Modelling Fluid Slosh for Performance Based Standards





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Abstract

Currently, there are no requirements in the Australian Performance Based Standards (PBS) scheme for assessors to model fluid slosh. The decision of whether and how to model slosh is left to each individual assessor, resulting in inconsistencies in assessments and potentially vehicles on the road which would not be acceptable if slosh were considered. Using a pendulum model to simulate slosh movement, this study investigated the effect of slosh on vehicle performance within a PBS framework. Slosh behaviour was analysed by varying fill levels in compartments, location of partially loaded compartments and fluid viscosity. A baseline combination was assessed with and without the implementation of a pendulum model. Results indicated that, unlike the simplified model, the combination did not meet the required standards when slosh was simulated. Moreover, static rollover threshold values were obtained using multiple methods with varying degrees of complexity. For static rollover threshold (SRT) a lateral centre of gravity offset method was shown to be in good agreement with the pendulum model at varying fill levels. Both off which indicated significantly lower values than the assumption of a rigid payload.

Keywords: Fluid Slosh, Tankers, Performance Based Standards, PBS, Heavy Vehicles, Freight Transport, Vehicle Dynamics.

1. Introduction

The Australian Performance-Based Standards (PBS) Scheme created by the National Transport Commission (NTC) and now administered by the National Heavy Vehicle Regulator (NHVR) is aimed to improve productivity and safety within the industry by assessing vehicle combinations that extend beyond the scope of prescriptive combinations. The scheme outlines a national set of guidelines and standards encompassing vehicle performance, gross combination mass (GCM) and dimensions to ensure that the combinations are appropriately fitted to road networks. The scheme requires accredited assessors to test a subject vehicle combination against a set of safety and infrastructure standards (NTC 2020).

The standards test different aspects of vehicle performance including impact on infrastructure, driveline performance, low speed manoeuvrability, high-speed stability (dynamics) and rollover resistance. Manoeuvres such as lane-change that test high-speed stability incur lateral acceleration over a short period of time, resulting in an oscillation of the vehicle combination. Methods employed to determine these values are more complex and require simulations used by PBS assessors to accurately predict the performance of the vehicle. Fluid slosh also plays a role in the Static Rollover Threshold (SRT) test causing the fluid centre of gravity (cg) to move as it is subjected to lateral acceleration. However, there are no current guidelines or rules necessitating internal dynamic load modelling such as the movement of slosh in tankers. Consequently, assessors are given the opportunity to disregard fluid slosh in simulations. Currently there is little reference material on the influence of slosh in a PBS framework.

2. Literature Review

The modelling of liquid slosh in mobile containers has been a significant engineering challenge since the 1960's when the issue became of interest for aeronautic and space applications (Abramson, NH., et al. 1966). In most automotive applications, loads within combinations are fixed and centred to improve performance and maintain safety. However, unrestrained loads can be displaced by inertial forces, potentially worsening vehicle stability. Frequently transported unrestrained loads include hanging meats, livestock and liquids such as milk, diesel and petrol. When assessing the impact of slosh on vehicle performance, steady and transient conditions must be considered alongside various other influencing factors that affect performance.

2.1 Steady State Conditions

During a cornering manoeuvre, centrifugal forces displace unrestrained liquids from a nominally centred position to one in which the free liquid surface is perpendicular to the resultant force induced by gravity and the cornering manoeuvre. Under these circumstances the vehicle can be simplified into a steady state condition. With low amounts of ullage, the effect of unrestrained liquid movement is minimal and the lateral cg offset is small. However, with larger ullage the liquid can displace a greater distance, resulting in a larger lateral offset of the fluid centre of gravity (cg). However, partially filled tankers will have less mass, creating a smaller destabilising moment for the same degree of lateral fluid cg offset. When coupled with an array of other contributing factors such as density, viscosity, cross-sectional shape and area the effect of static displacement of liquids in containers becomes difficult to analytically determine.

2.2 Transient Conditions

Transient manoeuvres can further worsen rollover stability. In transient manoeuvres with any form of abrupt steering such as lane change, sudden steps of lateral acceleration may lead to larger fluid displacement than steady state conditions such as cornering (Winkler, C. B., et al.. 1992). In these circumstances, the unrestricted liquid momentum has the potential to create an overshooting affect analogous to an under-damped pendulum.

