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EVALUATION OF THE ROLLOVER THRESHOLD OF TANK VEHICLES

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RESEARCH ARTICLE

ABSTRACT: The improvement of the driving safety and the eradication of accidents is a matter of high priority in research in the area of automotive engineering. Especially in heavy vehicles transporting dangerous goods, every accident means high cost due to probable loss of life, environmental pollution and infrastructure damage. The present paper focuses on the analysis of the dynamic behavior of tank vehicles used to transport flammable liquids. Its main purpose is to correlate the rollover threshold of tank vehicles to the geometry of the cross section of the tank taking into consideration the maximum allowed dimensions and gross weight. Firstly, a 4-axle truck is simulated using the multi-body software TruckSim® in order to monitor its dynamic behavior. Several simulation tests consisting of typical maneuvers were carried out considering different shapes of the cross section of the tank, considering equal volume of transported flammable liquid. For each simulation test several dynamic quantities have been monitored in order to estimate the safety against tank vehicle rollover. The results, among others, showed that the cross section providing the highest rollover threshold was an elliptical which looks like the box shaped. Furthermore, an important outcome of this paper is the determination of the maximum speed for each simulated maneuver and shape of cross section.

KEY WORDS: *tank vehicle, rollover, dynamic stability, tank cross section*

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OCENA PRAGA PREVRATANJA VOZILA CISTERNE

REZIME: Poboljšanje bezbednosti u vožnji i iskorenjivanje nezgoda je pitanje visokog prioriteta u istraživanju u oblasti vozila. Naročito kod teških vozila koja prevoze opasne materije, svaka nezgoda znači visoku cenu zbog verovatnog gubitka života, zagađenja životne sredine i oštećenja infrastrukture. Ovaj rad se fokusira na analizu dinamičkog ponašanja cisterni koja se koriste za transport zapaljivih tečnosti. Njegova osnovna namena je da poveže prag prevrtanja vozila cisterne sa geometrijom poprečnog preseka rezervoara uzimajući u obzir maksimalno dozvoljene dimenzije i bruto težinu. Prvo, 4-osovinski kamion se simulira pomoću softvera za više karoserija TruckSim® kako bi se pratilo njegovo dinamičko ponašanje. Urađeno je nekoliko simulacionih testova koji se sastoje od tipičnih manevara s obzirom na različite oblike poprečnog preseka rezervoara, s obzirom na jednaku zapreminu transportovane zapaljive tečnosti. Za svaki simulacioni test je praćeno nekoliko dinamičkih veličina kako bi se procenila bezbednost od prevrtanja vozila cisterne. Rezultati su, između ostalog, pokazali da je poprečni presek koji obezbeđuje najviši prag prevrtanja eliptičan koji izgleda kao kutija. Nadalje, važan ishod ovog rada je određivanje maksimalne brzine za svaki simulirani manevar i oblik poprečnog preseka.

KLJUČNE REČI: *vozilo cisterna, prevrtanje, dinamička stabilnost, presek rezervoara*

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INTRODUCTION

According to Eurostat [1], the share of dangerous goods road transport (in tkm) for 2019 and 2020 was around 4% in both years compared to the total transport. Since 2015 the transport of dangerous goods in EU fluctuated. More specifically, between 2015 and 2019, 11 member states registered an increase in the transport of dangerous goods. The highest increases were recorded for Slovenia (74.8%), Croatia (+55.4%) and Italy (+32.7%). Flammable liquids accounted for more than half of the transport of dangerous goods in the years of 2019 and 2020 [1]. Flammable liquids are usually transported with the use of tank vehicles. Tank vehicles that carry flammable liquids can be either articulated vehicles such as tractor-semitrailer or just tank trucks. If such a vehicle is involved in an accident the consequences are going to be important for the driver and the environment [2] due to both its high weight and the inherent danger of the transported material.

The most usual cause of a heavy vehicle accident is rollover; hence a lot of research has been done in order to improve the lateral stability of heavy vehicle and avoid a rollover accident. Bai Zhenyuan et. al [3] proposed a method of improving the lateral stability of a semi-trailer by using additional yaw moment of it. Dhruv Oberoi [4] developed an anti-roll control and optimized it in order to obtain better roll stability and directional performance of an articulated vehicle. However, it is very common especially, in small or developing countries, to transport flammable liquids like petrol (UN1202) and gasoline (UN1203) with tank trucks. Tian Xin et. al [5] has presented a research on the speed thresholds of trucks in a sharp turn based on dynamic rollover risk levels. Furthermore, Shimanovsky et. al [6] explained how baffles affect the dynamics of tank trucks which carry viscous liquids.

In this paper, the dynamic behaviour of a 4-axle tank truck with four tanks with geometrically different cross-sections is evaluated in TruckSim ® software. The dynamic behaviour of the tank truck is investigated in two different scenarios, tilt table and double lane change. Moreover, the dynamic response of the tank truck with each cross section in double lane change has been investigated with three different initial velocities and four different filling ratios.

1. MATERIALS & METHODS

For the analysis of the dynamic behaviour of heavy vehicles through numerical simulations TruckSim ® software is used. This software consists of three parts, the VS (VehicleSim) Browser (GUI), the VS Solver and the VS Visualizer and it utilizes ordinary differential equations (ODE) [8]. The equations simulate the choices made at the user interface (VS Browser) while the solution is coming from the VS Solver. Through VS Visualizer the results are presented in video and plot format. Using TruckSim, the user can select the technical characteristics of the heavy vehicle, the scenario and the driving conditions, for example the wind velocity.

