

ROLLOVER STABILITY ANALYSIS OF LIQUID TANK TRUCK TAKING INTO ACCOUNT THE ROAD PROFILES

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The rollover stability of the tank truck was quite poor compare with others due to the influence of the oscillating liquid inside the tank. In addition, it was also affected by road excitation during driving. Therefore, the paper presents the impact of the road profiles in turning and lane change maneuvers on the rollover stability characteristics of a liquid tank truck. Firstly, the study applies the quasi-static method and the roll model to built the dynamic model of a circular cross-section tank truck. After that, the Lagrange method and the D'Alembert's principle are used to set up the differential equations which are then used to investigate rollover stability of vehicle corresponding with each liquid level. The research used the value of the load transfer ratio (LTR), crest factor of LTR and the roll angle of suspension to evaluate vehicle stability in the time domain and the transfer function magnitude of LTR in the frequency domain. The simulation results had shown that the tank truck tends to a rollover phenomenon at the fluid level in tank of 50% and 75% (0.8m and 1.2m) when the vehicle ran survey road profiles in a steady state turning maneuver and in a lane change maneuver as there was not the road excitation. The research results can provide recommendations when operating liquid tank truck, developing control systems and warning of rollover.

Keywords: vehicle dynamics, tank truck, rollover stability, rollover model, road profile

1 INTRODUCTION

Rollover is one of the most dangerous phenomena for vehicles, although it rarely happens, but it leaves very serious consequences. National Highway Traffic Safety Administration (NHTSA) had reported the rate of rollover deaths increase 9% in 2020 than in 2019 [1]. There are many factors that cause roll instability indicated in report [2], including statistics on the element of lane change and off road. For the influence of the road profiles, in [3], the authors simulated suspension displacement and wheel motion at different working condition and experimented to definite stability velocity area of vehicle. Many studies also used quarter car model [4] or experiment [5] to analyze the vertical contact force that determine the speed at which the wheel is not in contact with the road surface cause risks to vehicle.

In addition, rollover stability is affected by center of gravity (C.G.) height of vehicle [6 - 10]. The authors [6] used the Free Body Diagrams (FBD) combined with simulation and experimental data to evaluate the vehicle roll stability. In [7], the biaxial truck model was simulated and analyzed vehicle dynamics base on four methods to find rollover thresholds with input signs include C.G. height, roll angle, velocity and rotation of steering wheel. For Sports Utility Vehicle (SUV), the study [8] analyzed more effect track width, wheel base by nonlinear model, Static Stability Factor (SSF), Roll Stability Factor (RSF) and Two Wheel Lift off Velocity (TWLV) during steering maneuver. Not only rollover dynamics was simulated to determine motions of a three degree of freedom model [9,10] but also experiments were carried out an actual truck to evaluate the effect of suspension parameters and roll steer to interaction between the planar and roll motion of a vehicle [9]. Besides, the stability conditions were defined on the Routh - Hurwitz criterion combined with dynamic stability factor (DSF) in turning and lane change, but rollover stability can be become better by optimizing the value of C.G. height, track width, steering angle, forward speed, tyres and suspension in the DSF[10].

The above studies mentioned the influence of factors that destabilize solids trucks, but liquid tank trucks were more complex [11] and the level of danger is higher than rigid tank trucks [12]. In [11], the motions of fluid were very complicated due to base on the size and shape of the tank, the viscosity and the mass of the liquid, therefore the cross section model was built to describe liquid movement in circular and rectangular tanks and determined rollover threshold corresponding to the load levels during turning maneuvers. The rollover threshold detection in [13] used Fluent to simulate motion of liquid in elliptical tank trucks by quasi - static method and Lagrange's equations to analyze the free vibration of liquid which it was replaced by the movement of trammel pendulum, the results showed the fluid level ratio from 40 to 60 percent of the fill tank was unstable stage in turning maneuver. For the case of braking stability [12], the authors described the movement of the liquid in tank by Ansys software, small holes were punched in the baffles of tank to decrease the stress in cover and partition of tank. Moreover, in [14,15] the authors used Navier - Stokes equations to investigate dynamics of liquid sloshing in tank corresponding with different conditions such as study [14] analyzed frequency and amplitude of liquid sloshing during braking and turning to determine stability threshold; for cylindrical tank containers in turning, the authors had surveyed on effect of viscosity, lateral acceleration and liquid level on stability characteristics [15]. In [16], pendulum model was substituted for the fluid slosh and LS-DYNA-3D models have inspect impact of tyre properties, lateral acceleration, frame on vehicle stability in braking and turning maneuvers. In addition, the authors in [17,18] defined the rollover threshold depending

on liquid level in the tank, but in [17] the authors used a quasi-dynamics roll plane model for circular tank in steady steer. A kineto-static roll plane model was used in [18] for the liquid tank shape during turning maneuvers. Similarly, the analysis in [19] presented to influence on the roll angle, lateral acceleration of vehicle correlating with ratio of fill level in the cylindrical tank by the roll plane model in a steady turning maneuver.

