it can cause departure of the car from the road, rollover or collision with other vehicle. The loss of lateral stability can happen mostly by cornering with great velocity or by avoiding an obstacle. Two cases of the stability loss are discussed:

- Side skid, caused by so great increase of outside forces acting on the car (e.g. centrifugal force, side wind force) that these forces can not be counterbalanced by tyre to road friction forces.
- Rollover which consists on rotation of the vehicle about its longitudinal axis. It happens when roll moment in cornering can not be counterbalanced by the moment of the vehicle weight.

SIDE SKID LIMIT

The side skid on a level road does not occur when the lateral forces Y acting in the ground plane counterbalance external lateral force F_y acting on the car. Thus the safety requirement is

$$\sum Y \geq F_y \tag{1}$$

In the cornering manoeuvre the centrifugal force is the predominating lateral force

$$F_y = \frac{m\,v^2}{R} \tag{2}$$

where:
m – vehicle mass,
v – longitudinal velocity,
R – radius of the curve.
With friction forces

$$Y = Z\,\mu \tag{3}$$

where:
μ - tyre-to-road friction coefficient
Z – vertical road-to-tyre reaction force
and with the sum of vertical road reactions equal to vehicle weight: $\Sigma Z = mg$

$$\sum Y = m\,g\,\mu \tag{4}$$

Finally the safety requirement

$$m\,g\,\mu \geq \frac{m\,v^2}{R} \tag{5}$$

And the maximum velocity on the curve with given radius R is

$$v \leq \sqrt{R\,g\,\mu} \tag{6}$$

QUASI-STATIC ROLLOVER LIMIT

The vehicle loaded with the lateral force F_y acting in its centre of gravity is shown in Figures 1 and 2. The vehicle here is treated as a rigid body, which means that the elasticity of the suspensions and tyres is not being taken into consideration. The rollover of the vehicle does not occur when the roll moment $F_y\,h$ can be counterbalanced by the moment of the vehicle weight

$$F_y\;h \leq m\,g\,\frac{b}{2} \tag{7}$$

where:
h – centre of gravity (CG) height over ground,
b – wheel track.
In the cornering manoeuvre the centrifugal force is the lateral force, also with F_y according to Equation (2)

$$\frac{m v^2}{r}\,h \leq m\,g\,\frac{b}{2} \tag{8}$$

Thus the safety requirement preventing the rollover is so that the vertical forces acting on the inside wheels should not decrease below zero (Figure 1). It means that in unstable equilibrium state the resultant force (i.e. the sum of centrifugal force and the vehicle gravity force mg) should not cross the ground outside the wheel track, also outside the line which joins outside wheels/road contact points (Figure 1). In the case of rollover the car rotates about this line. Thus this line can be called rollover axis.