2.3 Influencing Factors

The path that the cg follows as the fluid shifts during cornering can be easily predicted for a circular tanker due to radial symmetry. However, for more complex shapes the path of the fluid cg as a function of lateral acceleration becomes more difficult to determine. Kolaei, A., et al. (2014) developed an analytical approach to predict the static rollover threshold of combinations using the geometry of the tanker profile, fill levels of compartments and other vehicle properties used to predict the mechanics of the vehicle in roll (Kolaei, A., et al. 2014).

Moreover, dynamic motion produced by lane change or an evasive manoeuvre has the potential to invoke a frequency which can resonate with the natural frequency of the system. When this occurs, fluid motion is amplified, leading to a more unstable roll moment and premature rollover of the articulated vehicle (Kolaei, A., et. al 2014). Using a similar approach, Kolaei et al. (2014) developed an analytical model to predict the natural frequencies of fluids in containers. When compared to experimental and computational fluid dynamic solutions, the analytical model was able to accurately predict the natural frequencies of liquid motion for a given fill level and cross-sectional shape. In this report it was found that only the lowest few natural frequencies were required to analyse hydrodynamic forces as higher modes were heavily damped (Kolaei, A., et al. 2014).

In another study it was found that, for a half-filled, eight-foot-wide tanker, the natural frequency was approximately 0.5 Hz. Whereas, a six-foot-diameter circular tank had a frequency of approximately 0.6 Hz (Winkler, C. B. 1999). This can be of concern as abrupt high-speed manoeuvres may have steering frequencies that coincide with these values. For example, the PBS lane change manoeuvre has a frequency of 0.4 Hz. Baffles can be introduced to artificially shift resonant frequencies by altering the geometric profile of the tank. Longitudinal baffles, directed along the length of tankers, have been shown to offset resonant frequencies away from ranges of concern (Winkler, C. B. 1999). However, longitudinal baffles are not common as they are difficult to manufacture and would worsen braking performance of vehicles due to hydro-dynamic forces along the direction of travel. Compartmentalisation of tankers as shown in Figure 3 is a far more common method used to improve stability under partial loading (Winkler, C. B., et al. 1992).

Viscosity, compressibility and density are also important factors to consider when modelling fluid dynamics. In the study by Kolaei, A., et al. (2014) the analytical approach assumed incompressible and inviscid fluid which may not always be a valid assumption. However, a study performed by Wu, C.-H., and Chen, B.-F. (2009) stated that viscous effects can be ignored for sloshing analysis of fluids with low viscosity levels.

The ullage of road tankers transporting dangerous goods (such as petrol tankers) is regulated in the Australian Dangerous Goods Code outlined by the National Transport Commission. In this set of regulations, dangerous goods such as petrol cannot be filled to a percentage between 20% to 85% (NTC 2020).

2.4 Methods Used to Model Slosh

Several modelling methods have been developed to replicate and analyse the effect of fluid motion in containers with varying levels of complexity and accuracy. D'Alessandro, V. (2012) presented a comprehensive review of current approaches for analysis of sloshing fluid in partially filled containers. In these studies, container boundaries are considered as rigid bodies and deformation at these boundaries is deemed negligible. Moreover, the sloshing phenomena is commonly simplified down to a series of forces and moments that can be applied to a vehicle model. D'Alessandro, V. (2012) categorises these approaches into the quasi-static, mechanical analogy and computational fluid dynamics (CFD) methods with growing complexity and intended accuracy respectively.

2.4.1 Quasi-Static

The quasi-static method, otherwise referred to as the steady-state or roll-plane model, is arguably the most simplified and reduced method to simulate sloshing in a container. In this model, a lateral acceleration representative of centrifugal forces during cornering is applied to determine the position of the fluid within a roll-plane which in turn is used to determine the cg coordinates. From this, the effect of steady-state load shift is applied to assess the performance of vehicles.