From overview documents shows that most of the studies on liquids in tanks use finite element analysis software, a few studies focus on analyzing the interaction between the tank and vehicle. Therefore, in this study, the authors use Lagrange method combined with D'Alembert's principle to analyze the rollover stability characteristics and the magnitude of transfer function of LTR corresponding to the fluid level of tank truck with different road profiles based on a multi-object model of a liquid circular tank truck.

2 CIRCULAR LIQUID TANK MODELLING

In this study, the authors use a cross-sectional model of a circular tank. The overall model will be divided into two parts including the liquid tank and the vehicle. To analyze the liquid sloshing in the tank, the study applied of the quasi-static method, the motion of a trammel pendulum in research results [20,21]. The liquid surface is assumed that it is not broken and stable when the vehicle moves. Therefore, this model is shown in Fig. 1.

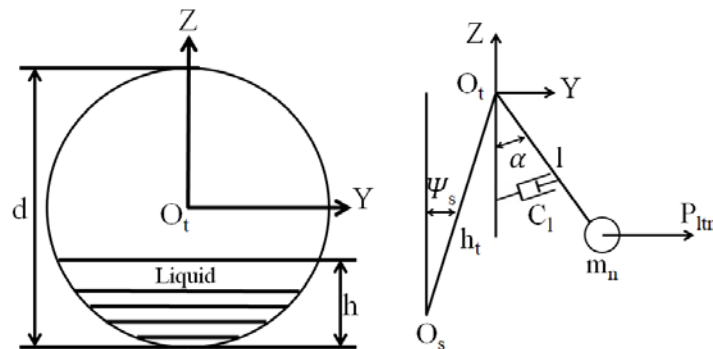


Fig. 1. Schematic diagram for the liquid sloshing is replaced by the movement of trammel pendulum

In the O_tYZ coordinate, O_t is the center of the tank which it's a distance h_t away from the roll axis of sprung mass O_s. In turning, the vehicle will cause the tank to an angle of inclination ψ_s and the liquid mass m_n to an angle α comparative with the vertical direction. At the same time, it creates an inertial force P_{lm} to impact on m_n, the lengths l is the distance from m_n to O_t and the value C_l is the viscosity of the liquid. The tank of the vehicle has length L, diameter d, volume 4m³ and foaming tank 0.4m³, the height h of the liquid.

According to Fig. 1, applying Lagrange method to establish the liquid motion equation, the results are shown as follows:

$$m_n l h_t \ddot{\psi}_s + m_n l^2 \ddot{\alpha} + m_n l h_t \alpha \dot{\psi}_s + m_n l^2 \alpha \dot{\alpha}^2 + m_n g l \sin \alpha + C_l \dot{\alpha} = P_{lm} l \tag{1}$$

In equation (1), vehicle's inertial force P_{lm} [22] and mass of fluid in tank m_n are presented as follows:

$$P_{lm} = m_n a_y \tag{2}$$

$$m_n = 1000.L \left(\frac{(2 \arccos(\frac{d-2h}{d})).d^2}{8} - (\frac{d}{2} - h)^2 \cdot (\tan(\arccos(\frac{d-2h}{d}))) \right) \tag{3}$$

$$l = \frac{d}{2} \frac{\frac{d^3 \cdot \arccos(\frac{d-2h}{d})}{8} - \frac{d^3}{12} \cdot \sin(\arccos(\frac{d-2h}{d})) - (\frac{d}{2} - h)^2 \cdot \tan(\arccos(\frac{d-2h}{d})) \cdot (\frac{2h}{3} + \frac{d}{6})}{\frac{d^2 \cdot \arccos(\frac{d-2h}{d})}{4} - (\frac{d}{2} - h)^2 \cdot \tan(\arccos(\frac{d-2h}{d}))} \tag{4}$$

The research uses the lateral acceleration a_y as an input signal to survey the rollover stability in the cornering [23] and lane-change maneuvers as a sine function of time [24] when vehicle is effected on the road profile by the mathematical equation:

$$a_y = \frac{v^2}{R} \tag{5}$$

$$a_y = \left(\frac{2\pi y_c}{t_t^2} \right) \sin \left(\frac{2\pi t_c}{t_t} \right) \tag{6}$$

3 VEHICLE MODELLING WITH A CIRCULAR LIQUID TANK

Based on a realistic mechanical model that has been tested accurately to build the equivalent dynamic model of the tank truck. Some assumptions are made to simplify the analysis of rollover stability of tank truck as follows:

- The vehicle and the liquid bulk are not mixed together.
- The sprung mass lies above on the suspension and be symmetrical about the longitudinal axis of the vehicle.