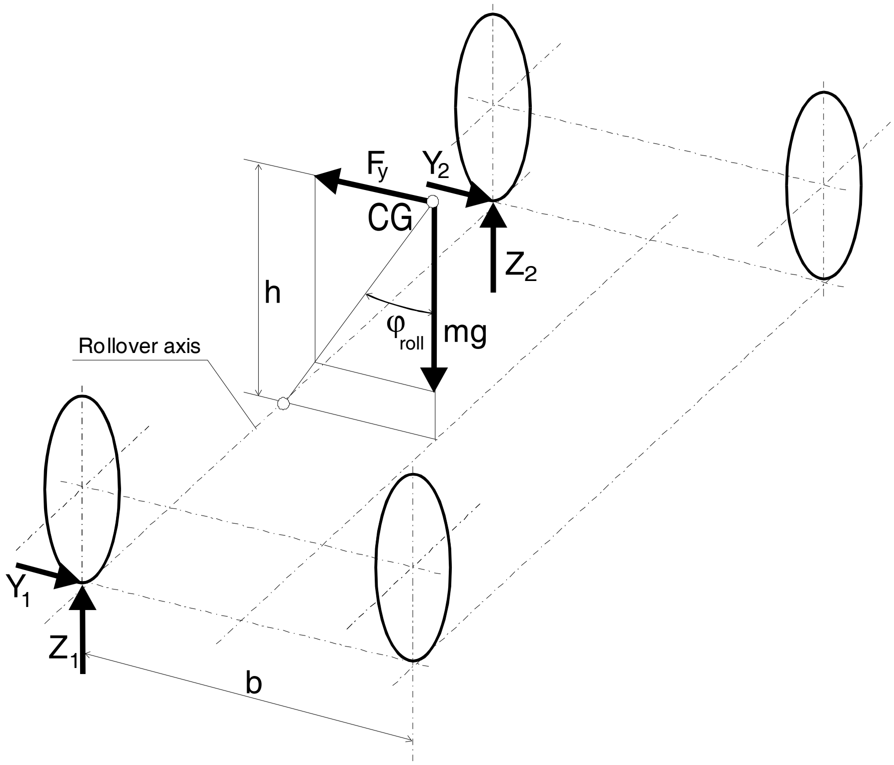

Figure 1. Forces acting on the car by cornering in the rollover limit condition, F_y – centrifugal force, mg – vehicle weight, Y, Z – lateral and vertical road reaction forces, CG – centre of gravity, h – CG height over ground, b - track

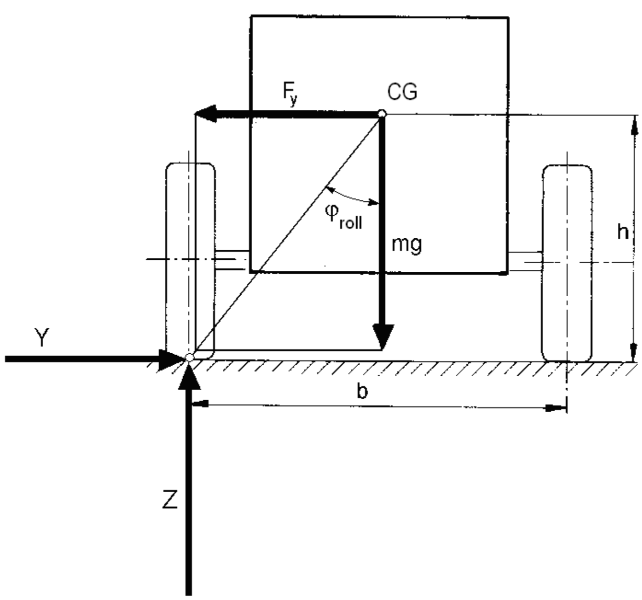

Figure 2. Forces acting on the vehicle (treated as a rigid body) in its cross section in unstable equilibrium

And finally the maximum velocity which does not cause rollover of the vehicle is

$$v \le \sqrt{R\,g\,\frac{b}{2h}} \tag{9}$$

It is commonly assumed that the side skid is less dangerous than the rollover. Also the maximum velocity calculated from the side skid limit should be smaller than the velocity calculated from the rollover limit

$$\sqrt{R\,g\,\mu} \le \sqrt{R\,g\,\frac{b}{2h}} \tag{10}$$

also

$$\mu \le \frac{b}{2h} \tag{11}$$

From the formula (11) it is evident that the rollover risk depends on one hand from the centre of gravity height in relation to the wheel track, on the other from the tyre-to-road friction condition. The value $b/(2h)$, called Static Stability Factor (SSF),

$$SSF = \frac{b}{2h} \tag{12}$$

is the first order measure of the vehicle resistance to rollover. However the influence of the tyre-to-road friction condition is so: The higher friction coefficient the higher possibility that the vehicle will roll instead slide.

In the Table 1 data of different types of motor vehicles are collected. They can be compared with the values of tyre-to-road friction coefficient which are being met on roads (Table 2). In most cases values of the friction coefficient do not exceed 0,9, also the vehicles mentioned in the Table 1 characterized with SSF value higher than 0,9 are not threatened with rollover. However in particular situations the friction coefficient can achieve value of 1,0 or more (very rough dry surface and good tyres) and the cars with relatively high CG position (vans, suvs or trucks) can be threatened with rollover.

Table 1.
Approximate values of the Static Stability Factor of different types of motor vehicles,

Vehicle type	**Static Stability Factor (SSF)**
Cars[1]	1,35 – 1,45
Vans[1]	1,10 – 1,25
Sport Utility Vehicles – SUV[1]	1,05 – 1,20
Trucks, pick-ups[1]	1,10 – 1,25
Double-decker buses[2]	0,60 – 0,75

[1]) based on [1]
[2]) calculated (see Appendix)

Buses with very high CG position (particularly double-deckers and high-flour buses) are much less safe. They can rollover even on the surface with the friction coefficient smaller than 0,8, that is with the value normally met on roads.

