Tank Vehicles: Modeling and Testing

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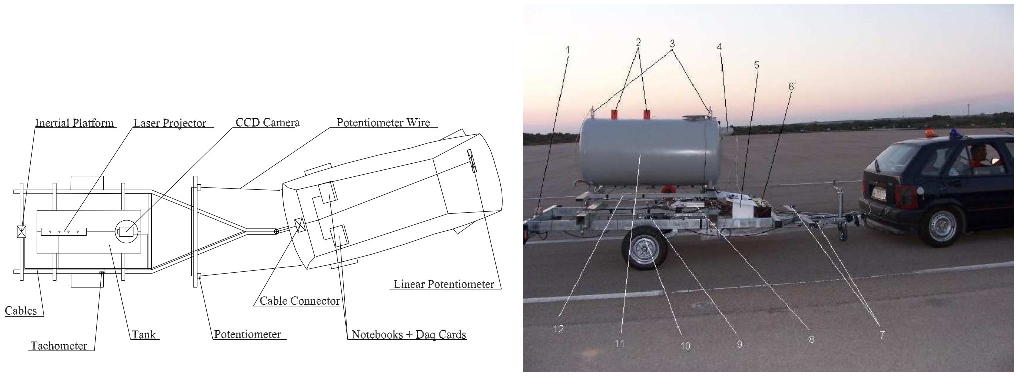
SUMMARY. This paper presents an experimental investigation of the handling performances of an articulated vehicle carrying liquid cargo and a comparison with mathematical model results. The test vehicle is a car with an instrumented single-axle trailer carrying a cylindrical tank. An original device for the visualization of the liquid free surface inside the tank is described. Besides, the authors present a simplified model of articulated vehicle carrying liquid cargo and a comparison between experimental data and the results of three different mathematical models. It is shown that the dynamical interaction between liquid and rigid cargo is considerably influenced by the type of maneuver performed and the sharpness of the steering inputs applied.

1 INTRODUCTION

The dynamic stability limits of heavy vehicles are worse than other road vehicles, because of the high center of gravity, and large weights and sizes [1]. Accidents involving roll-over are the most dangerous and harmful and they often occur under cornering, lane change and braking-in-turn maneuvers, especially in the case of partly filled tank vehicles. Tank vehicles are often partly filled: in gasoline, water and milk transportation it is common to encounter partly filled tank during local delivery. Rollover is also a consequence of jackknifing instability [2, 3] of the articulated vehicle. The fluid slosh within a partly-filled tank truck and its effects on the vehicle stability have been widely investigated by considering additional roll and pitch moments induced by the fluid cargo [4]. A lot of mechanical models based on the analogy with oscillating cargoes have been proposed to account for the dynamic fluid slosh and its effects on the directional response of the vehicle [5]. Some authors suggested the optimal shape of tank through quasi static approaches [6]. Anyway a few studies stressed that the magnitudes of forces and moments caused by transient fluid slosh are significantly greater than the steady state and quasi static models predictions. This consideration would suggest that quasi static and steady state slosh approaches may overestimate the directional stability limits of a tank vehicle. Additionally, there are very few works in the literature where the effect of the liquid cargo has been tested on the road in real maneuvers [7, 8] and so it is difficult to compare theoretical results with the poor experimental investigations available. Tests shown in [7] are very well described and refined; it's actually one of the few works available. However, the authors focused on a single rigid unit vehicle, that is very common in water and milk local delivery, while articulated tank vehicles are more widely used for the transportation of fuel and dangerous liquids. In our opinion a more specific investigation is needed. A suggestion on how to perform measurements of the liquid configuration inside the tank has been proposed in [8], and a more efficiently equipped experimental trailer has been presented in [9].

In this paper the authors describe a novel experimental tank-trailer which includes the visual device reported by [8]. The instrumentation gets the concurrent measurement of speed, accelerations, angular velocities, steering angle, etc., of the liquid configuration and also of the forces that the tank applies on the trailer. Moreover a simplified model of articulated tank vehicle is presented, which includes the liquid cargo and the roll motion. Standard maneuvers of double lane change and round-about performed at Nardò Technical Center (NTC) in Nardò (Lecce - Italy) are described. Effects of liquid have been studied thanks to the measurement of the forces and the moments between the tank and the trailer frame; moreover the visual technique proposed by [8] has been implemented too. Results of the measurements have been compared to those of mathematical models of different kinds: the dynamical model here proposed, a common quasi static approach and a model that neglects the liquid cargo. Results are shown by comparing peak values of dynamical indexes introduced in [10] and measured in the tests performed.

