



## Analysis of Roll Control System to Eliminate Liquid Sloshing Effect on Lateral Stability of an Articulated Vehicle Carrying Liquid

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### ABSTRACT

In this paper, in order to limit the liquid sloshing effect on lateral dynamic of an articulated vehicle carrying liquid, an active roll control system is proposed. First, a sixteen-degrees-of-freedom nonlinear dynamic model of an articulated vehicle is developed then, using TruckSim software the model is validated. Next, the dynamic interaction of the fluid cargo with the vehicle, by integrating a quasi-dynamic slosh model with a tractor semitrailer model is investigated. In order to design the control system, sliding mode control is used. Also, to investigate the rollover stability of the vehicle, lateral load transfer ratio is considered as an important factor. The dynamic system performance for different filled volumes is exhibited in stepsteer and slalom standard maneuvers. The simulation results show that the proposed roll control system performs appropriately in target control achievement and lateral load transfer ratio reduction.

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### NOMENCLATURE

$CS_{t(s)}$	damping of the tractor's (semitrailer's) suspension	$L_{ts}$	distance between the semitrailer axles
$C_w$	damping of the coupling point between the tractor and the semitrailer	$m_{s(ss)}$	semitrailer total mass(sprung mass)
$D$	Tank diameter	$m_{t(st)}$	tractor total mass(sprung mass)
$h_{ct(s)}$	height of the center of gravity of the tractor's (semitrailer) sprung mass to the roll axis	$R$	the cross section radius
$F_{fx(fy)}$	the longitudinal (lateral) coupling force	$R_{wi}$	wheel radius
$h_{wt(ws)}$	height of the fifth wheel to the roll axis of the tractor unit (semitrailer unit)	$T_i$	the input drive torque
$I_{wi}$	Wheel moment of inertia	$T_{wt(s)}$	track width of the trailer unit (semitrailer unit)
$I_{xxpt(ps)}$	roll moment of inertia of the sprung mass of the tractor unit (semitrailer unit)	$u_{t(s)}$	longitudinal velocity of tractor unit (semitrailer unit)
$I_{xzpt(ps)}$	roll-yaw product of inertia of the sprung mass of the tractor unit (semitrailer unit) measured about the center of gravity of the sprung mass	$v_{t(s)}$	lateral velocity of tractor unit (semitrailer unit)
$I_{zzt(s)}$	yaw moment of the total mass of the tractor unit (semitrailer unit) measured about the center of gravity of the total vehicle mass	$z_0$	the height of the liquid mass center in absence of roll angle and lateral acceleration of the semitrailer
$KS_{t(s)}$	roll stiffness of the tractor's (semitrailer's) suspension	$Z$	the vertical position of liquid center of gravity
$K_w$	roll stiffness of the coupling point between the tractor and the semitrailer	$\Gamma$	articulation angle
$L$	the length of tank	$\omega_i$	the rotational velocity of each wheel
$L_{ct}$	distance between the tractor's center of gravity and the coupling point	$\dot{\psi}_{t(s)}$	yaw rate of the tractor unit (semitrailer unit)
$L_{ft}(L_{rt})$	distance between the tractor's center of gravity and the front axle (the rear axle)	$\varphi_t(s)$	roll angle of the tractor unit (semitrailer unit)
$L_{fs}(L_{rs})$	distance between the semitrailer's center of gravity and the coupling point (the rear axle)	$\delta$	Steer angle

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1. INTRODUCTION

One of mechanical systems in which mutual interaction exists, is articulated vehicle carrying liquid. Fluid sloshing in the tanker exerts lateral forces and moments promoting earlier rollover than other types of vehicle [1]. Rollover accidents affect strongly highway safety, especially rollover of heavy-duty tankers carrying fuels and chemicals, which might result in explosions and catastrophic chemical spills. This fact made the study of rollover stability of various vehicles, especially articulated vehicle carrying liquid, a major concern for many vehicle manufacturers, organizations, and researchers. Strandberg et al. [2] studied the overturning risk of heavy-duty truck-trailer combinations both analytically and experimentally. Popov et al. [3] conducted a study to obtain an optimum shape of elliptical road containers in terms of minimizing the overturning moment resulting in a vehicle rollover. Ranganathan et al. [4] analyzed the stability of partially-filled tank vehicles through computer simulations. The equations of motion for sloshing fluid within an elliptical tank were derived using Lagrange's equation assuming small amplitudes of sloshing wave. Kang et al. [5] investigated directional stability of an articulated vehicle under combined turning and braking maneuvers, a quasi-dynamic sloshing model of clean bore tank coupled with the vehicle dynamics. Roll stability analyses of partially-filled tank vehicles have further indicated that magnitude of lateral liquid sloshing under various vehicle maneuvers is strongly affected by the tank geometry, specifically the cross-section [6-10]. Talebi et al. [11, 12] optimized the tanker rollover threshold for the articulated vehicle carrying liquid. Azadi et al. [13] investigated the effect of tank shape on the lateral dynamic of the vehicle.