1.1 Heavy vehicle model

In this paper, a 4-axle tank truck is used for the simulation of two different scenarios. In Figure 1 the tank truck model is presented.

Figure 1 Vehicle model

The technical characteristics of the vehicle such as masses, types of suspensions and its mechanical properties and the tires are the ones that the software has as default. In Table 1, the values of the sprung and the unsprung mass of the heavy vehicle are presented.

Table 1 *Sprung and unsprung mass of the vehicle*

Sprung mass (kg)	4455
Center of unladen sprung mass	(X, Y, Z) = (1175, 0, 1115) from the origin of sprung mass
Unsprung mass (kg)	
Steering axle	174
Driving axle	603
Tyre (Steering)	91
Tyre (Driving)	91
Total unsprung mass	2646

In Table 2 the mechanical properties of the suspension on each axle are presented

Table 2 *Mechanical properties of the suspensions*

	Spring rate [N/mm]	Damper rate [kN/(m/s)]	Technical capacity [tonnes]
Axle 1 (Solid)	200	10	4
Axle 2 (Solid)	200	10	4
Axle 3 (Dual tires - Drive)	700	30	15.5
Axle 4 (Dual tires - Drive)	700	30	15.5

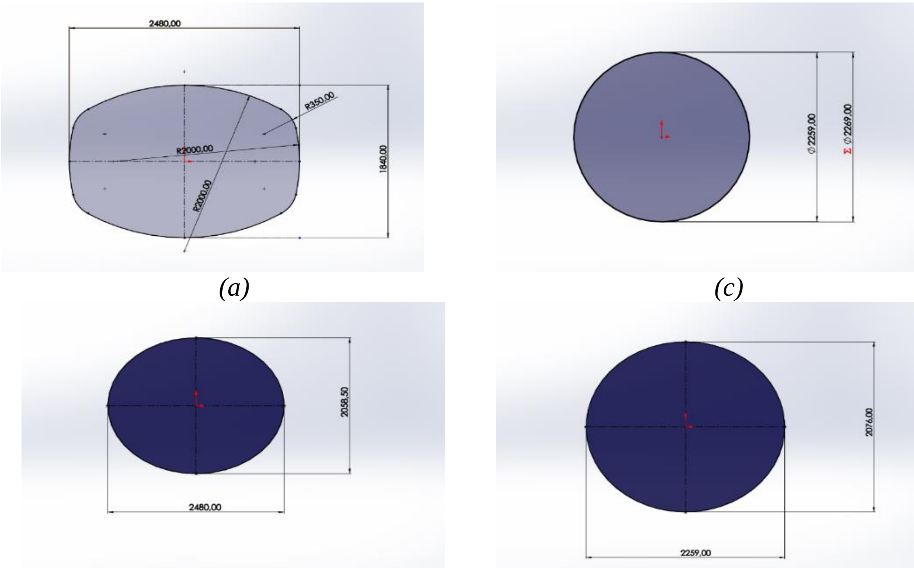
The engine of the vehicle is an internal combustion Diesel engine with 225 kW power at 2100 rpm. The transmission is automatic with 5 speeds and the shifts are made at 2100 rpm. The duration of the shift is 0.25 s.

1.2 Metallic Tank

Instead of the rectangular container shown in Figure 1, the tank vehicle has a metallic tank in order to transport the flammable liquid. This tank, according to EN13094 [9], can have a circular, an elliptical or a box-shaped cross-section. The box-shaped cross section consists of three circles of different radius.

In order to study the effect of the geometry of the cross section of the tank to the stability of the heavy vehicle, four different cross sections have been constructed in Solidworks

3DCAD software (Figure 2). Starting from a box-shaped cross section, the total volume of the tank has been calculated (28187 lt) and one equivalent (of the same volume) circular and two elliptical ones have been designed.



(a) *(c)*

(b) *(d)*

Figure 2 2D Sketch for the cross section (a) box shaped (M1) (b) circular (M2) (c) elliptical (M3)which looks like the circular (d) elliptical (M4) which looks like the box shaped

In Table 3 the main dimensions of each tank are presented.

Table 3 *Main dimensions of each tank*

Model	Cross-section	Width (mm)	Height (mm)	Length (mm)	Capacity (lt)
M1	Box-				2
	Shaped	480	840	595	8084
M2	Circular				2
		259	259	070	8336
M3	Elliptical				2
		259	076	636	8125
M4	Elliptical				2
		480	058.5	070	8347

In Table 4 the net weight of each tank, constructed of sheets of aluminium alloy with thickness equal to 5 mm is presented. The density of the aluminium alloy is equal to 2700 kg/m3.

***Table 4** Net weight of each tank*

Model	Net Weight (kg)
M1	792
M2	788
M3	704
M4	683

In TruckSim ® the different tanks have been defined through the Payload definition screen presented in Figure 3. For each tank the position of its center of mass has to be defined along with the corresponding inertia of each cross- section.