Table 2.
Exemplary values of tyre to road friction coefficient measured on dry road surfaces for summer and winter tyres of two manufacturers according to [7]

v [km/h]	manufacturer 1		manufacturer 2	
	summer tyre	winter tyre	summer tyre	winter tyre
30	0,74	0,88	0,79	0,86
60	0,64	0,81	0,64	0,78

Thus the first safety requirement is to prevent the roll-over, also the vertical forces acting on the inside wheels should not decrease below zero (Figure 1). It means that in unstable equilibrium state the resultant force, i.e. the sum of centrifugal force and the vehicle gravity force *mg* should not cross the ground outside the wheel track, also outside the line connecting outside wheels/road contact points. In the case of rollover the car rotates about this line. Thus this line can be called rollover axis.
It can be also introduced the rollover angle φ_{roll} as an angle between vertical line and the line drawn from centre of gravity perpendicularly to the roll axis (Figure 2).

$$\varphi_{roll} = \arctan\left(b/(2h)\right) \tag{13}$$

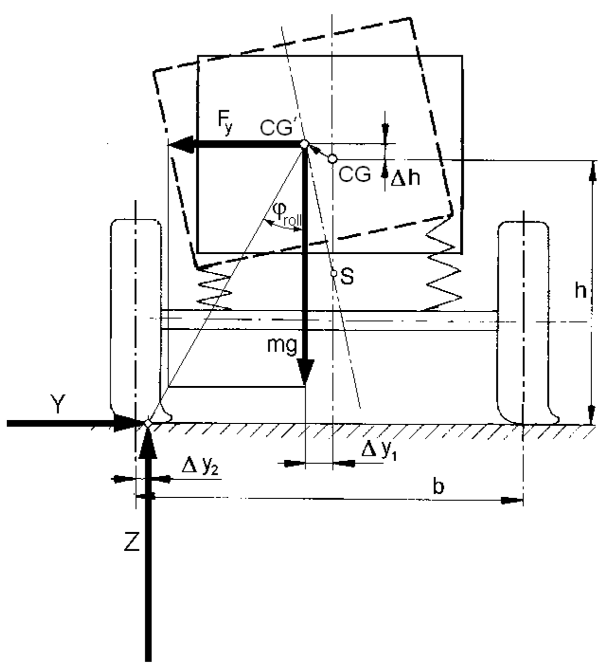

Figure 3. Forces acting on the vehicle in its cross section in unstable equilibrium, when elasticity of suspensions and elasticity of tires are taken into consideration

ROLLOVER ANGLE

Scheme shown in Figure 2 doesn't demonstrate all factors influencing the lateral stability of the vehicle. Therefore in Figure 3 it is shown the influence of body roll caused by compression and rebound of suspension and elasticity of tyres. Moreover one should notice that due to nonlinearities of suspensions characteristics their compression on outer side is smaller than rebound on inside site. As a result of these influences the centre of gravity is moving up and outside and the rollover angle is decreasing:

$$\varphi_{roll} = \arctan\left(\frac{0{,}5b - \Delta y_1 - \Delta y_2}{h + \Delta h}\right) \tag{14}$$

In consequence the stability of vehicle is decreasing and the roll-over limit can be modified as follows:

$$\mu \leq tg\,\varphi_{roll} \tag{15}$$

Based on comparing data from tables 1 and 2 it is possible to state, that in most cases requirement not to roll over is accomplished. However some accidents with rollover occur not rare.

TRIPPED ROLLOVER

It appears from statistics that about 63% of all rollover accidents is happening as a result of the blow of the car wheels in the curb or in the other similar obstacle ([3], [11]). The tripped rollover can be treated as the special case of rollover when the tyres coming across the surface with infinitely high value of friction coefficient, e.g. a quicksand on the shoulder of roadway or the curb.

The mechanics of rollover after contact with the curb will be discussed for an idealized situation when after loss of the adhesion the car slides with the velocity v_y at right angle to the curb and finally it hits the curb simultaneously with both wheels of one side. The movement of the car will be treated as the flat movement in the plane perpendicular to its longitudinal axis (Figure 4). In the Figure 4 the axis of rotation is represented by the point O. Force impulse, which appears as result of the hitting, causes that the side movement of the car is converted into a rotational movement about the impact point O (more precise - about rotation axis). It can be assumed that the car will roll over when the kinetic energy of its rotational movement will be enough to raise the car CG in this way that the CG will be placed direct over the rotation axis (Figure 4).