In this paper, the effect of the active roll control system on the lateral dynamic of an articulated vehicle carrying liquid is investigated. So, this paper is organized as follows. At first, a through nonlinear dynamic model of an articulated vehicle is developed. Next, dynamic interaction between the liquid and the vehicle, employing quasi-dynamic method is investigated. In the third section, in order to improve dynamic performance of the articulated vehicle carrying liquid, an active roll control system is proposed. In fourth section, the control system performance is evaluated during standard maneuvers. Finally, the results are provided.

2. DYNAMIC MODELING

The sixteen degrees of freedom model reflecting the directional characteristics of the articulated vehicle is

used. The tractor and semitrailer units are connected by the fifth wheel. The considered motions are the longitudinal, lateral, yaw and roll motions of the tractor unit, the articulation angle between the tractor and the semitrailer, the roll motion of the semitrailer and the rotational motion of each wheel. Five coordinate systems for the model are considered. The first is the inertial coordinate system  $x_n y_n z_n$  fixed to the ground. The second is the coordinate system  $x_t y_t z_t$ , which is fixed to the unsprung mass of the tractor unit. The third coordinate system  $x'_t y'_t z'_t$  is fixed to the tractor's sprung mass. Both the sprung mass and the unsprung mass of the tractor unit have the same yaw motion. Therefore, the coordinate system  $x'_t y'_t z'_t$  has a relative roll motion to the coordinate system  $x_t y_t z_t$ . Similarly, the coordinate systems  $x_s y_s z_s$  and  $x'_s y'_s z'_s$  represent the semitrailer's unsprung-mass coordinate system and the semitrailer's sprung-mass coordinate system, respectively.

The rate of the articulation can be represented by

$$\Gamma = \dot{\psi}_s - \dot{\psi}_t \tag{1}$$

The traction and side tire forces can be expressed in tractor and trailer coordinate systems as follows [14]:

$$\begin{aligned} F_{xi} &= F_{ti} \cos(\delta_i) - F_{si} \sin(\delta_i) \\ F_{yi} &= F_{ti} \sin(\delta_i) + F_{si} \cos(\delta_i), \end{aligned} \tag{2}$$

$i = 1, 2, \dots, 10$

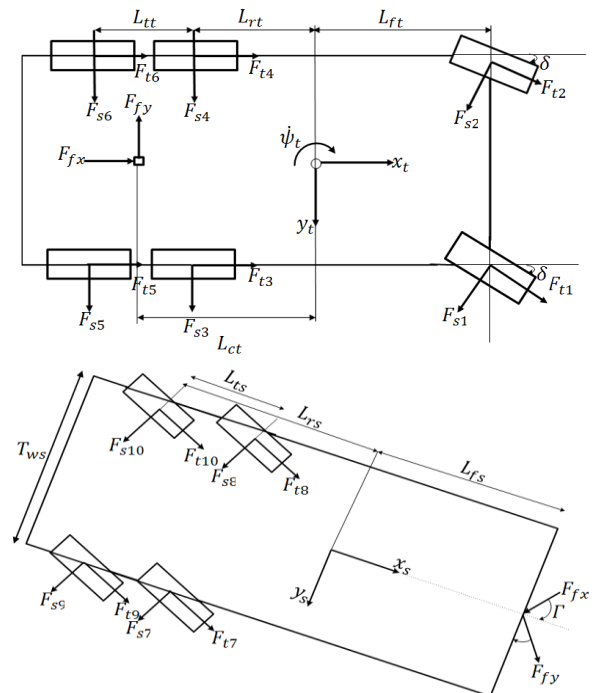


Figure 1. The effective external forces on tractor and semitrailer units.

**2. 1. Tractor Unit** Based on the Figure 1, the effective external forces on system dynamics are longitudinal and lateral forces which are created at the contact locations of the tires and road and constrain forces in fifth wheel.