From the above assumptions combined with the roll model in [25,26], the vehicle roll model is presented in Fig. 2.

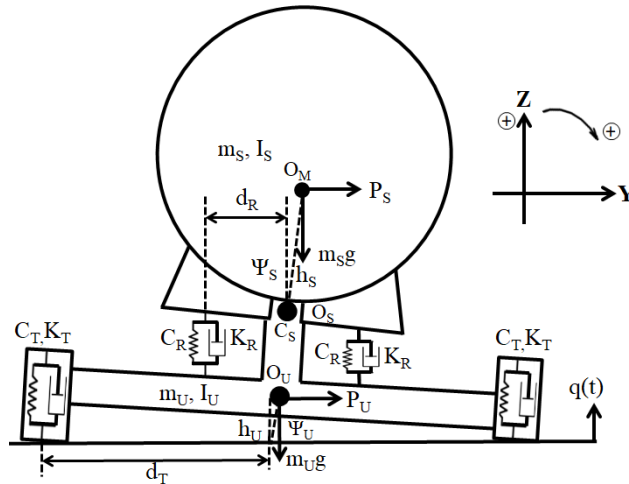


Fig. 2. The rollover stability model of vehicle

The expansion of coordinate has an origin to be put at the static equilibrium position of the model, the positive direction is opposite to the gravity acceleration and same direction with rotation clockwise. The system is divided to the sprung mass and the unsprung mass, then add the force components to consider the balance of the masses. By using the D'Alembert's principle, the vibration differential equations corresponding to 4 degrees of freedom model are presented as:

For the sprung mass:

$$(m_s + m_n)\ddot{Z}_S = -2C_R(Z_S - Z_U) - 2K_R(\dot{Z}_S - \dot{Z}_U) - m_n\dot{\alpha}^2 l \cos \alpha - m_n\ddot{\alpha} l \sin \alpha \tag{7}$$

$$I_S\ddot{\psi}_S = -(2d_R^2C_R + C_S)(\psi_S - \psi_U) - 2d_R^2K_R(\dot{\psi}_S - \dot{\psi}_U) + m_s a_y h_s \cos \psi_S + m_s g h_s \sin \psi_S \tag{8}$$

$$+ m_n g (h_t \sin \psi_S + l \sin \alpha) + m_n g a_y (h_t \cos \psi_S - l \cos \alpha)$$

$$+ m_n \dot{\alpha}^2 l h_t \sin(\psi_S + \alpha) + m_n \ddot{\alpha} l (l - h_t \cos(\psi_S + \alpha))$$

For the unsprung mass:

$$m_U\ddot{Z}_U = 2C_R(Z_S - Z_U) + 2K_R(\dot{Z}_S - \dot{Z}_U) - C_T(2Z_U - q_1 - q_2) - K_T(2\dot{Z}_U - \dot{q}_1 - \dot{q}_2) \tag{9}$$

$$I_U\ddot{\psi}_U = (2d_S^2C_R + C_S)(\psi_S - \psi_U) + 2d_S^2K_R(\dot{\psi}_S - \dot{\psi}_U) - C_T d_T(2d_T\psi_U - q_1 + q_2) \tag{10}$$

$$- K_T d_T(2d_U\dot{\psi}_U - \dot{q}_1 + \dot{q}_2) + m_u a_y h_U \cos \psi_U + m_u g h_U \sin \psi_U$$

The symbols and parameters of the tank are shown in Table 1, this table does not take into account the mass of the liquid.

Table 1. Parameter values of liquid tank truck and lateral acceleration

Symbols	Description	Values	Unit
m_s	Sprung mass	2305	kg
I_s	The moment of inertia of sprung mass	11174	kgm ²
m_u	Unsprung mass	1073	kg

Symbols	Description	Values	Unit
I_U	The moment of inertia of unsprung mass	1311.1	kgm ²
h_S	Height of sprung mass from the roll axis	0.61	m
h_U	Height of unsprung mass from the ground	0.525	m
h_t	Height of liquid tank from the roll axis	0.9	m
C_R	Stiffness of suspension	724704.5	N/m
K_R	Damping of suspension	42629	Ns/m
d_R	Distance of suspension from the roll axis	0.62	m
d_T	Distance of unsprung mass from the wheel track	1.025	m
C_T	Tyre cornering stiffness	1015000	N/m
K_T	Tyre roll stiffness	25000	Ns/m
C_S	Stiffness of anti-inclination bar	35800	N/m
L	Length of liquid tank	2	m
d	Diameter of liquid tank	1.6	m
C_l	Viscosity of liquid	0.5	
G	Gravity acceleration	9.81	m/s ²
a_y	Lateral Acceleration	-	m/s ²
R	The radius of turning	15	m
v	The vehicle speed	30	km/h
y_c	Lane-change total lateral displacement	3.66	m
t_t	Total time to complete the lane-change	-	s
t_c	Elapsed time into the lane-change	-	s
h	Height of liquid level in tank	-	m
l	Distance of liquid tank from the liquid mass	-	m
m_n	Mass of the liquid	-	kg
ψ_S	Sprung mass roll angle	-	rad
ψ_U	Unsprung mass roll angle	-	rad
$q(t)$	Road surface excitation at time t	-	
q_1	Road surface excitation at the left	-	
q_2	Road surface excitation at the right	-	