This method assumes that the cross-sectional profile of the fluid is constant along the length of the tank. The steady-state model can incorporate compressible liquids used to calculate distribution of mass but is unable to consider the effect of viscosity and dampening in dynamic manoeuvres (D'Alessandro, V. 2012). Moreover, this method provides a numerical approach to rapidly determine cg offset of tankers with a particular fill level and cross-sectional profile.

It was found that roll over stability of tankers is significantly worsened when liquid motion is considered compared to the assumption of a rigid body with the same mass (Rakheja, S., et al. 1988). Validation of the steady-state model has been completed using physical experiments which indicated that the two sets of results were in good agreement (Rakheja, S., et al. 1992). However, deviations between results have been noted, particularly at peak values revealing smaller roll angles during transient manoeuvres such as a lane change (Rakheja, S., et al. 1992). This has been attributed to the fact that a steady-state model does not accurately predict the behaviour of transient systems and the overshooting effect that is created in inertial frames of reference. Herein lies the greatest limitation of a quasi-static model.

2.4.2 Mechanical Analogy Method

As an alternative to quasi-static modelling, mechanical systems can be used to model the transient behaviour of liquid slosh in containers (D'Alessandro, V. 2012). These systems consider mass, moments of inertia, cg and equivalent frequencies of sloshing motion to predict the behaviour of the fluid and the dynamic stability of vehicles. In this sense, the system must consider a moving mass which can oscillate about a central point and respond to inertial forces. As such the analogy typically takes two different forms; a pendulum model and a mass-spring-damper model.

In mass-spring-damper models, the spring and damping constants are usually determined using linear theory or experimentally, with physical models to determine and validate harmonic frequencies (D'Alessandro, V. 2012). Pendulum models are created in a similar manner, with natural frequencies represented by the length of the pendulum arm. Variations of the pendulum model exist such as the damped torsional model used to incorporate damping and spring forces, and trammel pendulum used to accurately replicate elliptical fluid cg migration (D'Alessandro, V. 2012).

2.4.3 Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) offers a method to directly model fluid behaviour by solving the Navier-Stokes equations. Conditions involving low amplitude excitation can be simulated by assuming an ideal incompressible fluid with no viscosity and incompressible and irrotational flows. Herein the set of equations is simplified to a linear sloshing theory. For situations involving higher amplitude slosh, and for greater accuracy, non-linear slosh can be evaluated using the full set of equations. Experimental validation with scale model tanks has shown the high accuracy of CFD for modelling the frequency, forces and moments generated (D'Alessandro, V. 2012). However, assessing fluid slosh through a numerical CFD model requires significant computational resources. Additionally, the forces and moments generated must be integrated into a vehicle simulator to evaluate the overall vehicle dynamics.

3. Objectives

The purpose of this study is to provide insight into the influence of slosh on vehicle performance within a PBS framework. By varying fill level of compartments, location of partially filled compartments and fluid viscosity, this study aims to detail and further understand the behaviour of slosh and the impact this has on current safety standards. Moreover, the study compares current methods (or lack thereof) used to simulate slosh. In doing so, any issues with current PBS requirements may be highlighted and hopefully addressed in the future to improve road safety.

4. Vehicle pendulum slosh model

MSC Adams Car (2018) simulation software was used to assess the multibody vehicle dynamics of the subject vehicle. The software and vehicle modelling methods have been accredited by the National Heavy Vehicle regulator (NHVR) as well-suited for PBS assessments. A baseline truck and dog tanker as shown in Figure 3 was used as the standardised model for the various simulations. Fluid slosh was modelled as a pendulum coupled with torsional spring and damping forces. Each compartment was modelled with an individual pendulum and the pendulums have two degrees of freedom in the roll plane. Other degrees of freedom are not considered in this model.

Pendulum length and pivot height are calculated by considering the fluid body at three positions during roll. Much like the quasi-static method, a roll plane model is assumed, and the fluid cg coordinates are determined geometrically at 0%, 25% and 50% gradients to represent increasing lateral acceleration. Then the fluid cg location is used to estimate an average pendulum length and pivot height. Mass is determined by volume of the fluid and density. A simple pendulum is an inadequate model to describe both cg migration as well as the damping and associated natural frequencies of fluids in containers. Thus, the pendulum was coupled to a rotational spring and damper and the complete kinetic equation of motions were evaluated and plotted using inertial, damping and spring forces. Frequencies and damping coefficients were compared to and validated against values in
Figure 1 and Figure 2.