Tractor yaw moment is as below:

$$M_{ptz} = (F_{x2} + F_{x4} + F_{x6} - F_{x1} - F_{x3} - F_{x5}) T_w/2 + (F_{y1} + F_{y2})L_{ft} - (F_{y3} + F_{y4})L_{rt} - (F_{y5} + F_{y6})(L_{rt} + L_{tt}) \quad (3)$$

Tractor roll moment is as below:

$$M_{p_{tsx}} = m_{st}gh_t \sin(\varphi_t) - KS_t\varphi_t - CS_t\dot{\varphi}_t + KS_w(\varphi_t - \varphi_s) + CS_w(\dot{\varphi}_t - \dot{\varphi}_s) \quad (4)$$

**2. 2. Semitrailer Unit** The tractor yaw moment is as below:

$$M_{psz} = (F_{x8} + F_{x10} - F_{x7} - F_{x9}) T_{ws}/2 - (F_{y7} + F_{y8})(L_{rs} - L_{ts}) - (F_{y9} + F_{y10})L_{rs} \quad (5)$$

Semitrailer roll moment is as follows:

$$M_{p_{ssx}} = m_{ss}gh_s \sin(\varphi_s) - KS_s\varphi_s - CS_s\dot{\varphi}_s - KS_w(\varphi_t - \varphi_s) - CS_w(\dot{\varphi}_t - \dot{\varphi}_s) \quad (6)$$

**2. 3. The Articulated Vehicle of Equations of Motion** The governing equations of the articulated vehicle can be expressed as:

$$m_t\ddot{u}_t = m_tv_t\dot{\psi}_t + m_{st}h_t\dot{\varphi}_t\dot{\psi}_t + F_{xtt} + F_{fx} \quad (9)$$

$$m_t\ddot{v}_t + m_{st}h_t\dot{\varphi}_t = -m_tu_t\dot{\psi}_t + F_{ytt} - F_{fy} \quad (10)$$

$$I_{zz_t}\ddot{\psi}_t - I_{xz_{pt}}\dot{\varphi}_t = M_{ptz} + F_{fy}L_{ct} \quad (11)$$

$$I_{xx_{pt}}\ddot{\varphi}_t - I_{xz_{pt}}\ddot{\psi}_t + m_{st}h_tv_t = M_{p_{tsx}} - m_{st}h_tu_t\dot{\psi}_t \quad (12)$$

$$m_s\ddot{u}_s = m_sv_s\dot{\psi}_s + m_{ss}h_s\dot{\varphi}_s\dot{\psi}_s + F_{xss} - F_{fx} \cos(\Gamma) + F_{fy} \sin(\Gamma) \quad (13)$$

$$m_s\ddot{v}_s + m_{ss}h_s\dot{\varphi}_s = -m_su_s\dot{\psi}_s + F_{yss} + F_{fx} \sin(\Gamma) + F_{fy} \cos(\Gamma) \quad (14)$$

$$I_{zz_s}\ddot{\psi}_s - I_{xz_{ps}}\dot{\varphi}_s = (F_{fx} \sin(\Gamma) + F_{fy} \cos(\Gamma))L_{ws} + M_{psz} \quad (15)$$

$$I_{xx_{ps}}\ddot{\varphi}_s - I_{xz_{ps}}\ddot{\psi}_s + m_{ss}h_s\dot{v}_s = M_{p_{ssx}} - m_{ss}h_su_s\dot{\psi}_s \quad (16)$$

$$\dot{u}_t - \dot{u}_s \cos(\Gamma) + \dot{v}_s \sin(\Gamma) + L_{fs}\dot{\psi}_s \sin(\Gamma) + h_{ws}\dot{\varphi}_s \sin(\Gamma) = -\dot{u}_s \Gamma \sin(\Gamma) - \dot{v}_s \cos(\Gamma) - L_{fs}\dot{\Gamma}\dot{\psi}_s \cos(\Gamma) - h_{ws}\dot{\Gamma}\dot{\varphi}_s \cos(\Gamma) \quad (17)$$

$$\dot{v}_t - L_{wt}\ddot{\psi}_t + h_{ct}\dot{\varphi}_t - \dot{u}_s \sin(\Gamma) - \dot{v}_s \cos(\Gamma) - L_{fs}\dot{\psi}_s \cos(\Gamma) - h_{ws}\dot{\varphi}_s \sin(\Gamma) = u_s\dot{\Gamma} \cos(\Gamma) - \dot{\Gamma}v_s \sin(\Gamma) - L_{fs}\dot{\Gamma}\dot{\psi}_s \sin(\Gamma) - h_{ws}\dot{\Gamma}\dot{\varphi}_s \sin(\Gamma) \quad (18)$$