When the vehicle moves or changes the direction, and be affected by road, the vertical reaction force impacts on the left F_L and right F_R wheel changes, they are determined in equations (11,12) as follows:

$$F_L = 0.5g(m_s + m_n + m_U) - C_T(Z_U + \psi_U d_T - q_1) - K_T(\dot{Z}_U + \dot{\psi}_U d_T - \dot{q}_1) \quad (11)$$

$$F_R = 0.5g(m_s + m_n + m_U) - C_T(Z_U - \psi_U d_T - q_2) - K_T(\dot{Z}_U - \dot{\psi}_U d_T - \dot{q}_2) \quad (12)$$

In rollover state, the vehicle rolls to right, the vertical reaction force shocks on left wheel zero.

In fact, the rollover process happens quickly, especially at a high speed. When a wheel doesn't contact with road surface which it's sign to define destabilize state of vehicle. To evaluate the separation of the wheel on an axle i from the road vertically which can use the load transfer ratio (LTR_i) [27,28] determined as:

$$LTR_i = \frac{F_{Zi2} - F_{Zi1}}{F_{Zi2} + F_{Zi1}} \quad (13)$$

In which, F_{Zi1} and F_{Zi2} are the force acting corresponding to the left and right wheels of the axle i . When the load is distributed evenly on axle i that LTR_i is equal zero. In the case $LTR_i = +1$ respective to wheel separation i_1 and $LTR_i = -1$ respective to wheel separation i_2 .

In addition, the research also uses the crest factor (CF) mentioned in the study [29] to determine the dangerous liquid level that it tends to cause rollover vehicle through the root mean squared (RMS) value of LTR weight according to the formula (14,15) as follows:

$$CF = \frac{|LTR|_{PEAK}}{LTR_{wRMS}} \tag{14}$$

$$LTR_{wRMS} = \left[\frac{1}{T} \int_0^T LTR_w^2(t) dt \right]^{1/2} \tag{15}$$

Where: $|LTR|_{PEAK}$ is the maximum crest magnitude of LTR at the immediate time; $LTR_w(t)$ is weighted LTR varies with time; T is the measurement time.

4 ROAD PROFILE DESIGN

The road profiles are used in this research to deputize the road surface irregularities and they are set by different mathematical functions. The first excitation function is modelled as a random road according to the international standard of ISO 8608 was proposed which the power spectral density (PSD) of the vertical road surface displacement included Grade B and Grade C to be presented in [30,31] by the following equation:

$$\dot{q}(t) = 2\pi.n_0.w(t).\sqrt{G_q(n_0).v} - 2\pi.f_0.q(t) \tag{16}$$

The second excitation function is a sinusoidal road profile [32,33] which is described by the mathematical formulation as follows:

$$q(t) = d_1 \sin(2\pi \frac{v}{d_2} t) \tag{17}$$

The examined road profiles corresponding to a vehicle speed of 30 km/h are plotted in Fig. 3.

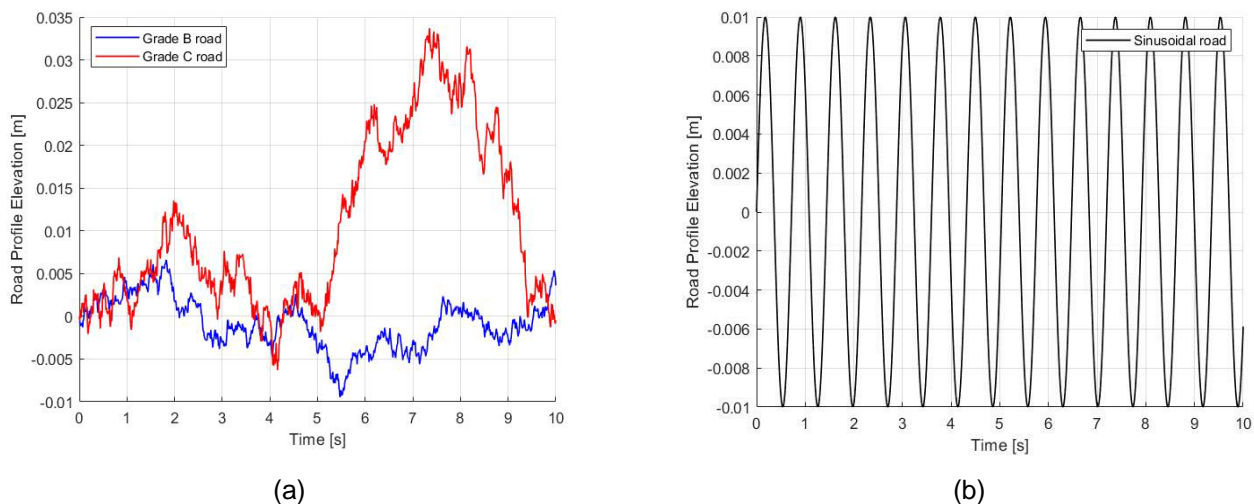


Fig. 3. Road profile of Grade B and C (a), Sinusoidal road profile (b)