2 MATERIALS AND METHOD



(a) (b)

Figure 1: (a) Schematic of the experimental apparatus made of a car with tow hook and the instrumented trailer and (b) picture of the experimental trailer. 1 - Inertial Platform; 2 - Laser caps; 3 - Magnetostrictive float sensors; 4 - Camera; 5 - Cable connections and data acquisition device; 6 - Batteries; 7 - Linear wire potentiometers; 8 - AC/DC Converter; 9 - Steam potentiometer; 10 - Tachometer; 11 - Tank; 12 - Force device: upper frame.

The instrumented test trailer is sketched in Figure 1 in detail. The trailer is a commercial single-axle naked metal frame with loading capacity of 1200 kg that can be towed by whatever car with a tow hook. A cylindrical tank of 1 m^3 has been mounted on a six-axis force measurement device constrained to the trailer. Therefore the measurement of the forces and the torques between the tank and the trailer can be performed on the road. The forward speed is measured by an optical wheel tachometer. The configuration of the suspensions arm is measured by two steam potentiometers. Two magnetostrictive sensors with floats measure the liquid level in two points and the configuration of the liquid is analyzed by means of a CCD camera based device. Moreover, an inertial platform gives the measurement of the acceleration and the angular velocity of the trailer. In the end, the articulation angle (relative yaw) is measured by two linear wire potentiometers. The trailer has been characterized in our facilities and its mechanical features are summarized in the Table 1. A more detailed description of each instrument follows.

2.1 *Measurement of Forces*

In the Figure 2 the six axis force measurement device is shown. It is made of two metal frames constrained by six tension-compression load cells. Each cell has a full scale capacity of 500 kg

$a = 1.016\ m$	$b = 1.524\ m$	$c = 1.974\ m$	$a_t = 2.725\ m$
$l_t = 2.85\ m$	$x_{tk} = 0.05\ m$	$h_G = 0.6\ m$	$h_{Gt} = 0.608\ m$
$z_f = 0.32\ m$	$z_{ft} = 0.328\ m$	$h_{tk} = 0.792\ m$	$L = 1.6\ m$
$R = 0.450\ m$	$h_{RC} = 0.25\ m$	$h_{RCt} = 0.32\ m$	$t = 1.4\ m$
$t_t = 1.450\ m$	$m = 1410\ kg$	$m_t = 360\ kg$	$J_{x'x'} = 500\ kg\ m$
$J_{x'z'} = -380\ kg\ m$	$J_{z'z'} = 1800\ kgm$	$J_{x'_t x'_t} = 300\ kg\ m$	$J_{x'_t z'_t} = 0\ kg\ m$
$J_{z'_t z'_t} = 500\ kg\ m$	$\chi = 55700\ \ N\ m/rad$	$\lambda = 111\ N\ m\ s/rad$	$\chi_t = 120800\ N\ m/rad$
$\lambda_t = 127\ N\ m\ s/rad$	$\chi_\eta = 0$	$\lambda_\eta = 0$	
$a_3 = 1601.8\ N/rad$	$a_4 = 6.4946\ kN$	$a_{3_t} = 588.6\ N/rad$	$a_{4_t} = 2.521\ kN$

Table 1: Geometrical and mechanical features of the experimental trailer.

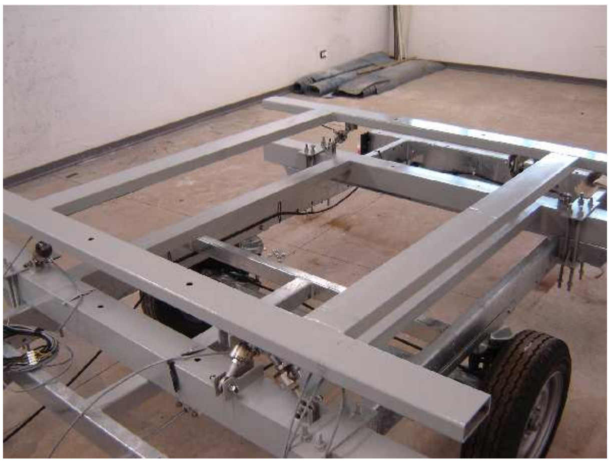


Figure 2: Six axis force measurement device: the lower frame is rigidly fixed to the trailer; the upper is mounted on six load cells. It measures forces and torques applied to the trailer.