### 3. ARTICULATED VEHICLE CARRYING LIQUID MODELING

In this study, in order to model the liquid in the tank and to study of the effect of liquid load transfer on lateral dynamic of the vehicle, the quasi-dynamic method is used. In the model, the liquid due to roll angle and lateral acceleration of semitrailer moves and the liquid free surface movement leads to change of the liquid center of mass location and its moment of inertia. Also, considering roll angle and lateral acceleration of semitrailer, calculating pressure gradient and assuming inviscid flow, the liquid free surface gradient is determined [15].

$$\tan(\vartheta) = \left( \frac{\varphi_s - a_t}{1 + a_t\varphi_s} \right) \quad (23)$$

For a tank of circular cross section, the vertical and lateral position of fluid center of gravity is calculated as below [16]:

$$Z = R - (R - Z_0) \cos(\vartheta) \quad (24)$$

$$Y = (R - Z_0) \sin(\vartheta)$$

where,  $R$  is the cross section radius and  $Z_0$  is the height of the fluid mass center in absence of roll angle and lateral acceleration of the semitrailer.

In addition, the liquid moment of inertia is calculated as below:

$$I_{xl} = I_{xl}^0 \quad (25)$$

$$I_{zl} = I_{zl}^0 (\cos(\vartheta))^2$$

where,  $I_{xl}^0$  and  $I_{zl}^0$  are the moment of inertia for the zero free surface gradient state.

Calculation of liquid center of mass acceleration:

$$a_l = \left( u_s - v_s\dot{\psi}_s - h_s\dot{\varphi}_s\dot{\psi}_s - Z\dot{\varphi}_s\dot{\psi}_s - X\dot{\psi}_s^2 - Y\dot{\psi}_s \right) \hat{i} + \left( v_s + u_s\dot{\psi}_s + h_s\dot{\varphi}_s - Y\dot{\varphi}_s^2 - Y\dot{\psi}_s^2 + Z\dot{\varphi}_s + X\dot{\psi}_s \right) \hat{j} + \left( Z\dot{\varphi}_s^2 + X\dot{\varphi}_s\dot{\psi}_s + Y\dot{\varphi}_s \right) \hat{k} \quad (26)$$

The longitudinal slip, the side slip angles and wheel dynamics related equations and equations of motions of an articulated vehicle carrying liquid as well as dynamic model validation can be found in our previous paper [16-18].

### 4. CONTROL SYSTEM DESIGN

**4.1.1. Tractor Unit** To design the controller, the simplified dynamic model Equation (9) is used.

A second-order system is considered as follows:

$$I_{xx_{pt}} \ddot{\varphi}_t = M_{p_{tsx}} - m_{st} h_t (\dot{v}_t + u_t \dot{\psi}_t) + M_A \quad (24)$$

We can get

$$f_1 = M_{p_{tsx}} - m_{st} h_t (\dot{v}_t + u_t \dot{\psi}_t) \quad (25)$$

Now we have

$$I_{xx_{pt}} \ddot{\varphi}_t = f_1 + M_A \quad (26)$$

Let  $e_1$  be the error between the desired roll angle  $\varphi_d$  and the output  $\varphi_t$ , i.e.,

$$e_1 = \varphi_t - \varphi_d \quad (27)$$

First, define the sliding surface function as:

$$s_t = \left( \frac{d}{dt} + \lambda_1 \right)^2 \int (\varphi_t - \varphi_d) dt \quad (28)$$

By simplifying, we will have

$$s_t = \dot{\varphi}_t + 2\lambda_1(\varphi_t - \varphi_d) + \lambda_1^2 \int (\varphi_t - \varphi_d) dt \quad (29)$$

Taking derivative of Equation (29) yields

$$\dot{s}_t = \ddot{\varphi}_t + 2\lambda_1 \dot{\varphi}_t + \lambda_1^2 (\varphi_t - \varphi_d) \quad (30)$$

Moreover, Exponential Reaching Law is as follows:

$$\dot{s}_t = -k_1 s_t - k_2 \text{sign}(s_t) \quad (31)$$

We will have

$$M_A = -I_{xx_{pt}} \left( \frac{1}{I_{xx_{pt}}} f_1 + (2\lambda_1 + k_1) \dot{\varphi}_t + (\lambda_1^2 + 2\lambda_1 k_1) (\varphi_t - \varphi_d) + k_1 \lambda_1^2 \int (\varphi_t - \varphi_d) dt + k_2 \text{sign}(s_t) \right) \quad (34)$$