In this case the vehicle movement can be divided into 2 phases [2]:

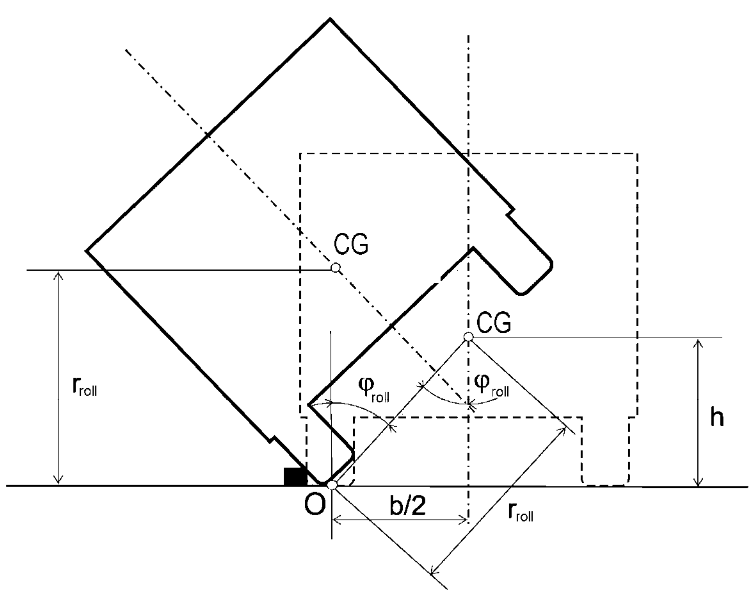

Figure 4. Vehicle rolling over after hitting in the kerb

Phase I – the hitting in the curb and the conversion of the translational movement into the rotational movement. From the law of conservation of angular momentum arises that the rotational momentum of the car after hitting $J_{\text{roll}}\,\dot{\varphi}$ should be equal to its moment of momentum around its rotation axis before hitting mv_yh

$$m v_y\, h = J_{roll}\,\dot{\varphi} \tag{16}$$

where:
- J_{roll} is the moment of inertia of the vehicle about its roll axis

$$J_{roll} = J_x + m\, r_{roll}^{\;2} \tag{17}$$

- J_x is the moment of inertia of the vehicle about its central longitudinal axis x and
- r_{roll} is the distance of CG from the roll axis

$$r_{roll} = \sqrt{(b/2)^2 + h^2} \tag{18}$$

Also after the conversion of Equation (16) the rotational speed after hitting is equal to

$$\dot{\varphi} = \frac{m v_y\, h}{J_{roll}} \tag{19}$$

Phase II – rotational movement. The kinetic energy of the rotational movement should be enough big in order to raise the car CG to its possibly highest position, also to the position in which the CG will be direct over the rotation axis. The kinetic energy of the rotational movement will be converted into an increase of the potential energy

$$\frac{1}{2} J_{roll}\,\dot{\varphi}^2 = m\, g\,(r_{roll} - h) \tag{20}$$

Also the rotational speed after hitting should be equal to

$$\dot{\varphi} = \sqrt{\frac{2 m\, g\,(r_{roll} - h)}{J_{roll}}} \tag{21}$$

After conversion of Equation (19)

$$v_y = \dot{\varphi}\,\frac{J_{roll}}{m h} \tag{22}$$

and with the use of Equation (21) it can be calculate the value of the lateral velocity v_y which is necessary to cause the rollover of the vehicle. This velocity is called Critical Sliding Velocity - CSV

$$\text{CSV} = v_y = \sqrt{\frac{2\, g\, J_{roll}}{m h^2}\left(r_{roll} - h\right)} \tag{23}$$

In praxis the value of CSV is higher then the value calculated from Equation (23) because in the calculation the car was treated as the rigid body and the losses of energy in shock absorbers and caused by tyres deflection are not taken into consideration.
The value of Critical Sliding Velocity is recognized as the evaluation criterion of the resistance of the vehicle to rolling over as the result of hitting the curb. In the Table 3 approximate values of CSV are presented for the same group of vehicles as in the Table 1. It can be observed from the table, that particularly buses on account of the very small value of CSV can roll over after hitting the obstacle on the roadway even at the slight skid.

