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ROLLOVER OF THE BIAXIAL VEHICLE (UNTRIPPED CASE)

Abstract: The paper describes the role of rollover accidents in the road transport. The influence of vehicle type and body CG position is considered. Manoeuvre induced rollover is being described. The paper presents the results of analytical and simulation investigations on maximum possible biaxial truck and LTV lateral acceleration without rollover during curvilinear motion on an ideally smooth, horizontal, high friction road surface (i.e. untripped case of rollover).
Keywords: vehicle safety, road vehicle dynamics, rollover

1. INTRODUCTION

Already data sources in the mid-90s of 20th century [1, 12, 13, 17, 18] suggested that if we include traffic accidents related to the car rollover to the group of "car crashes" (among themselves or with elements of the environment), they constituted from 8% to 22% of events (depending on the data source.) The car rollover was the reason for 4% (France), 8% (UK), 12% (U.S.), and 15% (Sweden) of lethal accidents occurred during the collision, and from 3% (France) up to 16% (Sweden) of heavy human body damage. Based on the NHTSA agency's data in 2002 [13] in the U.S., out of the examined 11 million accidents of passenger cars, SUVs, pickups, and delivery vans, only 3% had rollovers. The accidents, however, were a cause of 33% of deaths from all accidents of the vehicles [16]. In the period of 1995-2003, approximately 10,000 people died each year in those types of accidents and approximately 27,000 people were injured [13]. According to the NHTSA data [13], 95% of the single vehicle rollovers are "tripped rollovers". Those types of accidents are the following: on the soft soil; as a result of contact with the route protective barrier, especially its initial element ("guardrail"), the curb, ruts; and on a steep slope. Only 5% of single vehicle rollovers are "untripped rollovers". Studies of such cases are simpler and more unique in evaluation of the results. It is believed that if a vehicle shows a propensity or resistance to rollover in the "untripped" type of tests, then it shall be indicating similar characteristics during the "tripped" type of tests. Therefore, the untripped types of open-loop tests (without a vehicle-driver-environment feedback) are the most frequently conducted in experimental and simulation studies. Analysed are the cases of horizontal ground motion with a high coefficient of adhesion, and thus for the zero-lateral super-elevation and zero-longitudinal inclination of the road. Therefore, not included is the vehicle rollover, caused by contact of wheels with the obstacle (curb, shoulder), or a soft ground.

2. METHODS FOR EVALUATION OF VEHICLES RESISTANCE AGAINST ROLLOVER

2.1. Simple Computational Methods

In the basic theoretical training on the vehicle motion and dynamics [4, 7, 14, 18], the limit state of car curvilinear motion is analysed using a model of the vehicle presented as a flat, rigid figure supported at two points showing contact of the road with the left and right wheels (Fig. 1).

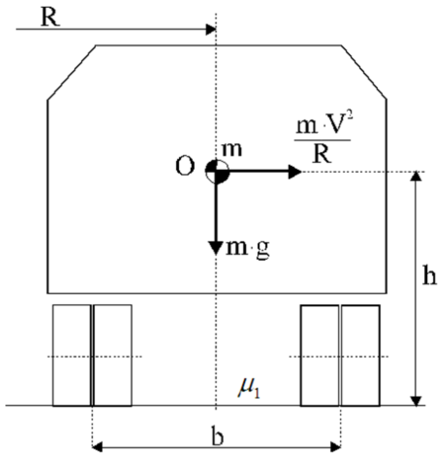

Fig. 1. The basic model for determining the limit states of a biaxial vehicle curvilinear motion. μ_1 –coefficient of adhesion peak value (wheels - the road surface), [-]; b – track of wheels, [m]; h – height of the centre of the vehicle mass, [m]; m – vehicle mass, [kg]; V – vehicle speed, [m/s]; R – radius of the motion trajectory, [m]; g=9,81 m/s^2 – gravity acceleration; O – the centre of the vehicle mass

The condition for occurrence of the vehicle large side slip prior to the rollover is the fulfilment of dependence (a description of the symbols is in the caption of Fig. 1).