**4.1.2. Semitrailer Unit** Similar to the process of tractor unit control input extraction, the semitrailer unit control input can be calculated as below:

$$M_B = - \left( I_{xx_{ps}} + I_{xl} \right) \left( \frac{1}{(I_{xx_{ps}} + I_{xl})} f_2 + (2\lambda_2 + k_3) \dot{\varphi}_s + (\lambda_2^2 + 2\lambda_2 k_3) (\varphi_s - \varphi_d) + k_3 \lambda_2^2 \int (\varphi_s - \varphi_d) dt + k_4 \text{sign}(s_s) \right) \quad (41)$$

### 5. SIMULATION RESULTS

In this section, the effect of controller on lateral stability of the vehicle is evaluated in standard maneuvers.

**5. 1. Slalom Maneuver** In this study, the vehicle at 60 km/h initial velocity on a dry road with 0.7 friction coefficient moves and steering input is as Figure 2:

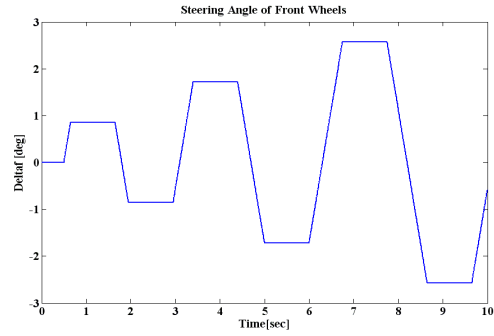
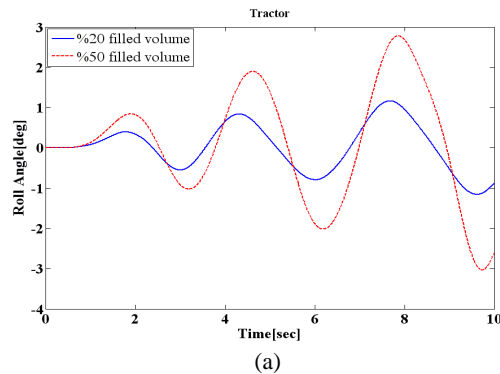


Figure 2. Steering angle.

The vehicle responses are shown in Figures 3 to 6 at two filled volumes, 20 and 50 percent. As can be seen from Figure 3, as the filled volume grows, the roll angle for the both units increases considerably. The amount of this increase is considerable at the 9.3 second for the semitrailer unit. It can be seen from Figure 4 that the robust controller can perform the control task successfully for the both states. Active roll control system improves the peak value and settling time significantly in comparison with uncontrolled condition. The control efforts are shown in Figure 5 for tractor and semitrailer units. It is clear that the shapes of the control torque curves are similar in both filled volumes. Lateral dynamic behavior of an articulated vehicle is investigated using lateral load transfer ratio (LTR). The LTR is defined as below [4]:

$$LTR = \sum_{j=1}^N \frac{|F_{zrj} - F_{zlj}|}{F_{zrj} + F_{zlj}} \quad (35)$$

The LTR starts from zero and becomes unit when there is no contact between the wheels and the road. The Figure 6 shows, for uncontrolled condition, the LTR increases as time progress. Using the control system, a considerable reduction is observed for the both of filled volumes due to control of the roll angles.



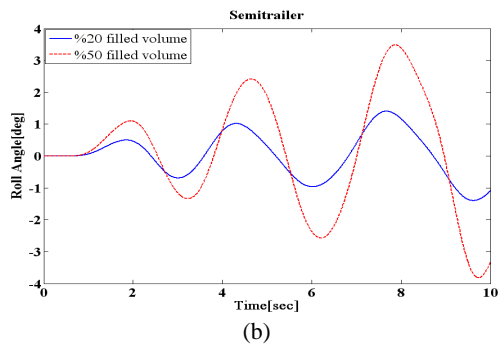


Figure 3. The roll angle without control: (a) tractor unit, (b) semitrailer unit.

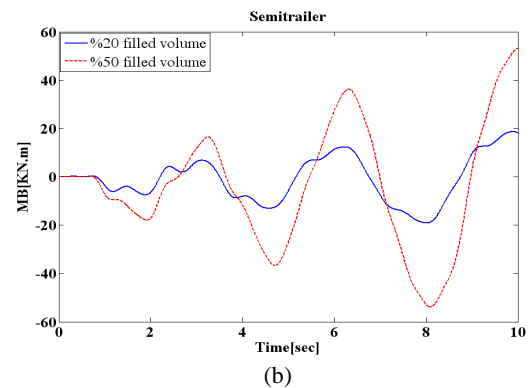


Figure 5. The control efforts: (a) tractor unit, (b) semitrailer unit.