and it is pinned to the frames by two spherical joints. Six properly placed cells make the whole structure statically determined and simple equilibrium arguments lead to the following matrix relation between the external forces applied on the tank $\{F_{ext}\}$ and the forces measured by each cell $\{F_{cells}\}$:

$$\{F_{ext}\} = [A]\{F_{cells}\} \tag{1}$$

The matrix $[A]$ is a function of the coordinates of the connection points of cells and of the orientations of cells axis. The orientation of cells have to be chosen in order to make $[A]$ non singular (system is statically determined). The matrix $[A]$ has been then calibrated in our facilities.

2.2 *Measurement of the Mechanical Properties of the Suspension*

Results of static vertical loading cycle gives an almost linear relation between the applied load and the displacement. Values of vertical stiffness are: global vertical stiffness $k_{tot} = 284.7$ N/mm, vertical stiffness of suspension $k_{susp} = 701.3$ N/mm and vertical stiffness of pneumatic tires is $k_{pneu} = 479.4$ N/mm. Similar investigations were performed to measure the static roll response of the trailer and its combined roll stiffness is $\chi_{roll} = 121000$ N m/rad.

2.3 *Measurement of Liquid Configuration*

Some previous experimental works about the argument were based on the use of a semi transparent tank and video cameras for the measurement of liquid configuration [7] but this procedure is limited to the two end plates. In a previous work of ours [8] we have developed a method to see the surface inside the tank in different transversal and parallel sections. The method is based on the projection of four laser light sheets on the free surface, tracked by a CCD camera (see [8, 9]). Each sheet is irradiated by a solid state laser diode whose light spot pass through a cylindrical lens to give a neat light sheet. Water is made reflective by a thin film of colored oil floating on the surface. The images are grabbed with a frame rate of 24 Hz and the sequence is stored in a notebook.

2.4 *Others*

The articulation angle is measured by means of two linear wire potentiometers as in [8]. The lateral acceleration and the yaw angular velocity of the trailer have been measured by a six axis inertial platform mounted on the rear section of the trailer. An optical tachometer is set on the right wheel of the trailer to measure the speed. Moreover the vehicle is endowed with an instrumented steer for the measurement of the steering angle. In the end we have employed two magnetostrictive sensors to get the liquid level in two points of the tank, for future investigations of braking performances.

3 MATHEMATICAL MODEL

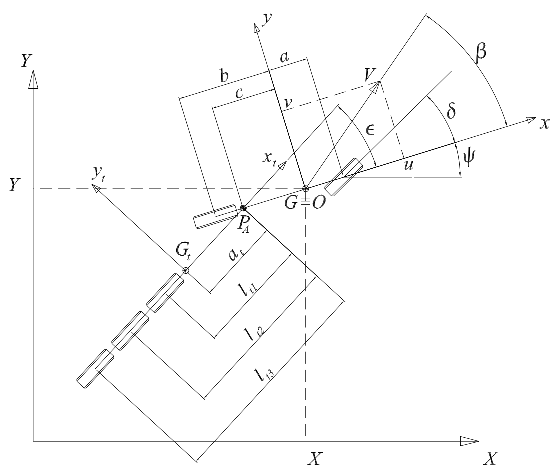


Figure 3: Reference systems and Lagrangian parameters

The mathematical model (schematics in Figures 3, 4) is a rigid body model developed under the following hypotheses. The front and the rear units are two rigid bodies constrained to each other with a torsionally yielding articulation (relative roll allowed). Vertical and roll motion of the unsprung masses are neglected. The whole vehicle rolls around a fixed horizontal roll axis and relative roll between the front and the rear unit occurs around a *relative roll axis*. The intersection between these