$$\mu_1 \langle \frac{b}{2 \cdot h} = SSF = RT \tag{1}$$

The ratio of the half width of the track of the wheels b/2 to height of centre of mass of the vehicle h is called *SSF* (Static Stability Factor) or *RT* (Rollover Threshold). Those are coefficients reflecting the propensity of the vehicle for rollover. The maximum achievable lateral accelerations values a_{pmax} [m/s^2] and vehicle velocity V_{max} [m/s] without rollover, for the model shown in Fig. 1 (there is also a description of symbols occurring in the formulas below) are as follows:

$$a_{p\max} = g \cdot \frac{b}{2 \cdot h} = g \cdot SSF \tag{2}$$

$$V_{\max} = \sqrt{g \cdot \frac{b \cdot R}{2 \cdot h}} = \sqrt{g \cdot SSF \cdot R} = \sqrt{a_{p\max} \cdot R} \tag{3}$$

Dependencies (1)÷(3) are often used in assessing the limit values of quantities that describe the curvilinear motion of the car. Fig. 2 shows the dependence of coefficient illustrating a frequency of occurrence of the rollover type of accidents against the *RT (≡SSF)* coefficient. There is a visible clear trend of a declining number of the rollover type of accidents with increasing values of *RT (≡SSF)* ratio, regardless of the type of the analysed vehicle type.

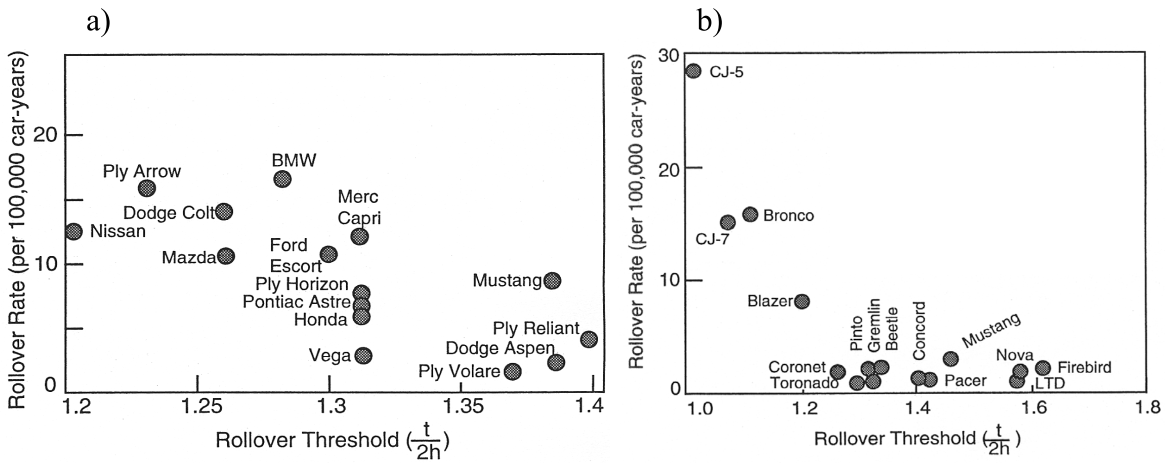

Fig. 2. The number of rollover cases of a given make and type of vehicles (calculated per 100,000 of vehicle-years) as a function of *RT* (≡*SSF*), calculated for the analysed vehicle (here t is denoted as b from Fig. 1).
a) Small cars [1]. b) Cars and commercial vehicles [15]

2.2. Use of *MBS* Structure Simulation Models

The model presented in Figure 1 does not include many properties of the actual vehicle, which affect its behaviour in curvilinear motion. These are: a phenomenon of side slip of tired wheels; spatial nature of the phenomenon (load changes, not only on the sides but also between the axles of the vehicle; lateral force does not generally act perpendicularly to the vehicle's plane of symmetry, which is due to the side slip of the car); compliances and damping of the suspension; flexibility of tires; vertical motion coupling of the vehicle body with the lateral tilt; nonlinearity of the elastic characteristics of the suspension; dry friction in the suspension; driving forces on driven wheels; geometrical parameters characterizing the so-called "steerable wheels setting" (camber angle, king-pin inclination, caster angle); geometric and elastic properties of the steering system; turn of the front axle wheels and self-steerability of driving axles, which affects the change in the location of points of contact with the road surface. More complex models of the vehicle motion and dynamics are multi-mass systems *MBS (Multi-Body Systems)*, consisting of rigid bodies (or flexible) combined by elastic-damping and guiding elements. Fig. 3 presents of two models of *MBS* type, built by the author.