Table 3.
Approximate values of Critical Sliding Velocity

Vehicle type	Critical Sliding Velocity (CSV)
Cars[1]	19 – 21 km/h
Vans[1]	17 – 19 km/h
Sport Utility Vehicles – SUV[1]	15 – 17,5 km/h
Trucks, pick-ups[1]	15,5 – 19 km/h
Double-decker bus without passengers[2]	14,4 km/h
Double-decker bus with passengers[2]	12,2 km/h

[1]) based on [1]
[2]) calculated (Appendix 1)

COURSE OF ROLLOVER ON THE FLAT SURFACE

The vehicle travelling in the steady state condition (with constant lateral velocity and constant angular velocity) on the flat surface can roll over in the case when the condition described with formula (5) or (6) is not met. This condition can not be met in the case of car with the big CG height (in relation to the tread): heavy trucks, delivery vans or busses, especially high-floor coaches and double-deckers. However other cars mentioned in table 1, especially very trendy at present SUVs and truck, can also undergo rolling over when the tyre-to-road friction coefficient would be extremely high, namely its value would exceed 1 or more.
The process of rollover begins, when $F_y/(mg) > \text{tg}\ \varphi_{\text{roll}}$. Because of a big value of the vehicle rolling moment of inertia about roll axis the angle of vehicle rotation φ is increasing gradually. The determining of the course of changes of this angle will allow assessing whether the driver can counteract the rollover when the process already began.

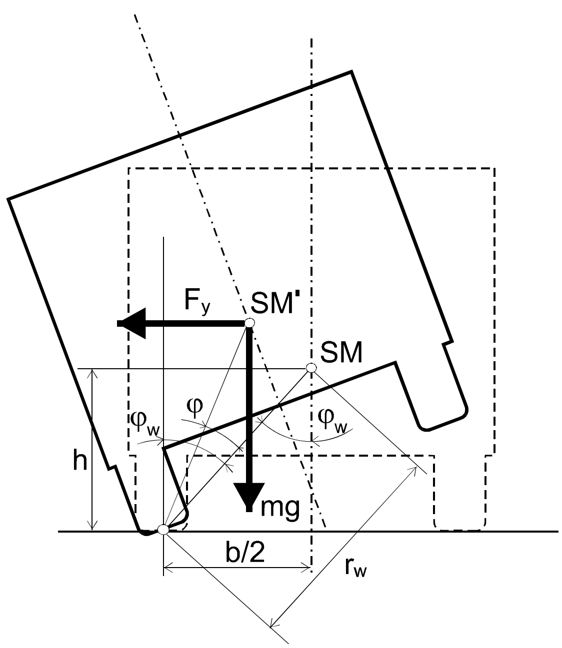

Figure 5. The car while rolling over for the angle φ

The moment M_φ which causes rollover is equal the difference between the moment of lateral force F_y and the moment of vehicle weight mg (Figure 5)

$$M_\varphi = F_y\, r_{roll} \cos(\varphi_{roll} - \varphi) - m\, g\, r_{roll} \sin(\varphi_{roll} - \varphi) \tag{24}$$

Since the angular acceleration $\ddot{\varphi}$ is proportional to the rolling moment M_φ and inversely proportional to the moment of inertia J_{roll}

$$\ddot{\varphi} = \frac{M_{roll}}{J_{roll}} \tag{25}$$

is also a function of the rotation angle φ.
During the rotation of the vehicle for the angle φ the rolling moment M_φ does the work

$$L_\varphi = \int_0^\varphi M_{roll}\, d\varphi = \int_0^\varphi \left[F_y\, r_{roll} \cos(\varphi_{roll} - \varphi) - m\, g\, r_{roll} \sin(\varphi_{roll} - \varphi)\right] d\varphi \tag{26}$$

After integration

$$L_\varphi = F_y\, r_{roll}\, [- \sin(\varphi_{roll} - \varphi) + \sin\varphi_{roll}] + m\, g\, r_{roll}\, [- \cos(\varphi_{roll} - \varphi) + \cos\varphi_{roll}] \tag{27}$$

On the flat surface, if the deflections of suspensions are neglected, it can be assumed that $\sin\varphi_{froll} = 0{,}5\ b/r_{roll}$ and $\cos\varphi_{roll} = h/r_{roll}$. Thus

$$L_\varphi = [0{,}5\ b - r_{roll} \sin(\varphi_{roll} - \varphi)] + m\, g\, [h - r_{roll} \cos(\varphi_{roll} - \varphi)] \tag{28}$$