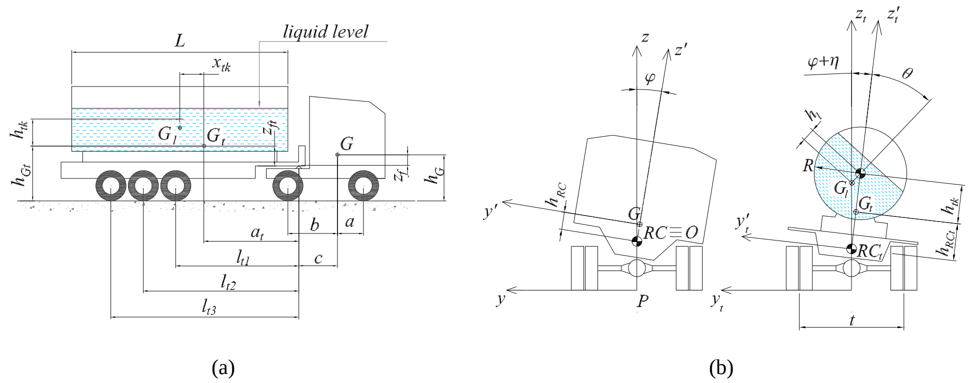


Figure 4: (a) Longitudinal and (b) transversal section of the truck-semitrailer

two axes and a transversal plane are respectively RC and RC_t (roll centers) in the Figure 4b. Since the model is aimed at the simulation of constant speed maneuvers in normal driving conditions, pitch and vertical motions are neglected, and the longitudinal and lateral dynamics are uncoupled. The roll angles, the articulation angle and the side slip angles are considered small and the equations of motions will be linearized. We remember for the reader's convenience that according to [3] the whole liquid cargo can be modeled as a continuous distribution of pendulums with infinitesimal longitudinal thickness, and that we work under hypotheses that allow to model the whole continuous distribution with two further degrees of freedom only. The full derivation of the equations of motion is here omitted and the reader is addressed to [9] for a better understanding. The final matrix form of the equations of motion of the system is

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F\} \tag{2}$$

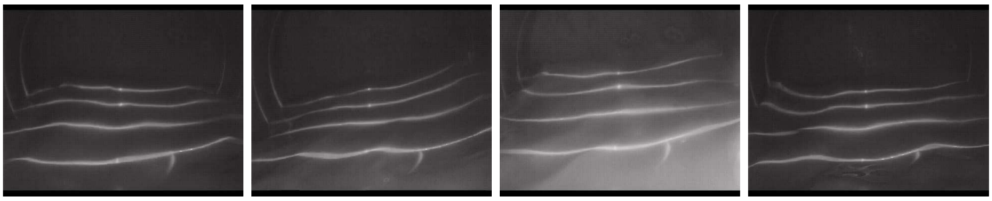
where $\{x\} = \{y, \psi, \varphi, \eta, \varepsilon, \vartheta_0, c\}^T$ is the vector of Lagrangian parameters that we define as follows. V is the velocity of O (see Figures 3, 4) and it has components u, v in the x, y plane. We define a quasi coordinate y so that $\dot{y} = v$. Other parameters are: the yaw angle ψ, the roll angle (of the whole vehicle) φ, the relative roll angle between the front and the rear unit η, the articulation angle ε, the angle of inclination ϑ_0 of the pendulum in the mid-section of the tank, and c that is the angular coefficient of the straight line which connects all pendulums centers of mass. The equations of motion are finally derived by means of the Lagrange equations:

$$\frac{d}{dt}\frac{\partial T}{\partial \dot{q}_i} - \frac{\partial T}{\partial q_i} + \frac{\partial U}{\partial q_i} + \frac{\partial R}{\partial \dot{q}_i} = Q_i \tag{3}$$

where $L = T - U$ is the Lagrangian function, T, U are the kinetic and potential energy of the mechanical system and R is the function of Rayleigh; $q_i, \dot{q}_i$ is the *i-th* parameter of Lagrange and its time derivative, Q_i the *i-th* generalized force. Each function is given by the sum of three terms: the first for the front unit, the second is for the rear unit and the third is for the liquid cargo. For a better understanding the interested reader is referred to [9, 10]

4 EXPERIMENTAL TESTS

Preliminary tests on the road has been carried out for a first comparison with theoretical results and the understanding of simulation potentials. A lot of sequences of images have been recorded for



(a) (b) (c) (d)

Figure 5: Image sequence in lane change. (a) Before turning, (b)-(c) in bend, (d) straight end.

each maneuver. An example is made in Figure 5 where it is shown the light sheets have an almost straight shape.