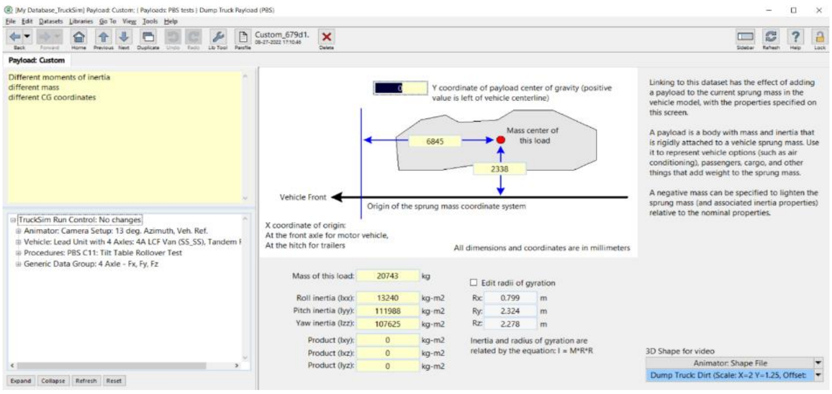


Figure 3 Payload definition in TruckSim

In Table 5 the position of the centre of mass for each tank on the x-z plane is presented. The origin for the measurements of these coordinates is the origin of the sprung mass.

***Table 5** Position of center of mass for each cross section*

Model	X-axis	Z-axis
M1	6803 mm	2220 mm
M2	6535 mm	2429,5 mm
M3	6845 mm	2338 mm
M4	6535 mm	2329 mm

Furthermore, in Table 6, the moments of inertia change according to the shape of the cross-section of the tank are presented.

***Table 6** Moments of inertia for each cross section*

Moment (kg·m^2)	M1	M2	M3	M4
Ixx (Roll)	14336	14497	13240	14687
Iyy (Pitch)	103829	99966	111988	97416
Izz (Yaw)	103123	95201	107625	95244

In order to calculate the mass of load, i.e. the mass of transported liquid, UN1203 has been considered, with density equal to 750 kg/m^3.

1.3 Driving scenarios

In order to evaluate the dynamic behaviour of the tank truck with the different tank cross-sections two different scenarios have been simulated. The first scenario is the quasi-static a tilt-table test [7]. During this test, the vehicle is fully loaded and mounted on a table with its longitudinal axis parallel to an axis that gradually tilts about the table. The simulation stops when the vehicle becomes unstable in roll.

Actually, every non-zero tilt angle simulates a non-vibratory steady state turn. The scope of this test is to define the steady-state rollover threshold of the vehicle, i.e., the maximum lateral acceleration the vehicle could deploy in steady state turn without rolling over [10]. The tilt rate is equal to 0.2^o/s. The variables of interest are the roll angle and the lateral acceleration. The second driving scenario is double lane change. During this scenario, the vehicle, having an initial velocity, changes lane twice in opposite directions and in short time. During this scenario, roll angle, lateral acceleration, yaw rate and vertical tire forces are monitored.

All the above-mentioned values as well as the scenarios are input in the software through the Run Control Interface that is presented in Figure 4.

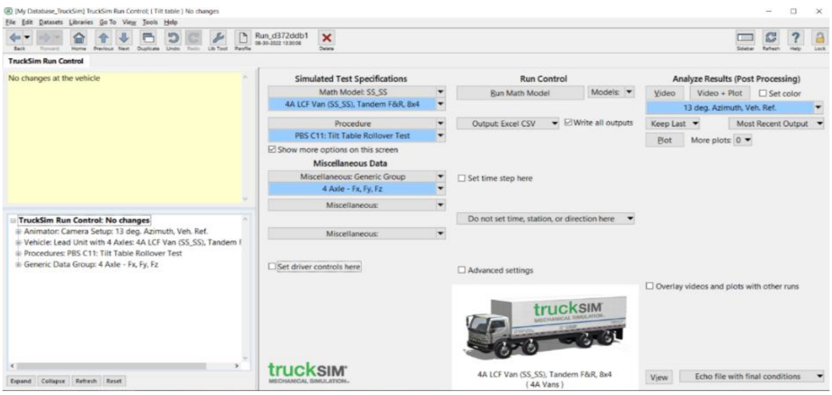


Figure 4 TruckSim Run Control interface

2. RESULTS

Firstly, the results for the scenario of tilt table test are presented for all the cross-section shapes. Then the double lane change scenario with constant velocity 30 km/h and 95% of the maximum payload for every tank cross section is presented.

2.1 Tilt-table test method

In the Figure 5 (a) the change in roll angle against time is presented for all cross-sections while in Figure 5 (b) the lateral acceleration versus time is presented.