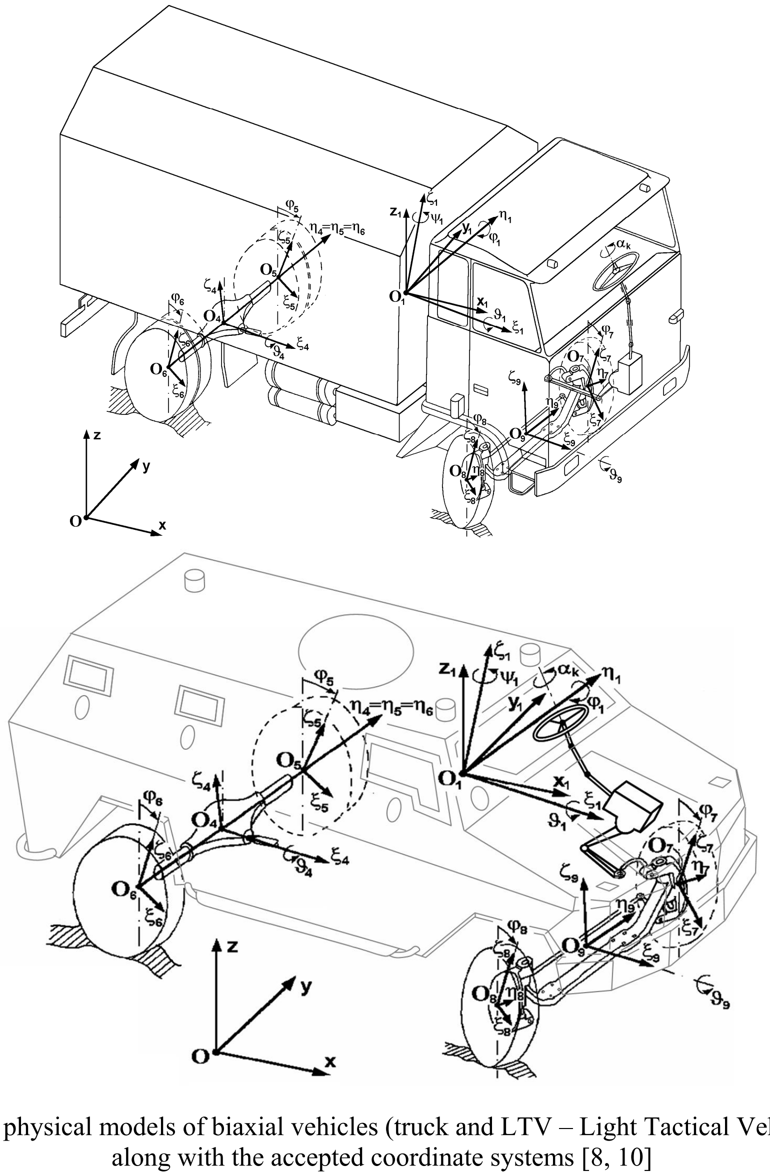

Fig. 3. Two spatial physical models of biaxial vehicles (truck and LTV – Light Tactical Vehicle) of *MBS* type along with the accepted coordinate systems [8, 10]