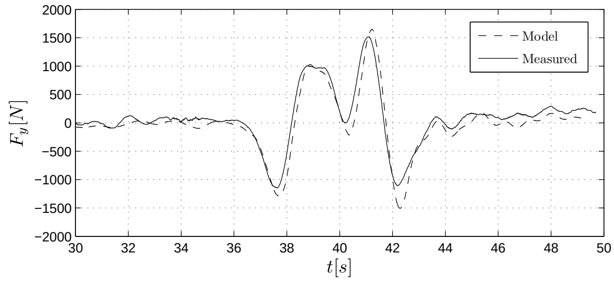
The main purpose of the present work is to make an experimental investigation and the validation of simplified models of articulated vehicles carrying liquids. When handling performances have to be investigated on, it is necessary to reach the desired value of speed and to keep the speed constant until the longitudinal oscillations are almost completely dampened. The maneuver can finally take place. We performed our tests with the experimental apparatus described in [9] at the Nardò Technical Center (NTC) in Nardò (LE) an infrastructure for testing purposes. The maneuvers performed on NTC's handling track are summarized in the Table 2. We have taken under consideration the severe double lane change manoeuvre (DLC) in order to understand the effects of the liquid moving cargoes on the handling, when sudden variations of the lateral acceleration occur. The ISO/TR 3888:1975 was followed as guideline in the data collection process. Manoeuvre has so been performed as follows:

- A straight lane of about 550 m is used to accelerate the vehicle until the desired velocity is reached
- Two different speeds are chosen, that are 40, 50 km/h in four different loading conditions, that are empty tank, 20%, 35% and 50% of the loading capacity
- after the lane change a straight trajectory should be taken at a constant velocity, before braking.

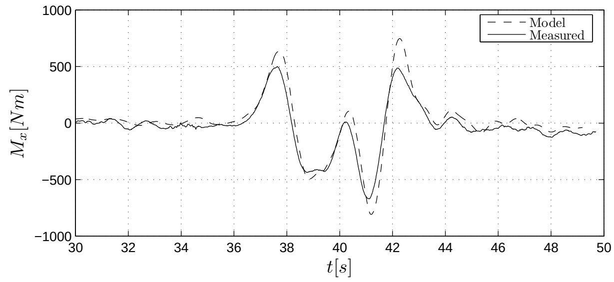
One of the most dangerous situations for an articulated tank vehicle is driving on a roundabout, as on railways often happens. When approaching the curve the vehicle has a side acceleration that in the transient phase may induce large oscillations of the sprung masses, and in partially filled conditions, of the liquid inside too. In this manoeuvre there is an high risk of rollover, so we investigate roundabout vehicle response. A radius of curvature of 100 m has been considered. The curve is approached tangentially and the effects of the liquid cargo are recorded until the transient phase is completed. Four fill levels are analyzed: empty tank, 20%, $\%35$ and 50% for two different values of the forward speed, that are 50 and 70 km/h.

Manoeuvre	V [km/h]	fl [%]
Double Lane Change	40, 50	0, 20, 35, 50
Roundabout 100[m]	50, 70	0, 20, 35, 50
Braking	40, 60, 80	0, 20, 35, 50

Table 2: List of test performed



(a)



(b)

Figure 6: Time histories of (a) the lateral force F_y and (b) the roll moment M_x. Fill level is 35% and the longitudinal speed is 50 km/h.

5 RESULTS

Results of the experimental investigation are shown. Figure 6 shows the time histories of the side force F_y and the roll moment M_y during a double lane change at 50 km/h. The comparison between experimental measurements and model results (simplified dynamical model) shows a very good agreement. Moreover we have calculated and compared the ratio of peak values of side forces and roll moments over side acceleration, something like an "effect over cause" ratio. We have compared results of: equivalent rigid cargo, quasi static and simplified dynamical model. Figure 7 shows the ratios $(F_y)_{peak} / (a_y)_{peak}$ and $(M_x)_{peak} / (a_y)_{peak}$ in the double lane change as measured in our experimental investigation and as computed through the three different cited approaches. As far as the force is concerned, dynamical model gives a better estimation (Figure 7 (a)), with a light overestimation of the force; on the other hand, quasi static model and equivalent rigid cargo underestimate the value of the side force. Moreover, it can be noticed that the differences are greater for higher values of the speed because dynamical effects are higher and more visible. Both dynamical model and quasi static model give a good estimation of the roll moment (Figure 7 (b)), while rigid cargo dangerously underestimates its peak values. The error of prediction computed via the quasi static model is lower then the error estimated with the dynamical model, but while dynamical equivalent model tends to an overestimation, quasi static approach underestimates it in general. The same results for the roundabout show quite a different situation (Figure 8). The estimation of the side force is good when it is performed with whatever model implemented (Figure 8 (a)), for both values of speed; roll moment shows a situation that is similar to the previous one, where equivalent rigid cargo model fails