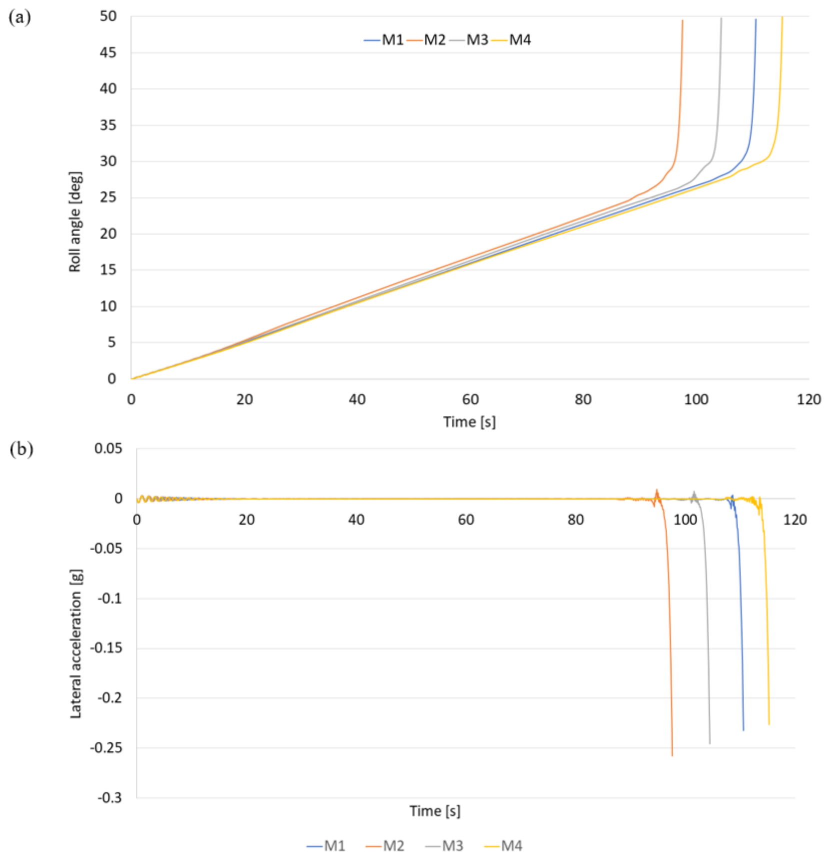


Figure 5 (a) Roll angle and (b) Lateral acceleration in tilt table test method

In Figure 5 (a) is obvious that the last cross-section to overturn is M4 followed by M1.

Rollover threshold is the maximum value of lateral acceleration a vehicle can sustain during steady-state cornering on a flat surface without rolling over [7]. The calculation for the rollover threshold is based on the equation:

$$Rollover\ threshold = \frac{mg \sin \varphi_C}{mg \cos \varphi_C} = \tan \varphi_C$$

where φ_C: tilt table angle the moment of critical wheel lift

Critical wheel lift is defined as the moment, in s, when the vehicle has a lateral acceleration equal to the rollover threshold [7], which is the moment of the first loss of contact of one axle to the tilt-table. Thus, the equilibrium at the roll plane cannot be established. Usually, the first axle which loses the contact with the table is one of the driving one. The rollover threshold of every cross section is presented in the Table 7.

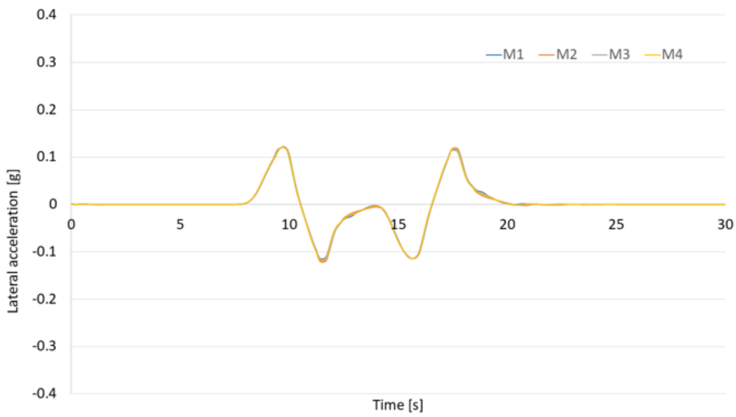
Table 7 *Tilt table test results*

Model	Critical wheel lift [s]	First loss of contact	Time of Rollover [s]	**Rollover threshold [g]**
M1	102.0	Axle 3	108.5	0.37
M2	87.4	Axle 3	94.7	0.32
M3	96.1	Axle 3	101.5	0.35
M4	105.4	Axle 3	113.6	0.39

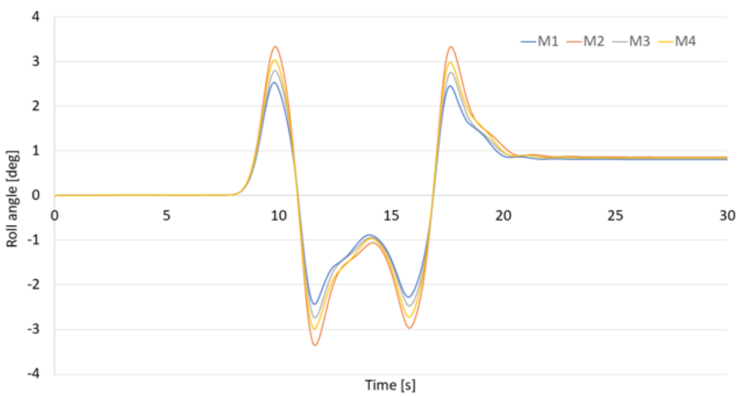
2.2 Double lane change

In the Figure 6, the most important dynamic quantities for the double lane change driving scenario are presented.