Both are seven-mass systems with 14 degrees of freedom [4, 5, 6, 8, 9, 10, 11]. Rigid bodies of models are: vehicle body, 2 driving axles, 4 wheels. Coordinates that describe a motion of the models are: x_{O1}, y_{O1}, z_{O1} (coordinates defining the location of the center O_1 of the vehicle body mass in inertial reference system Oxyz), ψ_1, φ_1, ϑ_1 (coordinates that describe spherical motion of the vehicle body against its centre of the mass O_1; they are quasi-Euler angles – yaw, pitch and roll angle); ζ_{1O4} (coordinate describing the motion of the mass centre O_4 of the body of the rear axle against the vehicle body, it takes place towards $O_1\zeta_1$ of the system $O_1\xi_1\eta_1\zeta_1$); ϑ_4 (roll angle of the rear axle body against the vehicle body), ζ_{1O9} (coordinate describing the motion of the mass centre O_9 of the front axle beam body against the vehicle body, it takes place towards $O_1\zeta_1$ of the system $O_1\xi_1\eta_1\zeta_1$); ϑ_9 (roll angle of front axle body against the vehicle body); φ_5, φ_6, φ_7, φ_8 (angles of wheels rotation: rear, left and right, front, left and right). The elastic-damping characteristics of the suspension, steering system and wheels with tires are strongly nonlinear. They correspond to the real properties of the vehicle. The models have been successfully verified experimentally for typical manoeuvres recommended by ISO [8].

The models described have been used to assess the value of the maximum achievable lateral acceleration a_{pmax}, [m/s^2] (compare relation (2) for the simple computational methods). The steady motion was simulated with velocity of V= 22.22 m/s = 80 km/h along the circles with different radii on dry asphalt-concrete pavement. Movement to the right and the left was assessed. The state of the vehicle motion was described by lateral acceleration, roll angle of the vehicle body, and the values of normal reactions of the road for each of the wheels. Detachment of two inner wheels from the road surface was adopted as a criterion of the vehicle rollover. In the case of a real car and its complex model, the extreme lateral acceleration value is reached (in most analysed tests) after isolation of the first and before detachment of the second inner wheel. The computational results shall be presented in the next section of the paper.

3. COMPARISON OF CALCULATIONS RESULTS USING SIMPLE COMPUTATIONAL METHODS AND *MBS* TYPE OF SIMULATION MODELS

Simulation computations for a truck were performed for the state without a payload (but with the driver; specialised swap body, total weight of 6900 kg) and for three load cases placed in a specialised swap body (total vehicle weight of 9165 kg), located at different heights.

Research studies performed on the LTV vehicle were carried out for six vertical positions of the centre of mass of the vehicle with unchanged total weight (5975 kg).

Table 1 shows the results of computations of *SSF* (≡*RT*) coefficient and the maximum lateral acceleration a_{pmax} for both tested vehicles in various loaded states, using the model shown in Fig. 1.

Table 1.

Values of the key parameters of the truck and the LTV and the computed values of *SSF* coefficient and acceleration a_{pmax} (the model shown in Fig. 1 was used)

Vehicle	Track of wheels b [m]	Height of mass centre h [m]	*SSF* Factor *SSF*=b/(2·h) [-]	Maximum lateral acceleration a_{pmax} [m/s^2]
Truck	1.868	1.509	0.619	6.07
Truck	1.868	1.556	0.596	5.85
Truck	1.868	1.736	0.538	5.28
Truck	1.868	1.846	0.506	4.96

LTV	1.700	0.800	1.063	10.43
LTV	1.700	0.900	0.944	9.26
LTV	1.700	1.000	0.850	8.34
LTV	1.700	1.066	0.797	7.82
LTV	1.700	1.200	0.708	6.95
LTV	1.700	1.300	0.654	6.42

Fig. 4 summarizes the results of computations of the maximum lateral acceleration a_{pmax} as a function of *SSF (≡RT)* coefficient, using a simple computational method (see Fig. 1 and dependencies (2) and (3)) and models with *MBS*-type of structures (Fig. 3). They refer to biaxial vehicles: a truck and LTV vehicle, characterized by the location of the centre of mass, as described in Table 1.