An effect of the done work is an increase in the kinetic energy

$$E_\varphi = \frac{J_{roll}\, \dot{\varphi}^2}{2} \tag{29}$$

After comparing of the kinetic energy and the done work the angular velocity $\dot{\varphi}$ can be calculated

$$\dot{\varphi} = \sqrt{\frac{2\, L_\varphi}{J_{roll}}} \tag{30}$$

Since the work L_φ is a function of the angle φ, for the small increase of the rotation angle $\Delta\varphi = \varphi_i - \varphi_{i-1}$, it is possible to calculate angular velocities $\dot{\varphi}_{i-1}$ and $\dot{\varphi}_i$ for two successive values of rotation angles, and next its increase $\Delta\dot{\varphi} = \dot{\varphi}_i - \dot{\varphi}_{i-1}$, beginning from its null value. With the use of earlier calculated from Equation (25) values of angular accelerations $\ddot{\varphi}_i$ and $\ddot{\varphi}_{i-1}$ and their mean value $\ddot{\varphi}_{sr} = 0{,}5(\ddot{\varphi}_i + \ddot{\varphi}_{i-1})$ it can be calculated the time interval Δt in which this increase took place

$$\Delta t = \frac{\Delta\dot{\varphi}}{\ddot{\varphi}_{sr}} \tag{31}$$

After adding values of time intervals Δt calculated for successive values of rotation angles φ the times of achieving these angles can be calculated. Finally it is possible to obtain the course of the rotation angle φ as the function of time t.
Exemplary calculations of the course of vehicle rollover were carried out for the double-decker bus in two loading states: without passengers and with passengers. In calculation data taken from [8] and [9] was used. Data and preliminary calculations are placed in the Appendix. The bus with passengers is characterized by

greater mass, the higher put centre of gravity and the greater moment of inertia. In calculations a radius of the curve was assumed equal 60 m, and the vehicle velocity equal 80 km/h, that is higher than rollover limit for the bus without passengers (see the Appendix).
The results of calculations are shown on the Figure 6 and they are compared with the values of roll angles (Equation (13)) for both states of loading. From the diagram it is evident, that the higher the centre of gravity is located the faster the rotation angle increases. The vehicle with the higher position of the centre of gravity reaches the roll angle in the shorter time then the vehicle with lower centre of gravity; here appropriately in circa 1,05 s and 1,3 s.
Furthermore the increase in the rotation angle is progressive. In a few first tenth parts of the second the angle of the rotation is still small. For example, in the case 1 (bus without passengers) it does not exceed the value of 10° during 0,85 s from the beginning of rolling over and for the case 2 (the bus with passengers) respectively 0,65 s. It gives to the driver the chance to correct the movement of the vehicle using steering wheel or decreasing the velocity. However the driver has this time less, if the centre of gravity is put higher (case 2, bus with passengers).