(a)



(b)



(c)

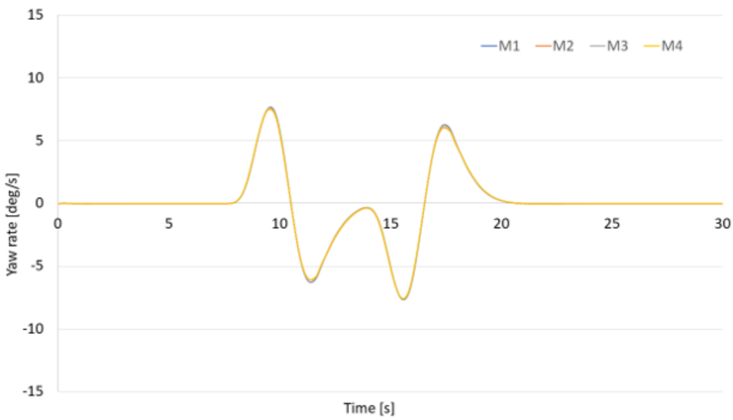


Figure 6 (a) Lateral acceleration, (b) roll angle and (c) yaw rate in double lane change with constant velocity 30 km/h

In Figure 6, is obvious that there is no effect of the cross-section geometry of the tank in the lateral acceleration and the yaw rate of the vehicle while there is a slight difference on the maximum and minimum values of the roll angle during each lane change.

Furthermore, the distribution of the weight of the tank truck in each axle has been investigated and presented in Table 8. The load was monitored in each axle through the vertical forces acting on the wheels during the phase of driving on a straight path i.e. after 22 s when the at steady state has been accomplished.

Table 8 *Axle load for each cross section*

Cross section	Forces per Axle (N)				Total load [kg]
	1	2	3	4	
M1	25952	26109	1 10966	1 11522	2 7987
M2	30570	30706	1 07262	1 07735	2 8065
M3	25172	25332	1 11448	1 12017	2 7928
M4	30577	30712	1 06781	1 07251	2 8162

For M1 and M3 cross sections, the front load axle (Axle 1) is lower compared to this of M2 and M4. On the other hand, the rear load axle (Axle 4) is larger. The last column in Table 8 is the total weight of the vehicle equipped with a tank of the corresponding cross section and 95% of the maximum capacity payload.

Total load = Sprung mass + Unsprung mass + Tank net weight + Transported Liquid weight.

3. DISCUSSION

The results of the first scenario showed that the rollover threshold resulting from tilt-table test is highly dependent on the geometry of the cross-cross section of the tank. On the other hand, the results of the second scenario did not show such dependency. In order to further investigate the effect of the tank cross-section to the lateral stability of the tank truck during double lane change two more velocities have been simulated.

3.1 Parametric study of constant velocity

In both velocities (50 km/h and 70 km/h) the roll angle, the lateral acceleration and the yaw angle are presented for 50 km/h (Figure 7).

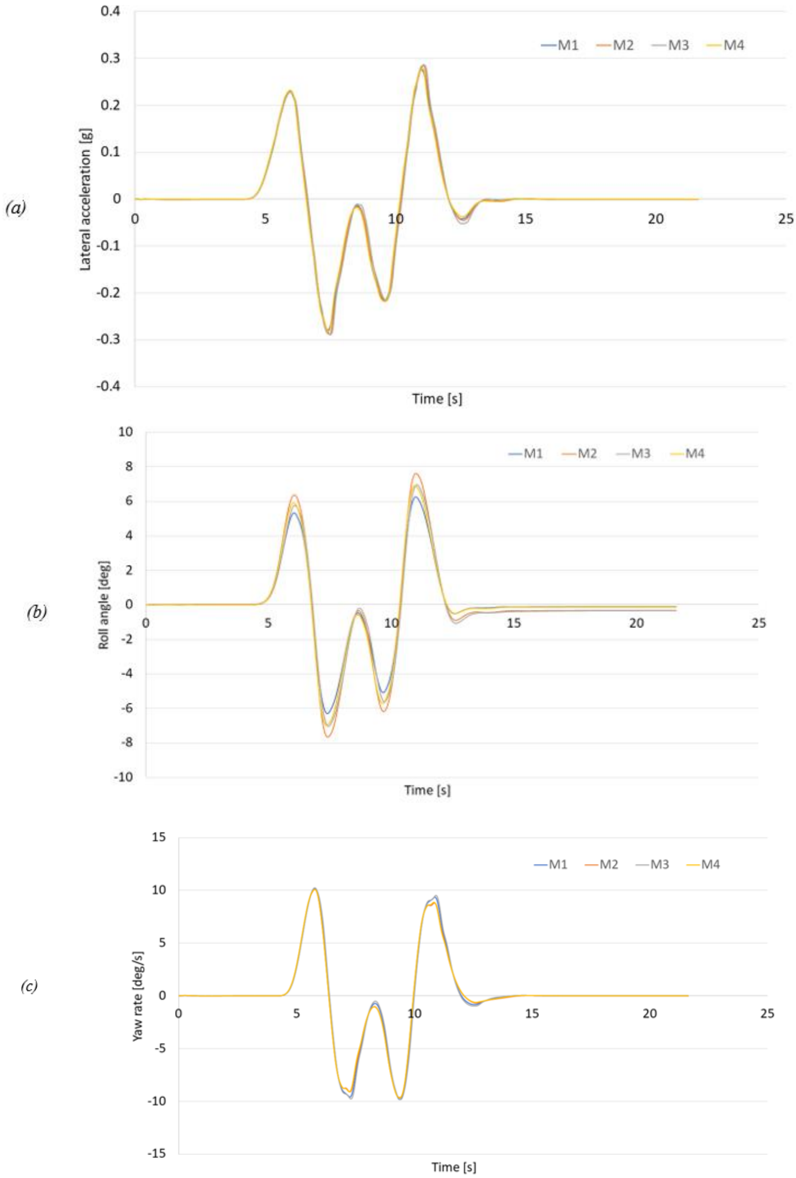


Figure 7 (a) Lateral acceleration (b) Roll angle (c) Yaw rate in double lane change with velocity 50 km/h

In Figure 8 the same dynamic quantities are presented for constant velocity of 70 km/h.