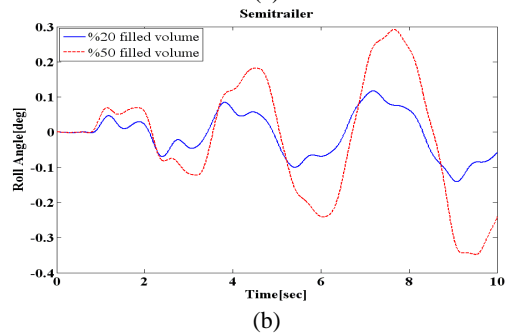
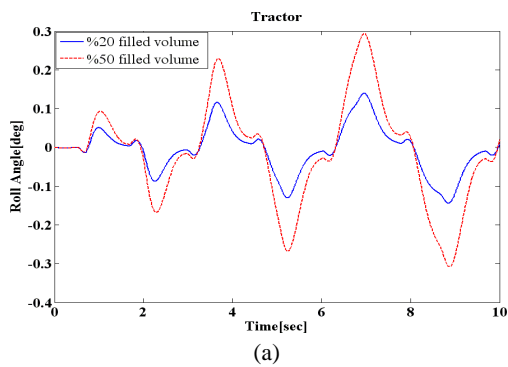


Figure 4. The roll angle with control: (a) tractor unit, (b) semitrailer unit.

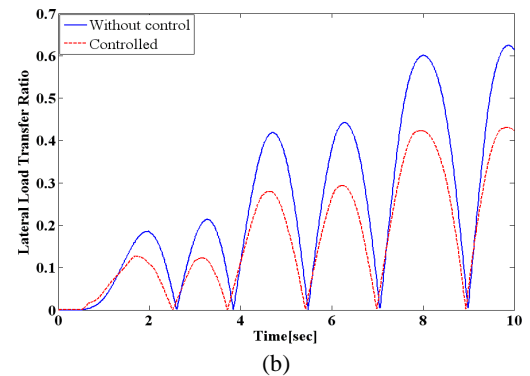
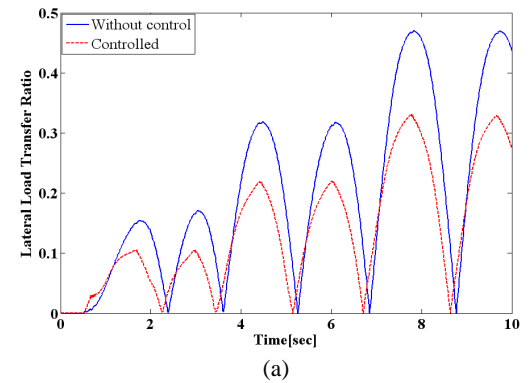
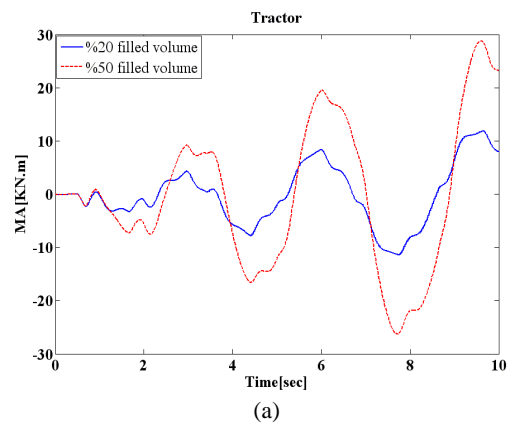


Figure 6. Lateral load transfer ratio (a) %20 filled volume, (b) %50 filled volume.



**5. 2. Stepsteer Maneuver**

In this maneuver, the vehicles run on a level icy road with a friction coefficient of 0.4 at the constant speed of 90 km/h and the steering angle input shown in Figure 7.

The simulation results for the most important roll dynamic responses of an articulated vehicle carrying liquid are shown at two filled volumes, 60 and 90 percent. Figures 8 and 9 illustrate the roll angle of the both units with and without control system.