With t is time that vehicle moves through road profiles, sign and parameters are found in Table 2.

Table 2. Parameter values of road profiles

Symbols	Description	Values	Unit
$q(t)$	Road profile excitation at time t	-	
n_0	Reference spatial frequency	0.1	m^{-1}
$w(t)$	Time domain Gaussian white noise signal	-	-
$G_q(n_0)$	The reference PSD of the spatial frequency	64.10^{-6} (Grade B)	m^{-3}

Symbols	Description	Values	Unit
		256.10 ⁻⁶ (Grade C)	m ⁻³
f_0	Cut-off frequency	0.0628	Hz
d_1	Amplitude of sine wave	6	m
d_2	Wavelength of road profile	0.01	m

5 SIMULATION EVALUATIONS

For the tank contains a liquid part, when the vehicle moves on the road at the high speed which it creates the vibration due to the motion of the liquid in the tank, and when the tank is full that liquid and the tank make a solid block. The research is simulated in Matlab/Simulink by Runge-Kutta method.

5.1 Simulation result in the time domain

The rollover stability math model of the liquid tank truck on an axle in turning maneuver and to be excited about the lateral acceleration, the road profiles corresponding with h at the rate of 25%, 50%, 75% and 100% compared to the tank diameter d .

The Fig. 4 shows the load transfer ratio (LTR) of liquid tank truck in steady state turning maneuver when the left wheel is effected on road profiles with Grade B road profile (a), Grade C road profile (b), a sine function (c) and in case (d) is a sine function with the phase π difference between the left and right wheel as follows:

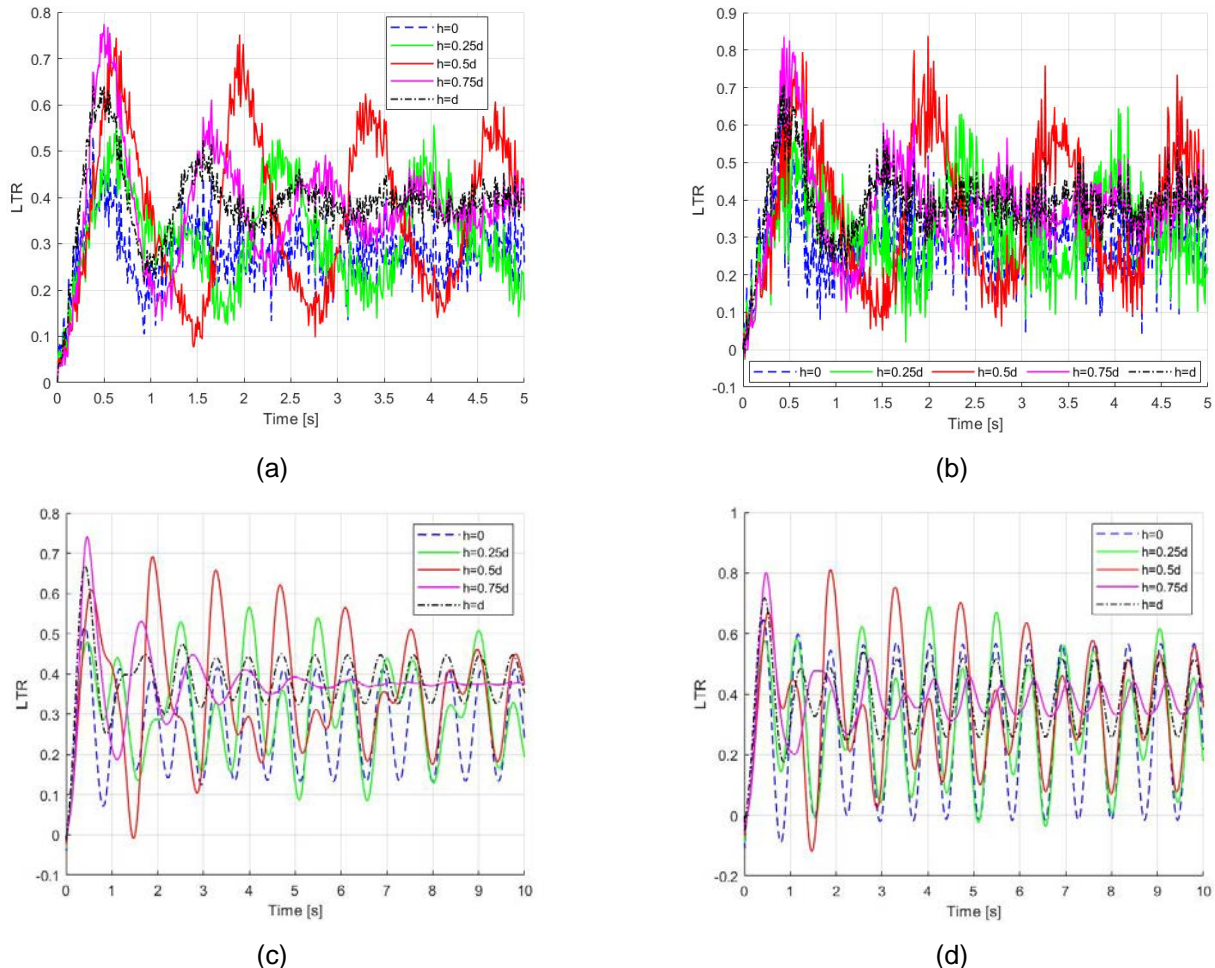


Fig. 4. The load transfer ratio (LTR) of liquid tank truck in steady state turning

Table 3. The crest factor value of LTR corresponding to the liquid level in the tank in the case of steady state turning influenced by road profiles

The rate of liquid in tank	Crest factor value of LTR			
	Grade B road profile	Grade C road profile	A sine function road profile	A sine function road profile with the phase π difference between the left and right wheel
0%	1.878	2.082	1.752	1.849
25%	1.721	2.062	1.703	1.897

The rate of liquid in tank	Crest factor value of LTR			
	Grade B road profile	Grade C road profile	A sine function road profile	A sine function road profile with the phase π difference between the left and right wheel
50%	1.988	2.150	1.810	2.019
75%	2.002	2.116	1.922	2.047
100%	1.639	1.777	1.699	1.778

From simulation results in the graphs above, the load transfer ratio values at differential fluid levels are less than ± 1 for the road profiles. This value is still within the allowable threshold. When the height of the liquid level in the tank is 50% and 75% compared to the diameter of the tank (corresponding to the liquid level is high 0.8m and 1.2m) which the vehicle is more unstable than the rigid load (in the case of 100%, the height 1.6m) and cases less than 50% for road profiles based on crest factor value of LTR in Table 3.