(a)

(b)

(c)

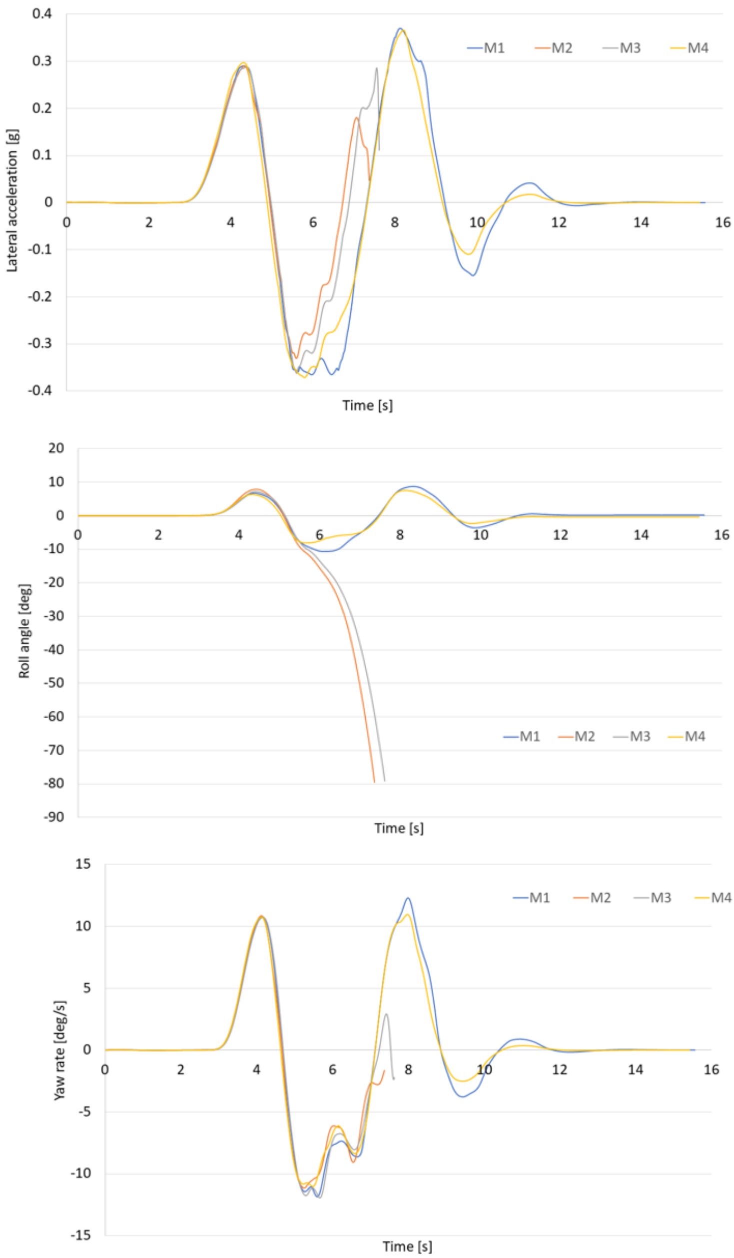


Figure 8 (a) Lateral acceleration (b) Roll angle (c) Yaw rate in double lane change with velocity 70 km/h

In Figure 8 (a) and (b), for constant velocity of 70 km/h, is obvious that the tank truck with tank cross-sections M2 & M3 rollover after almost 6 s and after the first lane change. In Figure 7 there is no overturn but the increase in velocity causes an increase of the minimum and maximum values. In Figures 9, 10 and 11 the maximum and minimum values of lateral acceleration, roll angle and yaw rate are presented for all constant velocities (30 km/h, 50 km/h and 70 km/h).

(a)

(b)