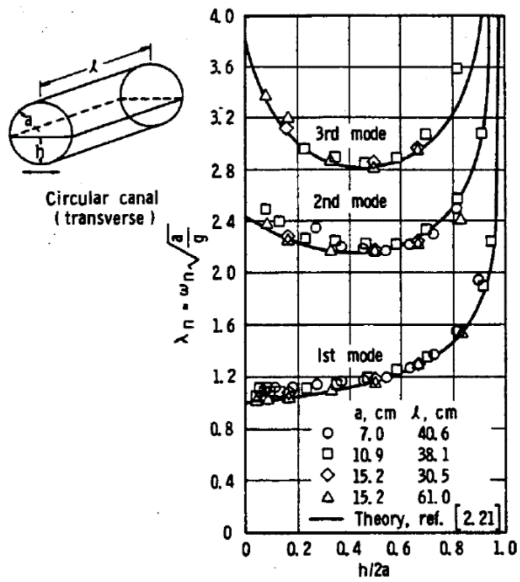

Figure 1: Source of frequency model, Abramson, H., and Silverman, S. (1966)

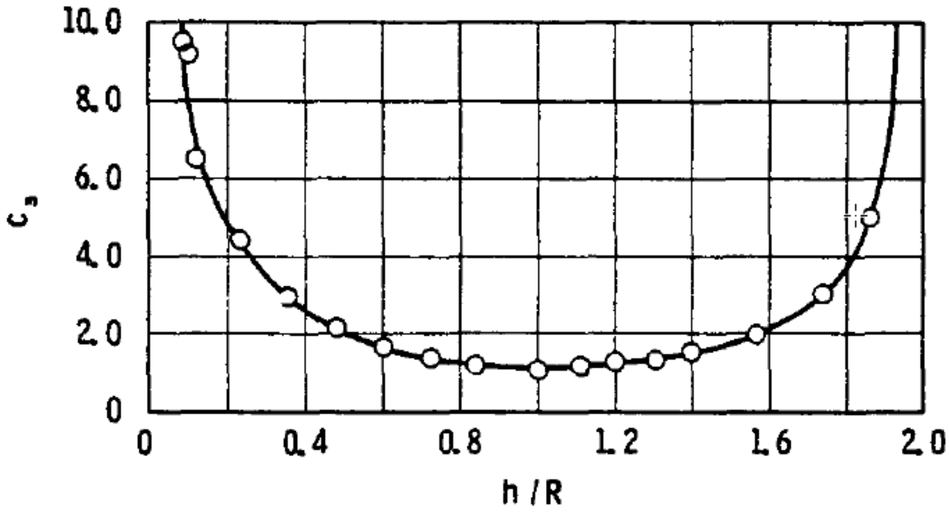

Figure 2: Viscous damping coefficeint of a spherical tank, Abramson, H., and Silverman, S. (1966)

The damping coefficient C_3 of the fluid was obtained from physical data of damping in a spherical tank. No physical data of fluid damping in a horizontal cylindrical shape resembling a tanker was found. The spherical tank was deemed to be the most suitable geometry available for empirical damping data. The damping coefficient C_3 was used together with the viscosity factor B from Equation 1 to calculate damping ratio δ_r using Equation 2. Both equations are sourced from Abramson, H., and Silverman, S. (1966).

$$\boldsymbol{B = \frac{10^4}{2\sqrt{2}} v R^{-3/2} g^{-1/2}} \qquad \textbf{(1)}$$

$v = kinematic\ viscosity\ (stokes)$
$R = fluid\ height\ (cm)$
$g = gravitational\ acceleration\ (ms^{-2})$

$$\boldsymbol{\delta_r = 0.08347 C_3 B^{1/2}} \qquad \textbf{(2)}$$

$C_3 = Viscous\ damping\ coefficient$
$B = Viscosity\ parameter$

Abramson, H., and Silverman, S. (1966) state that these equations are valid when the liquid dynamic behaviour is assumed to be linear and that the mechanisms which produce energy dissipation are thought to be known qualitatively, but only a few mechanisms have been described quantitatively. Additionally, viscous damping contributes to only one aspect of total damping. Other forms of damping such as turbulence, boundary layer friction, and interchange of energy between different sloshing modes have not been modelled in this simulation.