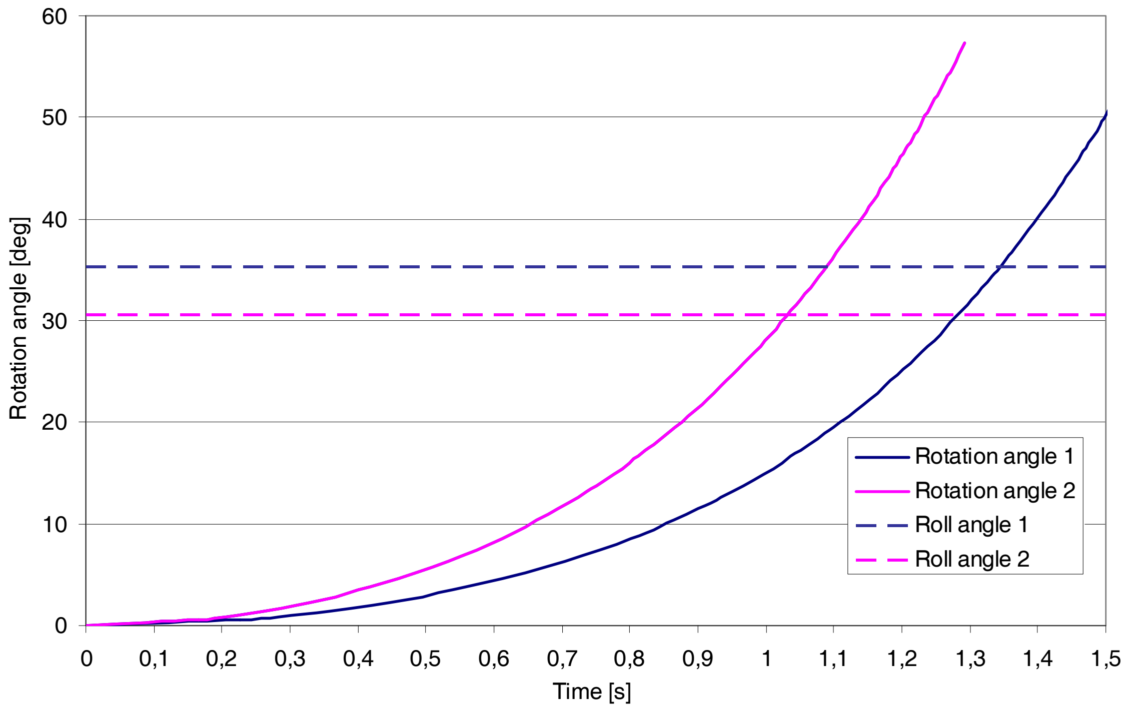

Figure 6. The rotation angle of the bus as the function of time for two loading states: without passengers (1) and with passengers (2). Curve radius - 60 m, vehicle velocity - 80 km/h

CONCLUSIONS

The majority of passenger cars is designed in order to prevent the rollover on flat surface with normal friction coefficient. Their Static Stability Factor is higher than the tyre-to-road friction coefficient. However in the case of these vehicles the rollover can also happen when the friction coefficient will be extremely high or the height of the centre of gravity will be bigger then the height assumed by the designers, e.g. as the result of improper loading.
In case of the tripped rollover, which can be treated as the special case of rollover, when the tyres coming across the surface with infinitely high value of friction coefficient, the Critical Sliding Velocity is assumed as the safety criterion. Its value is about 20 km/h for passenger cars or respectively smaller for vehicles with

higher positioned centre of gravity (vans, trucks, SUVs) and especially small (less than 15 km/h) for double-deckers and high-floor buses.
The conducted calculations show that during the rollover the rotation angle of the vehicle increases progressively. It can be noticed that the higher is positioned the vehicle centre of gravity the increase the rotation velocity is the greater. Furthermore it can be stated, that in the initial phase of the rollover the increase in the angle of the rotation is enough small, that is giving to the driver the chance to correct the vehicle motion.

REFERENCES

[1] Heydinger G.J., Bixel R.A., Garrott W.R., Pyne M., Hove J.G., Guenther D. A. 1999. "Measured Vehicle Inertial Parameters – NHTSA's Data Through November 1998". SAE Paper 1999-01-1336
[2] Huang M. 2002. "Vehicle crash Mechanics". CRC Press 2002
[3] Linstromberg M., Scholpp G., Scherf O. 2005. "Test and Simulation Tools in a Rollover Protection Development Process". 19th International Technical Conference on the Enhanced Safety of Vehicles (ESV). Paper No. 05-0122
[4] Matolcsy M. 2007. "The Severity of Bus Rollover Accidents". 20th Conference. ESV. Lyon 2007. Paper No. 07-0989.
[5] McLean J., Kloeden C., Ponte G. 2007. "Characteristics of Rollover Creshes". 20th International Technical Conference on the Enhanced Safety of Vehicles (ESV). Paper No. 07-0479
[6] NHTSA Report. 2002. "Characteristics of Fatal Rollover Crashes". NHTSA Technical Report DOT HS 809 438, April 2002
[7] Pokorski J., Reński A., Sar H. 2012. "Investigation of adhesion characteristics of different tyre types in different weather conditions". Journal of KONES Powertrain and Transport, Vol. 19, No. 3, 2012
[8] Prochowski L., Zielonka K, Muszyński A. 2012. "Analysis of the Process of Double-deck Bus Rollover at the Avoidance of an Obstacle Having Suddenly Sprung up". Journal of KONES Powertrain and Transport, Vol. 19, No. 3, 2012
[9] Prochowski L., Zielonka K. 2014. "Analysis of the risk of double-deck bus rollover at the avoidance of an obstacle (analytical approach and computer simulation)". Eksploatacja i Niezawodnosc – Maintenance and Reliability 2014; 16 (4)
[10] Viano D.C., Parenteau, Ch.S. 2004. "Rollover Crash Sensing and Safety Overview". SAE Technical Paper No. 2004-01-0342
[11] Young D., Grzebieta R.H., Rechnitzer G., Bambach M., Richardson S. 2008. "Rollover Crash safety. Characteristics and issues". Accident Reconstruction Newsletter. Issue 95, June 2008

APPENDIX. CALCULATION

Data for the exemplary calculation related to the rollover of the double-decker bus in two states of loading was taken from [8] and [9].