According to the Figure 8, the roll angle increases for the both units when the filled volume goes up. The amount of this increase for the first peak is more in comparison with roll angle in second peak. However, control system is able to reduce the tractor and semitrailer roll angles in comparison with uncontrolled state. For controlled condition, at 60 percent filled volume, the semitrailer roll angle reaches to zero after 7 seconds while this portion is 10 seconds for the 90 percent filled volume. The control efforts for tractor and semitrailer units are given in Figure 10.

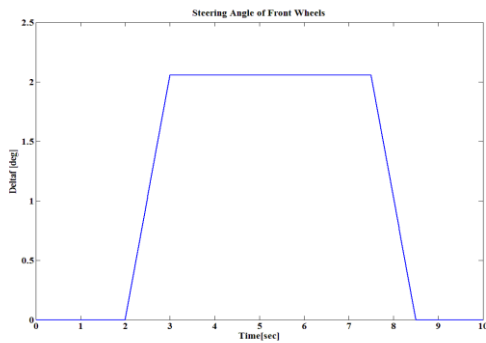
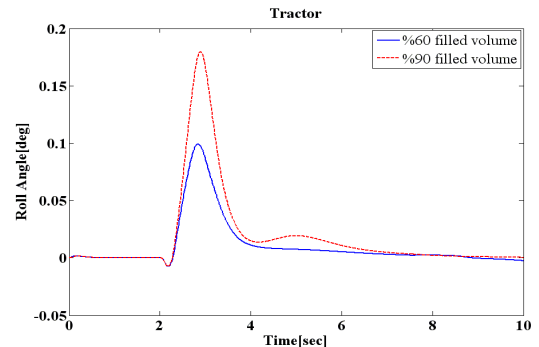
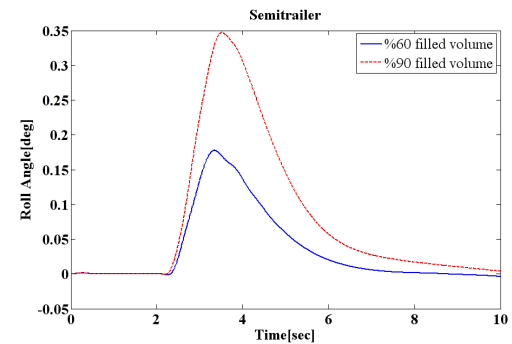


Figure 7. Steering angle.

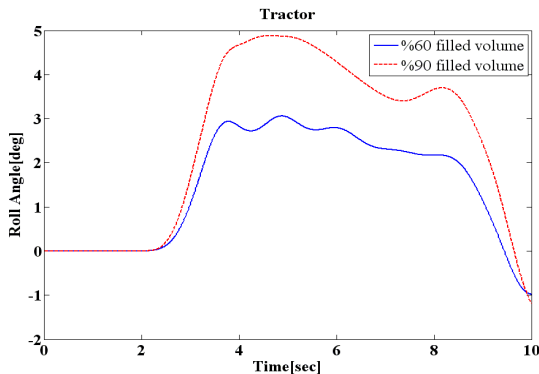


(a)

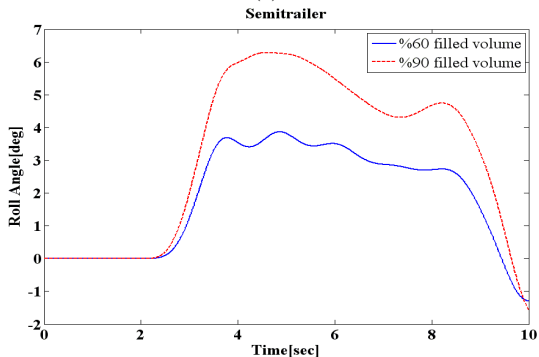


(b)

Figure 9. The roll angle with control: (a) tractor unit, (b) semitrailer unit.

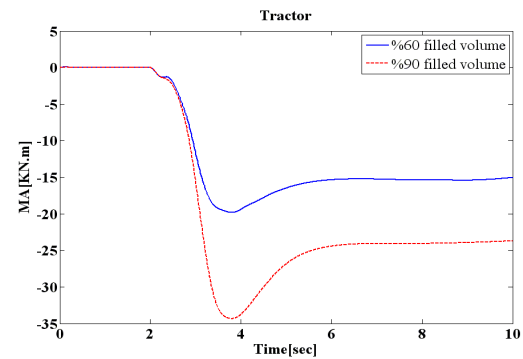


(a)

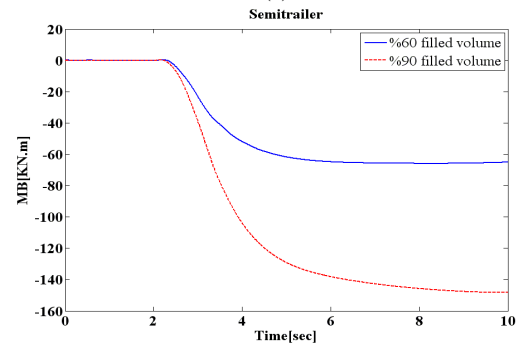


(b)

Figure 8. The roll angle without control: (a) tractor unit, (b) semitrailer unit.