The pendulum slosh model does not consider fluid movement in the longitudinal direction as the PBS assessment rules currently to do require simulations of braking and acceleration (except for simple driveline tests). All high-speed stability standards are primarily designed to test for lateral stability and produce minimal longitudinal acceleration. There is the PBS directional stability under braking standard, however, simulation is very rarely used because the standard can be automatically satisfied by fitting the vehicle with compliant braking systems.

5. Vehicle and test specifications

The tanker truck and dog trailer used for simulations was based on a real combination used during a PBS assessment. However, it has been modified to remain as realistic as possible without disclosing or identifying the client's vehicle. The longitudinal dimensions (Figure 3) have been altered to allow for realistic full loading of diesel and petrol in compartments such that the combination reached HML axle loads listed in Table 1.

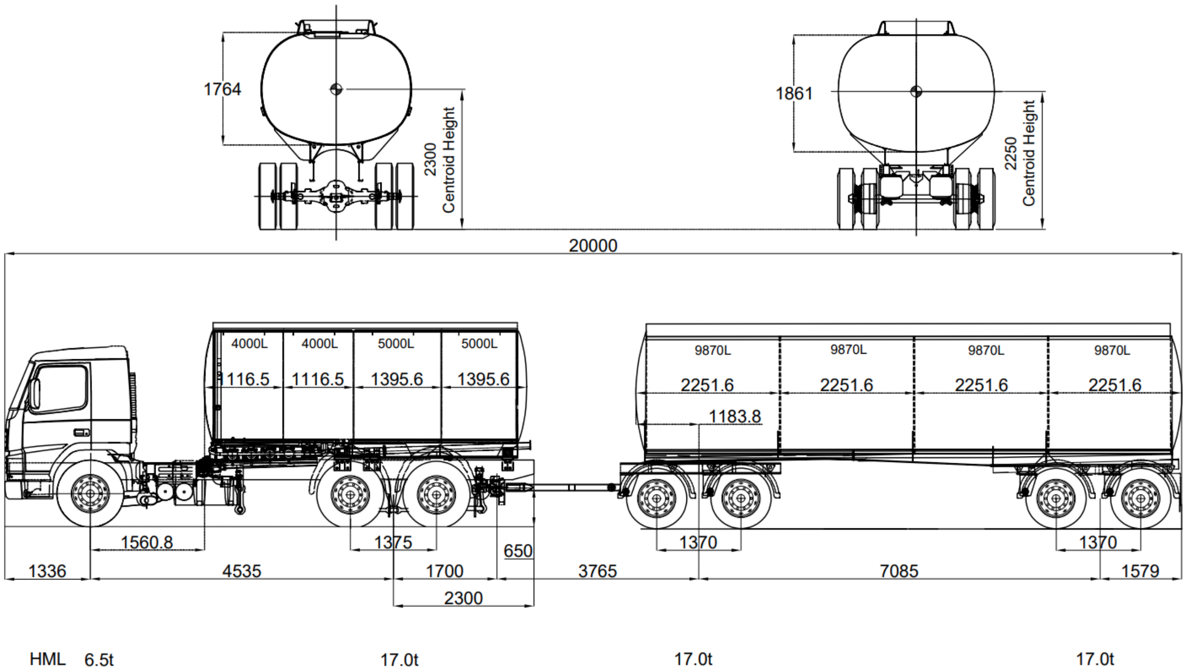

Figure 3: Dimensions of the subject vehicle

Table 1: Subject vehicle axle loads at HML (57.5t)

	Steer Axle	Drive Axle Group	Trailer Front Axle Group	Trailer Rear Axle Group
Tare mass (t)	5.24	6.04	4.33	2.87
Payload mass (t)	1.23	10.96	12.67	14.13
HML axle loads (t)	6.5	17.0	17.0	17.0

The simulated truck and trailer were fitted with average performing suspension and high performing tyres; 295/80R22.5 on the steer axles and 11R22.5 on the drive and trailer axles. The components were chosen based on their performance level to ensure a realistic representation whilst ensuring it passed PBS standards.