The bus without passengers:
- vehicle mass m = 17 300 kg,
- mass moment of inertia about the vehicle centre longitudinal axis J_x = 34 600 kg m^2
- wheel track b = 2,05 m,
- CG height h = 1,45 m.

The Static Stability Factor (SSF) for the bus without passengers according to Equation (12) is equal to

$$\mathrm{SSF} = b/(2h) = 2{,}05/(2\cdot 1{,}45) = 0{,}71$$

and roll angle (Equation (13))

$$\varphi_{roll} = \arctan\big(b/(2h)\big) = \arctan\big(2{,}05/(2\cdot 1{,}45)\big) = 35{,}3\ [°]$$

The radius of rotation of the centre of gravity about the rotation axis (Equation (18)) is equal to

$$r_{roll} = \sqrt{(b/2)^2 + h^2} = \sqrt{(2{,}05/2)^2 + 1{,}45^2} = 1{,}78 \text{ [m]}$$

Also according to Equation (17) the mass moment of inertia J_{roll} about the rotation axis can be calculated as follows:

$$J_{roll} = J_x + m\, r_{roll}^2 = 34\,600 + 17\,300 \cdot 1{,}78^2 = 89\,400 \text{ [kg m}^2\text{]}$$

and finally according to Equation (23) the Critical Sliding Velocity is equal to

$$\text{CSV} = \sqrt{\frac{2\,g\,J_{roll}}{m h^2}\left(r_{roll} - h\right)} = \sqrt{\frac{2 \cdot 9{,}81 \cdot 89400}{17300 \cdot 1{,}45^2} \cdot \left(1{,}78 - 1{,}45\right)} = 4{,}0 \text{ [m/s]} = 14{,}4 \text{ [km/h]}$$

In the similar way for the bus with passengers:
- vehicle mass m = 25 000 kg,
- mass moment of inertia about the vehicle centre longitudinal axis J_x = 48 700 kg m^2
- wheel track b = 2,05 m
- CG height h = 1,73 m

$$\text{SSF} = b/(2h) = 2{,}05/(2 \cdot 1{,}73) = 0{,}59$$

$$\varphi_{roll} = \arctan\left(b/(2h)\right) = \arctan\left(2{,}05/(2 \cdot 1{,}73)\right) = 30{,}6\ [°]$$

$$r_{roll} = \sqrt{(b/2)^2 + h^2} = \sqrt{(2{,}05/2)^2 + 1{,}73^2} = 2{,}01 \text{ [m]}$$

$$J_{roll} = J_x + m\, r_{roll}^2 = 48\,700 + 25\,000 \cdot 2{,}01^2 = 153\,000 \text{ [kg m}^2\text{]}$$

$$\text{CSV} = \sqrt{\frac{2\,g\,J_{roll}}{m h^2}\left(r_{roll} - h\right)} = \sqrt{\frac{2 \cdot 9{,}81 \cdot 153000}{25000 \cdot 1{,}73^2} \cdot \left(2{,}01 - 1{,}73\right)} = 3{,}4 \text{ [m/s]} = 12{,}2 \text{ [km/h]}$$

Since in both cases SSF is smaller than the friction coefficient the bus is exposed to rolling over on the ordinary, flat road surface ($\mu \approx 0{,}8$).
If the bus without passengers is moving on the curve with radius equal of 60 m, the rollover limit can be calculated from the Equation (9)

$$v = \sqrt{R\,g\,\frac{b}{2h}} = \sqrt{60 \cdot 9{,}81 \cdot \frac{2{,}05}{2 \cdot 1{,}45}} = 20{,}4 \text{ [m/s]} = 73{,}4 \text{ [km/h]}$$

and for the bus with passengers

$$v = \sqrt{R\,g\,\frac{b}{2h}} = \sqrt{60 \cdot 9{,}81 \cdot \frac{2{,}05}{2 \cdot 1{,}73}} = 18{,}7 \text{ [m/s]} = 67{,}2 \text{ [km/h]}$$