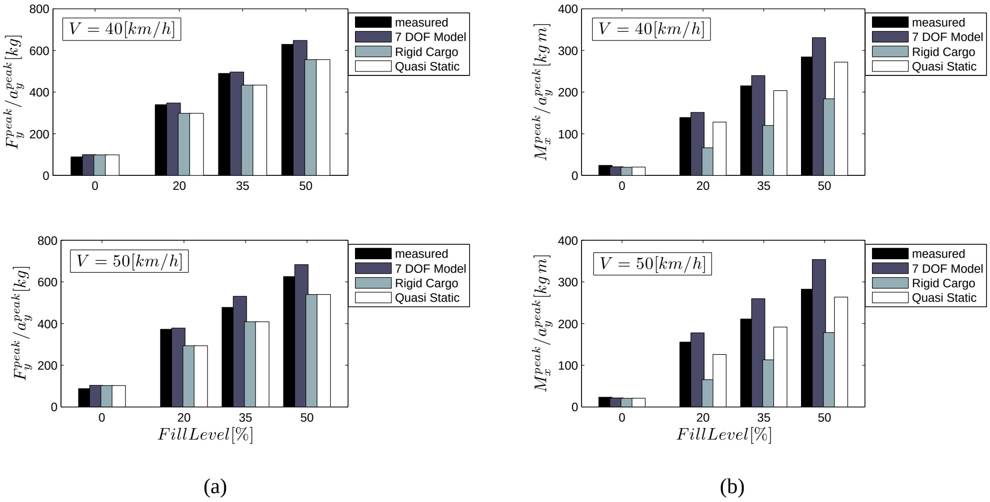
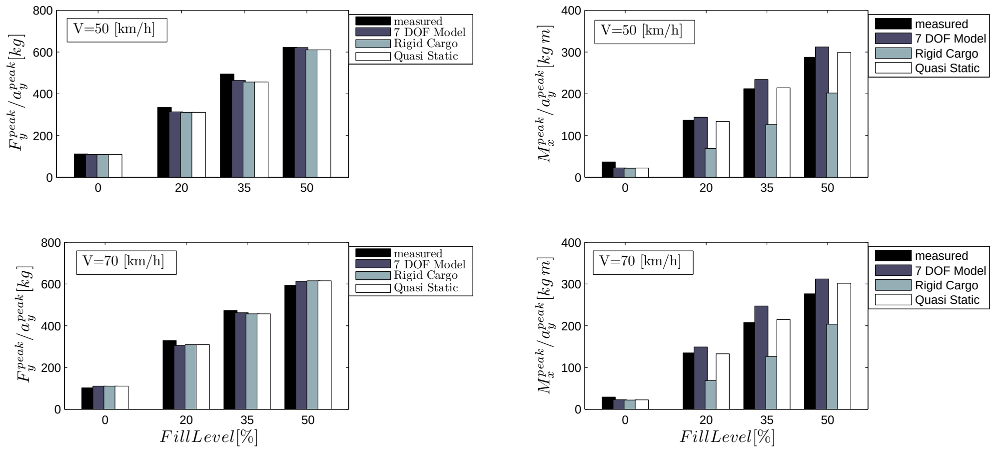


Figure 7: (a) Peak value of the lateral force F_y over the side acceleration a_y and (b) peak value of the roll moment M_x over the side acceleration a_y as a function of the fill level and for two different speeds (40 and 50 km/h) in a double lane change maneuver. Figure shows measurements and simulations results of three different mathematical models: full dynamical 7 DOF, quasi static and equivalent rigid cargo.