The standards investigated in this paper were limited to those relating to high speed stability and rollover resistance. The details of each standard and the relating test used are as follows:

- SRT – tested by the PBS circuit method.
- Rearward Amplification (RA) and High Speed Transient Offtracking (HSTO) – tested by the "Single Lane-Change", "Single Sine-Wave Lateral Acceleration Input", specified in ISO 14791:2000(E) (International Standards Organisation, 2000).
- Yaw Damping Coefficient (YDC). Only the yaw rate was investigated for simplicity and consistency between tests. Tested by the "Pulse Input", "Steer Impulse", method specified in ISO 14791:2000(E). (International Standards Organisation, 2000).

- Tracking Ability on a Straight Path (TASP), tested at 90 km/h using a road profile supplied by the NHVR.

6. Research approach

It is evident that numerous key parameters affect the pendulum movement and thus the dynamic and static performance of the heavy vehicle. As such, the paper is divided into five parts to investigate the impact fluid slosh has on vehicle performance under a PBS framework. A summary is provided in Table 2.

Table 2: Summary of tests performed

	Description
Part 1 A	Varying fill level with constant density (0-100%)
Part 1 B	Varying fill level with constant GCM and HML axle loads (70-100%)
Part 2	Comparison of four PBS compliant vehicles modelled with diesel, petrol and solid payloads, all complying to HML axle loads.
Part 3	Varying viscosity (1-100cst)
Part 4	Varying location of a partially loaded container. (C1-C8)
Part 5	Comparison of three methods used to model fluids for SRT

Part 1 was designed to assess the impact of varying fill levels on vehicle performance. The fill level was adjusted uniformly such that all compartments of the vehicle in one test case had the same fill level. Part 1 was divided into two sub-parts.

6.1 Part 1A

Part 1A investigates the performance of the vehicle when reducing the fill levels at increments of 10% beginning from 100% full (57.5t GCM) to 0% (unladen) while keeping density constant. This is representative of vehicles such as milk tankers which can be partially load and unload on their journey. Results were compared to values obtained in a similar study conducted by UMTRI (2001).

6.2 Part 1B

For Part 1B the fluid density was adjusted to maintain the GCM at 57.5t while fill levels were reduced in 10% increments ranging from 100% full to 70%. This is representative of situations where density and fill levels change but mass remains constant, which often occurs in fuel carrying vehicles. For example, it is common for a tanker to be used to transport petrol, diesel and/or other fuels while remaining loaded to maximum legal axle loads to maximize productivity. Petrol and diesel have quite different specific-gravity (SG) petrol has a SG of 0.73 and diesel has a SG of 0.84. Therefore, for a given mass, diesel will occupy less volume than petrol. Fill levels below 70% were not investigated in this study as the SG required to maintain HML at lower fill levels was deemed to be uncommon.

6.3 Part 2

In practice, it is uncommon for all compartments to be filled equally. Often this results in overloading on certain axle groups and underloading on others. To achieve a maximum payload mass, each axle group must be loaded to its maximum rating (HML). This is done by tuning the fill level of individual compartments to distribute the desired load onto the axle groups. Part 2 assesses four combinations that have been loaded in such a way; two containing diesel and two containing petrol. Within the two diesel and two petrol tests, Case 1 consists of maximum fill in the two outer compartments of each vehicle unit and partial fill for the two inner. Case 2 consists of maximum fill in the first and third compartments of each unit and partial fill in the remainder. The fill levels for all four cases are listed in Table 3.