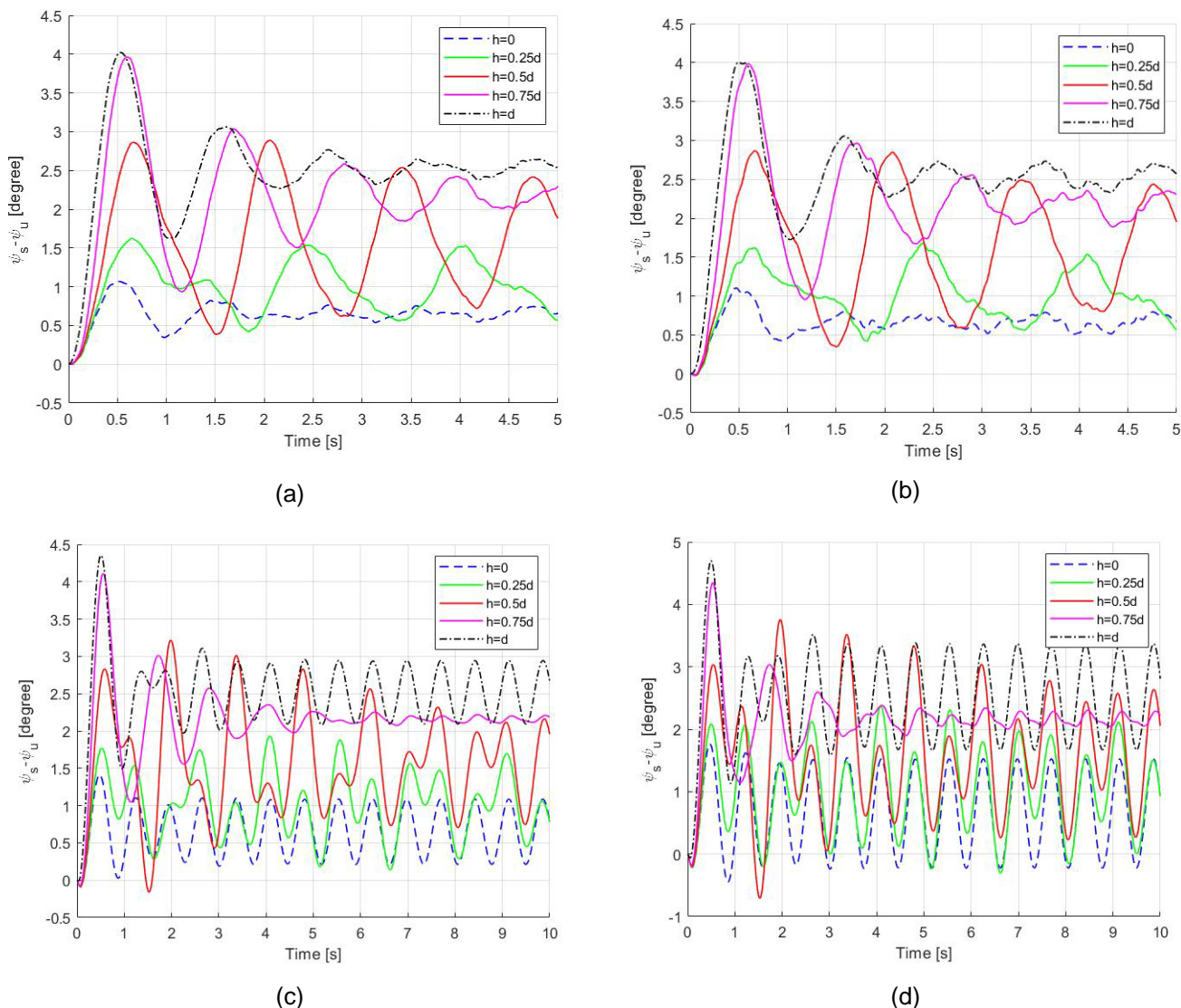


Fig. 5. The travel of suspension of liquid tank truck in steady state turning

Fig. 5 shows the travel of suspension as the roll angles between Ψ_S and Ψ_U of tank truck in case of the excitation function similar to the road profiles in Fig. 4 which is smaller than 50 for the different liquid levels. However, this value is still within the authorized limit [34]. At the fluid level in tank truck are 75% and 100% (1.2m and 1.6m), it gets the highest scope.

For the lateral acceleration is a lane-change maneuver when there is not affected from the road profile in Fig. 6, with the load transfer ratio (LTR) is on the left (6a), the roll angle of suspension is on the right (6b) in case the lane change speed is 20 m/s.

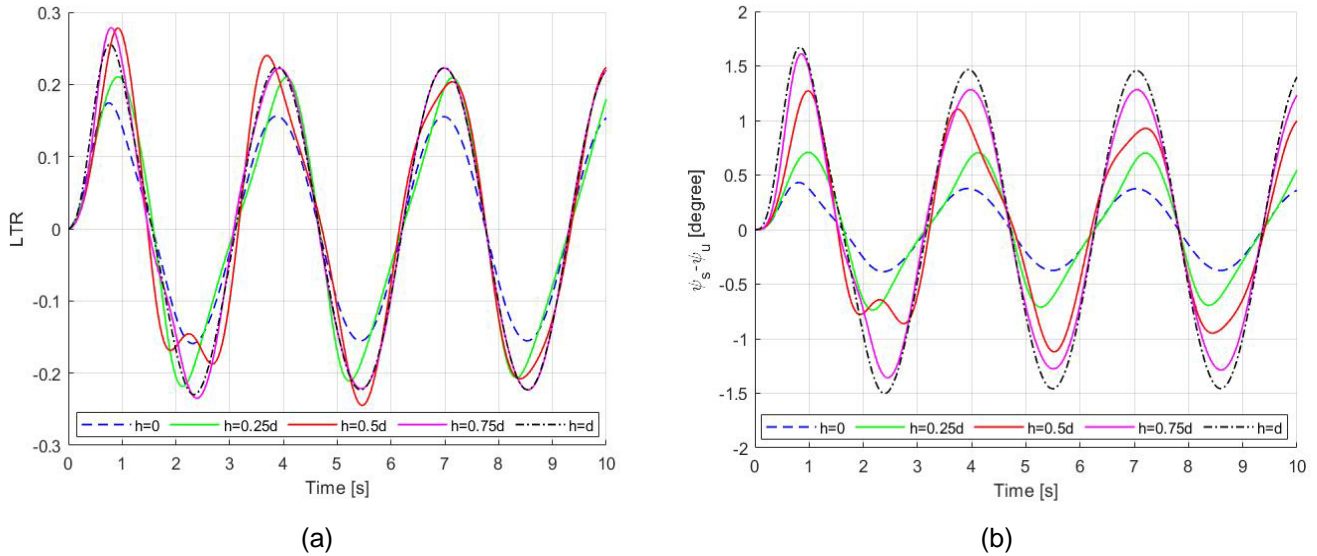


Fig. 6. The load transfer ratio (LTR) and the suspension roll angle of liquid tank truck in a lane-change maneuver

Table 4. The crest factor value of LTR corresponding to the liquid level in the tank in a lane-change maneuver

The rate of liquid in tank	0%	25%	50%	75%	100%
Crest factor value of LTR	1.593	1.597	1.785	1.760	1.626

The graphs in Fig. 6a indicate value of LTR is the highest when the fill level of fluid are 50% and 75% (0.8m and 1.2m). Besides simulation results, the data in Table 4 shows the tank truck has a tendency to rollover at the liquid level of 50% and 75% because CF value of LTR of them are bigger than others. In addition, the roll angle of suspension reaches the biggest value at fill level of 75% and 100% (1.2m and 1.6m) but this value is less than 7o to 8o [34,35] in Fig. 6b.