completely, and quasi static and dynamical models give almost the same results, with the former in general underestimating the measurements, while the latter gives an overestimation. The difference in the comparison of the peak values of the force can be easily explained because of the different amount of "‘dynamical content"’ of the two maneuvers. The time of execution of the maneuver is critical in both cases, but in the former the frequency of the "‘sinusoid"’ is an harmonic excitation that can interact with natural frequencies of the vehicle system, that are dependent on its cornering and inertial properties, suspension stiffness and fill level. Moreover, because we found a good estimation of both force and moment with the full dynamical model tested, we computed the actual value of the LTR of the trailer to see the effect of the fill level and speed. LTR quantifies the lateral transfer of load on a vehicle unit, and is defined as $LTR = \sum_{i=1}^{n} |F_{zl_i} - F_{zr_i}| / \sum_{i=1}^{n} (F_{zl_i} + F_{zr_i})$ where F_z is the vertical load on the wheel, the subscript l stays for left and r stays for right, while n is the number of axles of the trailer. We can refer to the LTR of the trailer alone because in our situation the roll behavior of the front and the rear unit are almost completely uncoupled. As easily predictable Figure 9 shows that both fill level and speed have negative effects on the LTR, that grows as the fill level grows, and as the speed grows, as obvious. We can also see that we have reached values of the LTR that are quite high: in the literature it is frequent to read that it should be advisable to keep it under 0.6; we slightly overpassed such a limit in the roundabout.

6 SUMMARY AND CONCLUSION

Validation of mathematical models of articulated vehicles with partly filled tanks needs experimental investigations on the road. An experimental apparatus for the measurement of dynamical parameters and for understanding the interaction between liquid and vehicle dynamics has been used for such a purpose. The system is made of a metal frame trailer with a circular cross sectional



(a) (b)

Figure 8: (a) Peak value of the lateral force F_y over the side acceleration a_y and (b) peak value of the roll moment M_x over the side acceleration a_y as functions of the fill level and for two different speeds (50 and 70 km/h) in a roundabout. Figure shows measurements and simulation results of three different mathematical models: full dynamical 7 DOF, quasi static and equivalent rigid cargo.

tank, that has been fully instrumented. A six axis force measurement device estimates the forces and the moments exchanged between the tank and the trailer in dynamic conditions. The trailer is endowed with sensors for the measurement of its dynamic behavior. Standard maneuvers as ISO double lane changes and roundabouts have been performed, with different fill levels and with stationary speeds. A mathematical model including a dynamical model of liquid cargo based on a mechanical analogous system has been implemented and results have been compared to the measurements. Mathematical models based on different approaches, as quasi static modeling of liquid and equivalent rigid cargo have been compared. In double lane change, dynamical model is the one which estimates the peak value of the side force with minimum error, while quasi static and rigid model give an underestimation. Situation is different for the roll moment: the estimation given by dynamical and quasi static model are both good, but as the former overestimates the peak value, the latter underestimates it; rigid model fails in general. In the roundabout no meaningful difference can be seen between the three models in the estimation of the forces. It is concluded that limitations of each model are maneuver dependent, it is *advisable* to include dynamical effects of lateral liquid sloshing *even with simplified approaches*.

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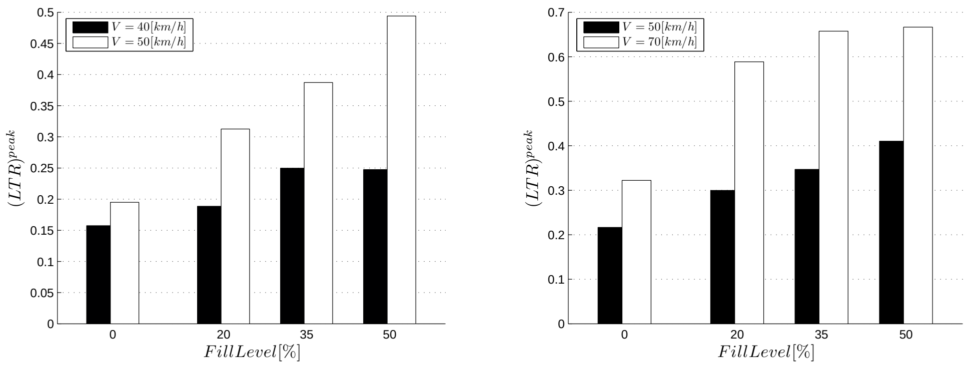

(a) (b)

Figure 9: Predicted Load Transfer Ratio (LTR) as function of the fill level for different values of constant longitudinal speed in (a) a double lane change and (b) roundabout. Measured steering angle is given as input.

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