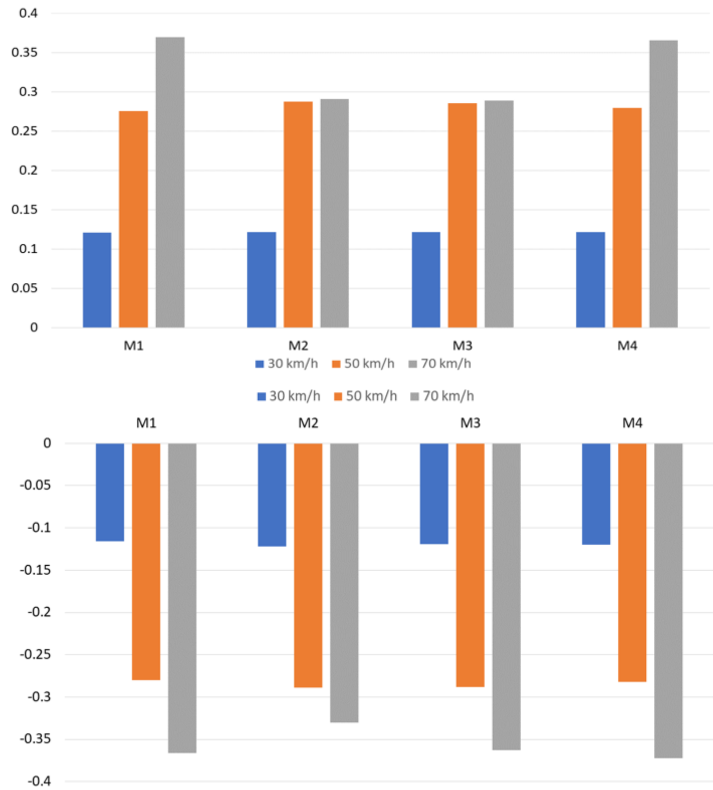
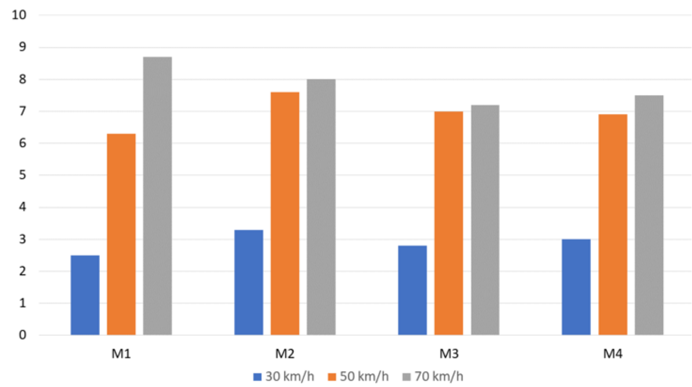


Figure 9 (a) Positive (b) Negative lateral acceleration in double lance change driving scenario for 30,50 and 70 km/h

For the cross sections M1 and M4, the absolute maximum values of the lateral acceleration increase as the velocity increases. Nevertheless, for the cross sections M2 and M3, the transition from 50 to 70 km/h does not affect the maximum and minimum values, only the dynamic behaviour, since rollover happens.

(a)



(b)

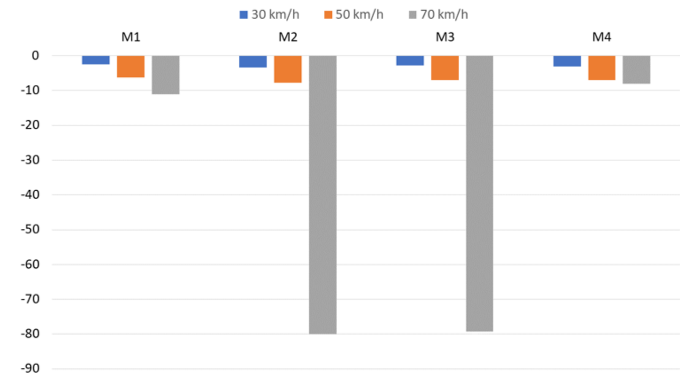


Figure 10 (a) Positive (b) Negative roll angle in double lance change driving scenario for 30,50 and 70 km/h

The results for the roll angle, in Figure 10, are similar to the ones for the lateral acceleration. Increasing velocity creates higher value of the roll angle. Again, is pointed out that the cross sections M1 and M4 carry out successfully the double lane change with every velocity. On the other hand, the cross sections M2 and M3 at velocity 70 km/h rollover.

(a)

(b)

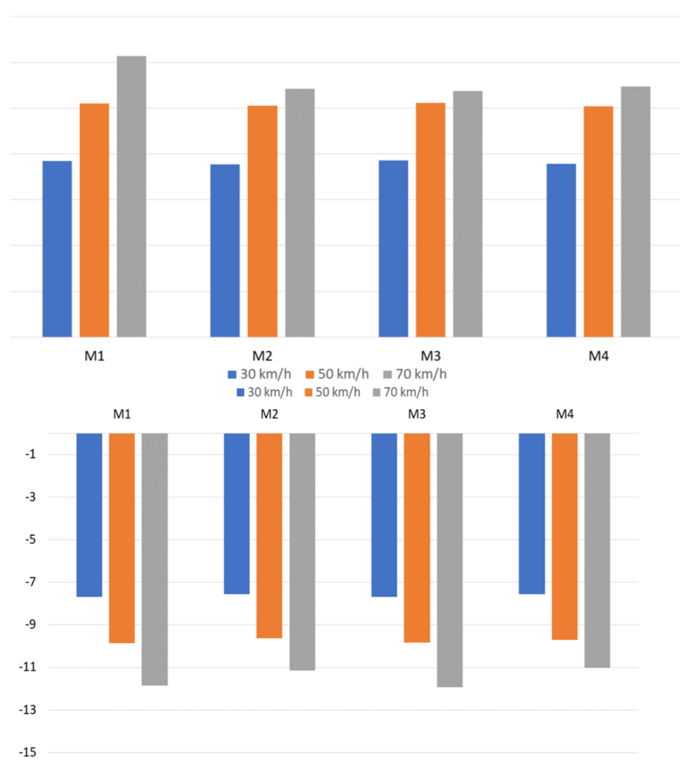


Figure 11 (a) Positive (b) Negative yaw rate in double lance change driving scenario for 30,50 and 70 km/h

The yaw rate, in Figure 11, does not change versus the velocity and does not seem to be affected by the geometry of the cross-section of the tank.