5.2 Simulation result in the frequency domain

The amplitude-frequency characteristics of system is used to assess working of equipment or to indicate condition, limit of parameters relate to operation of system. The more the transfer function amplitude value is high, the more the signal is sensitive with excitation frequency. The article [34,36] presents optimization results of the active anti-roll bar controller through the simulation of the normalized load transfer. This research also analyzes the transfer function magnitude of LTR in the frequency domain to determine the dangerous liquid level of the tank truck.

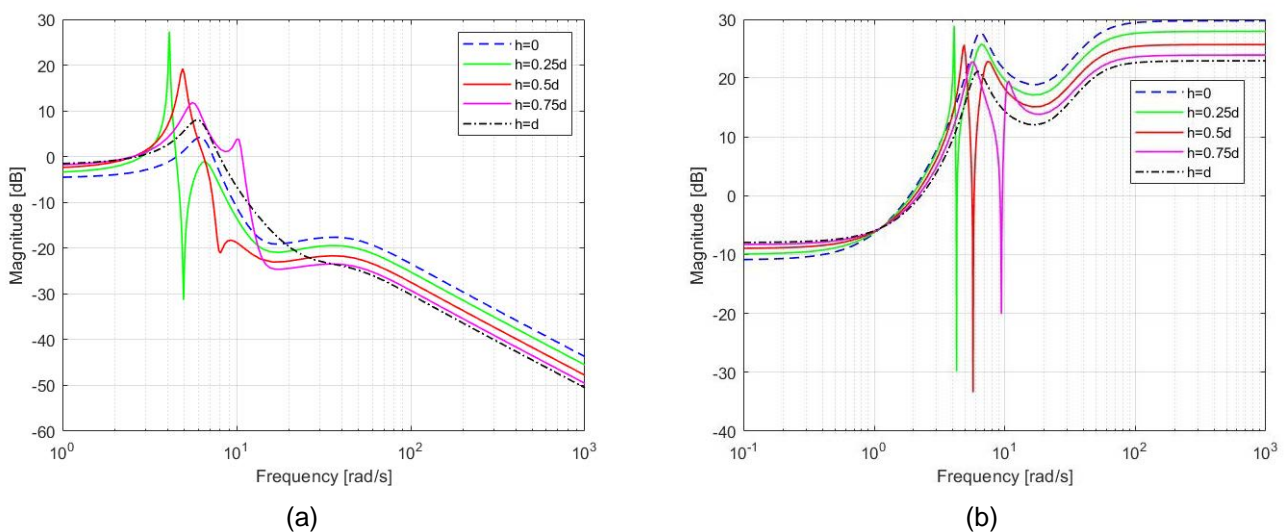


Fig. 7. The transfer function magnitude of the load transfer ratio (LTR) of liquid tank truck

Fig. 7a shows the transfer function magnitude of the load transfer ratio (LTR) in frequency range of the lane change maneuver. It shows that the tank truck tends to be rolled at the fill level of 25%, 50% in the frequency array up to 4 rad/s [34]. Fig. 7b presents the transfer function magnitude of LTR in frequency range of the road profile. Simulation results show the response signal at the liquid level of 0%, 25% is sensitive in the frequency range up to 100 rad/s [37]. Therefore, at this position, the tank truck tends to cause rollover instability.

6 CONCLUSIONS

The research shows building a dynamical model of liquid tank trucks which is separated into the trammel pendulum and the roll model. Analysis results are evaluated by the load transfer ratio and crest factor value of LTR. In a steady state turning maneuver with survey road profiles, the liquid tank truck is the most stability at full load. Similar the vehicle run a lane-change maneuver and it is not impacted the road excitation. Although, the travel of suspension is still within the allowable range at the different fluid level.

Besides, the tank truck tends to rollover instability at the liquid level height of 0.4m, 0.8m in the lane change maneuver frequency range and at no-load, the height of 0.4m in the road excitation frequency range. So drivers need to pay attention to risk frequency array from the road excitation and a lane-changing to ensure the rollover stability of the tank truck.

The research is also the foundation for developing stability control system and warning system of the vehicle rollover phenomenon.

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