(a)



(b)

Figure 10. The control effort: (a) tractor unit, (b) semitrailer unit.

## 6. CONCLUSION

In this paper, an active roll control system is used to reduce the liquid sloshing effect on rollover stability of an articulated vehicle carrying liquid in transient and steady state maneuvers. At first, a thorough nonlinear model for the articulated vehicle is developed. Then, using quasi-dynamic method for the carried liquid modeling, the dynamic interactions between the vehicle and the liquid is studied. Afterward, the roll control system performance is investigated in slalom and stepsteer maneuvers for different filled volumes for which the following conclusions are derived.

- The rollover stability of the vehicle is strongly subjected to the liquid sloshing effect.
- As the filled volume ascends, the roll angle for the both units increases.
- Increasing the liquid volume lateral load transfer ratio increases. Using the controller, a considerable reduction is observed in LTR during slalom maneuver.
- The simulation results show that controller is able to increase the rollover stability of an articulated vehicle carrying liquid during critical maneuvers.

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## APPENDIX

TABLE 1. Vehicle parameters

Parameter	Value	Unit
$CS_{tf(tr)}$	4.05(6.88)	KN. m. s/rad
$CS_s$	23.9	KN. m. s/rad
$C_w$	700	KN. m. s/rad
$D$	2.03	m
$h_{ct(s)}$	0.438(1.8)	m
$h_{wt(ws)}$	0.63(1)	m
$I_{wi}$	11.63	Kg. m <sup>2</sup>
$I_{xxpt(ps)}$	3335(120024)	Kg. m <sup>2</sup>
$I_{xzpt(ps)}$	602(5756)	Kg. m <sup>2</sup>
$I_{zzt(s)}$	20679(238898)	Kg. m <sup>2</sup>
$KS_{tf(tr)}$	380(684)	KN. m/rad
$KS_s$	800	KN. m/rad
$K_w$	30000	KN. m/rad
$L$	10	m
$L_{ct}$	1.959	m
$L_{fs}(L_{rs})$	5.653(2.047)	m
$L_{ft}(L_{rt})$	1.115(2.583)	m

$L_{tt}(L_{ts})$	1.31	m
$m_{s(ss)}$	6525(4819)	Kg
$m_{t(st)}$	33221(30821)	Kg
$R_{wi}$	0.4	m
$W_{t(s)}$	2.04(2)	m
$\rho$	1000	Kg/m <sup>3</sup>

## Analysis of Roll Control System to Eliminate Liquid Sloshing Effect on Lateral Stability of an Articulated Vehicle Carrying Liquid

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در این مقاله برای محدود ساختن تاثیر تلاطم سیال بر دینامیک جانبی خودروی مفصلی حامل سیال، یک سیستم کنترل رول فعال ارایه شد. برای این منظور، ابتدا یک مدل دینامیکی شانزده درجه آزادی از خودروی مفصلی توسعه داده شد و سپس با استفاده از نرم افزار تراک سیم در مانور استاندارد صحنه گذاری گردید. سپس اندرکنش دینامیکی بین بار سیال و خودرو با ترکیب روش شبه دینامیکی برای مدل سازی سیال درون مخزن و بکارگیری یک مدل دینامیکی غیرخطی شانزده درجه آزادی خودروی مفصلی مورد بررسی قرار گرفته است. برای طراحی سیستم کنترل رول فعال، روش کنترل مدل لغزش بکار گرفته شد. سپس جهت بررسی پایداری واژگونی خودروی مفصلی حامل سیال، نسبت انتقال بار جانبی به عنوان یک عامل مهم مورد بررسی قرار گرفت. عملکرد سیستم دینامیکی برای حجم پرشدگی های مختلف در مانورهای استاندارد گردش و مارپیچ نشان داده شده است. نتایج شبیه سازی نشان می دهند که سیستم کنترل رول فعال در دستیابی به هدف کنترلی و کاهش نسبت انتقال بار جانبی عملکرد موثری دارد.

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