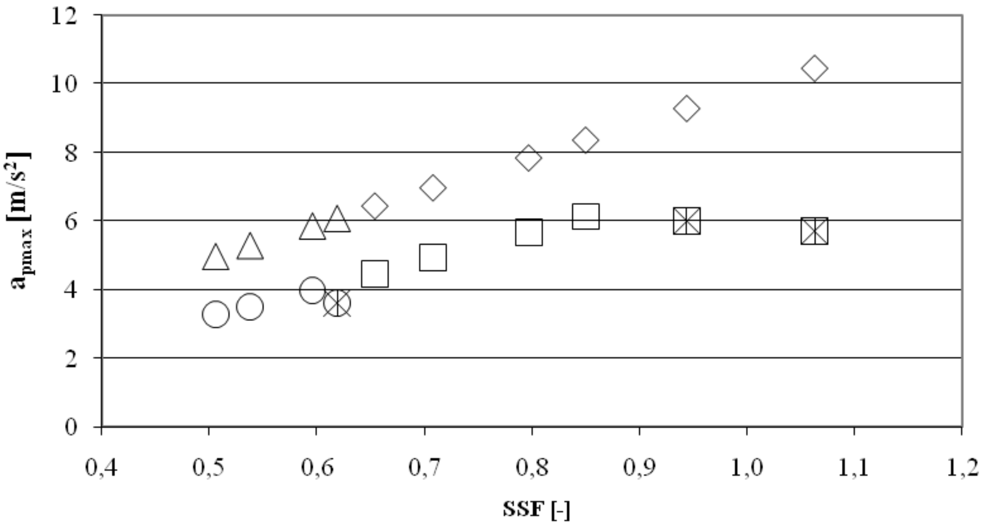

Fig. 4. The results of computations of the maximum lateral acceleration a_{pmax} as a function of *SSF* (≡*RT*), using a simple computational method ("simple model", see also Fig. 1) and models with *MBS*-type of structure (“*MBS* model ", see also Fig. 3). Two biaxial vehicles: a truck and LTV (Light Tactical Vehicle). Cases marked additionally by the "×" symbol refer to states in which the vehicle does not rollover

In three cases in which the *MBS*-type model was used (additionally marked by the "x" symbol), the vehicles did not rollover. This limit state was characterized by significant side slip angles or a significant decrease in the vehicle speed, resulting from a detachment or a considerable counterbalance of the inner propelling wheel – as a result, the wheels drive cannot have been realized. In other cases, the cars rolled over. For both models used hereto, there is a visible trend of growing maximum lateral acceleration of the vehicle a_{pmax} with the increasing values of *SSF (≡RT)* coefficient. Large values of a_{pmax} for high values of *SSF* and the low ones for small values of *SSF* indicate a decreased propensity to the vehicle rollover along with the increasing *SSF*. This is also confirmed by the statistics presented in Fig. 2.

Using the simulation model with *MBS* structure (Fig. 3) leads to the receipt of the limit values of lateral accelerations a_{pmax} by about 30% lower than those derived using a simple model (Fig. 1 and 3, Table 1). This indicates the important impact of the model structure on the results of computations of values that characterize limit states of the car curvilinear motion. The complex models, experimentally validated allow for more realistic (and less optimistic) assessment of the vehicle rollover risk.

4. CONCLUSIONS

Height of the vehicle's centre of mass is important in terms of its propensity to rollover. Cars using persons, especially commercial vehicles and trucks, should pay attention when loading them so that the value of the centre of mass height h (Fig. 1) would be as small as possible, which in turn leads to high values of *SSF (≡RT)* coefficient (dependency (1)).

Using a more complex model of the vehicle motion and dynamics allows for more realistic assessment of the vehicle rollover risk.

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WYWRACANIE SIĘ SAMOCHODU DWUOSIOWEGO NA BOK (PRZYPADEK RUCHU NA RÓWNEJ POZIOMEJ NAWIERZCHNI DROGI)

Streszczenie: Artykuł omawia znaczenie wypadków drogowych kończących się wywróceniem pojazdu na bok. Oceniana jest rola wysokości środka masy pojazdu. Rozważany jest przypadek wywrócenia pojazdu spowodowanego manewrem, wykonywanym przez kierowcę na drodze poziomej, idealnie równej, o wysokim współczynniku przyczepności. Przedstawiono wyniki rozważań wykorzystujących modele analityczne i symulacyjne. Oceniano maksymalne możliwe do uzyskania przyspieszenie poprzeczne pojazdu, nie wywołujące jego wywrócenia na bok. Wyniki otrzymano dla dwóch pojazdów dwuosiowych: samochodu ciężarowego i samochodu patrolowo-interwencyjnego LTV.
Słowa kluczowe: bezpieczeństwo ruchu samochodu, dynamika samochodu, wywracanie samochodu na bok