3.2 Parametric study of filling ratio

Since M2 and M3 rollover during double lane change with 70 km/h a parametric study of the degree of filling has been considered for M1 and four different degrees of filling, namely, 0% - 20% - 80%- 95%.

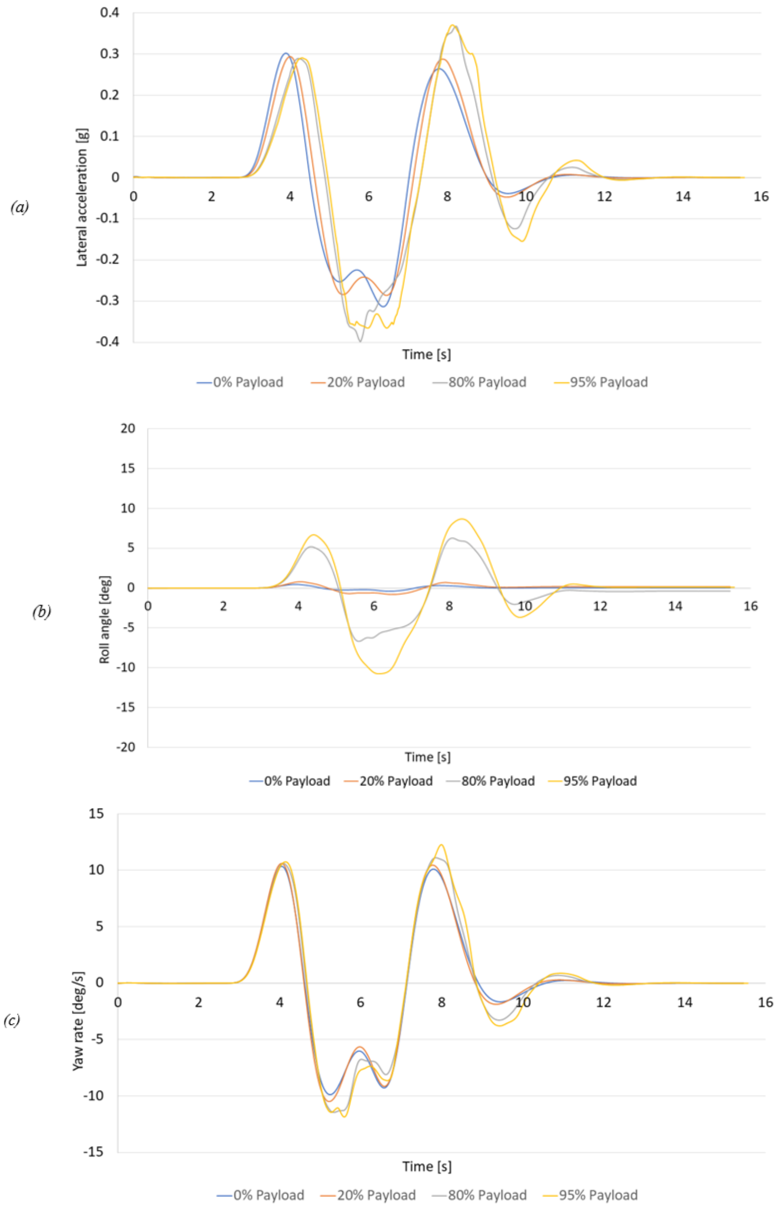


Figure 12 (a) Lateral acceleration (b) Roll angle (c) Yaw rate in double lane change with 4 different payload conditions, 0%-20%-80%-95%

In Figure 12 is shown that as the filling ratio increases the more difficult it is to avoid rollover. However, the M1 cross section is a safe option even if driving with 70 km/h and fully loaded truck. In the first lane change, the lateral acceleration and yaw rate are approximately the same regardless the payload. Changing from 20% to 80% filling ratio makes the vehicle heavier and dynamically unstable. In other words, the vehicle starts oscillating after the first lane change with lateral acceleration close to 0.4g and roll angle close to 10 degrees but at the end, it returns to its safe steady-state.

4. CONCLUSIONS

In the present paper, the effect of the geometry of the cross section of a tank for the transport of flammable liquids in the rollover threshold of the heavy vehicle has been performed. The heavy vehicle has been a 4-axle tank truck and it has been tested in two scenarios and the risk of rollover has been evaluated using the TruckSim ® mechanical simulation software. The shape of the cross sections is (a) one box shaped, (b) one circular and (c) two ellipticals having the same maximum capacity. The scenarios used in the investigation are the tilt table test and a double lane change. Lateral acceleration and roll angle have been monitored in the first scenario and lateral acceleration, roll angle, yaw rate and vertical tire forces have been monitored in the second scenario.

According to the results of the tilt-table test, the safest cross-section is M4 with rollover threshold of 0.39 g. The same conclusion can be drawn also from double lane change scenario where the cross section with the lower risk of rollover is M4 (elliptical) followed by the M1 (box-shaped) that do not rollover in double lane change with constant velocity of 70 km/h. In the double lane change, with constant velocity of 30 km/h, the dynamic responses of all tank cross-sectional geometries are quite similar.

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