Table 3: Fill levels of vehicles assessed in Part 2

Compartment Number		1	2	3	4	5	6	7	8
Fill Level %	Diesel case 1	94.25	75.65	59.63	95.40	97.00	64.55	64.72	97.00
	Diesel case 2	94.25	51.93	95.40	78.60	97.00	48.41	97.00	80.86
	Petrol case 1	94.25	93.77	88.97	95.40	97.00	88.90	89.08	97.00
	Petrol case 2	94.25	89.51	95.40	92.38	97.00	85.00	97.00	93.04

6.4 Part 3

In part 3 the influence on fluid viscosity was assessed. Viscosity governs damping and the motion of the pendulum and therefore was expected to have an impact on dynamic PBS tests. The exact viscosity of transported fluid can be difficult to obtain for assessment purposes. Furthermore, viscosity is influenced by temperature, impurities and other factors. Consequently, Part 3 was created to determine the sensitivity of fluid behaviour, and therefore vehicle performance, as a function of fluid viscosity. All tests performed in Part 3 used the Part 2 Diesel Case 2 combination, varying only the viscosity value of the fluid from 1 centistoke to 1 stoke.

6.5 Part 4

Part 4 consisted of one compartment loaded to 50%, with the remaining compartments loaded to maximum fill levels. Starting from the compartment at front of the truck (C1) the location of the partially loaded compartment was shift one position at a time until the rearmost compartment of the combination was reached (C8). For consistency, the volume of all the compartments in the truck were adjusted to be equal at 4500L. Cross sectional profile did not change, only the length of the compartment was adjusted to account for changes in volume.

6.6 Part 5

Part 5 compared three different methods that can be used to model fluids for a PBS SRT assessment. The solid body method models the fluid as a solid body by taking the mass and centre of gravity from the density, volume and compartment location. This offset was determined by rotating the free liquid surface by the sum of the body roll angle at the point of rollover, and the angle generated by the lateral acceleration during the SRT manoeuvre. The final method was the complete pendulum model.

6.7 Validation

The two critical areas for validation were identified and both were tested, these were fluid frequency and fluid damping. Vehicle models used for assessments have been accredited by the NHVR.

The validation tests were done using an extremely stiff suspension and tyres, extremely heavy tare mass and very low speed. This was done to remove any vehicle effects and focus only on the characteristics of the fluid. Essentially, the tests aimed to replicate a static test rig using a vehicle. An initial force was applied to the end of the pendulum to angle it in preparation for release, then the force was removed, allowing the pendulum to swing freely. Tests were conducted at 30%, 50% and 70% fill levels to validate a range of data points.

For the validation to be more robust it was conducted against a separate source than what was used to construct the model. For the frequency, this source was Yan et. Al. (2009). The results of the frequency validation study are shown in Table 4. As can be seen, the error between the two sets of data is minimal and this was deemed to be acceptable.

Table 4: Frequency validation results

Frequency (Hz)		
Physical Data[1]	Current Study	Error
0.813	0.875	7.6%
1	0.955	-4.5%
1.125	1.083	-3.7%

[1] Yan et al.. 2009

Investigations were conducted to find a source which reported experimental damping data (rather than CFD or numerical data) and tested for multiple fill levels with a shape and dimensions resembling a tanker vehicle. Unfortunately, a suitable second source to validate against was not found. Consequently, validation was done against the reference used to build the damping model (Abramson, H., and Silverman, S. 1966,). The results are shown in Table 5. As can be seen, the error between the two sets of data is minimal and this was deemed to be acceptable.

Table 5: Damping validation results

Damping ratio		
Physical Data[2]	Current Study	Error
0.0425	0.0441	3.8%
0.0207	0.0223	7.4%
0.0262	0.0286	9.5%

[2] Abramson, H., and Silverman, S. (1966)

7. Results and Discussion

The results of dynamic and static PBS tests have been plotted for each part of the study. Roll Coupled Unit 1 (RCU1) denotes the SRT value for the truck and Roll Coupled Unit 2 (RCU2) denotes the SRT value for the trailer. SRT was not determined in part 3 as viscosity has no effect on static tests.

7.1 Part 1A

As shown in Figure 4, SRT stability improves exponentially with decreasing fill levels due to a coupled relationship of both reduced fluid mass and height. Individually, these physical characteristics reduce the vertical cg of the fluid and the vehicle, thus improving stability.

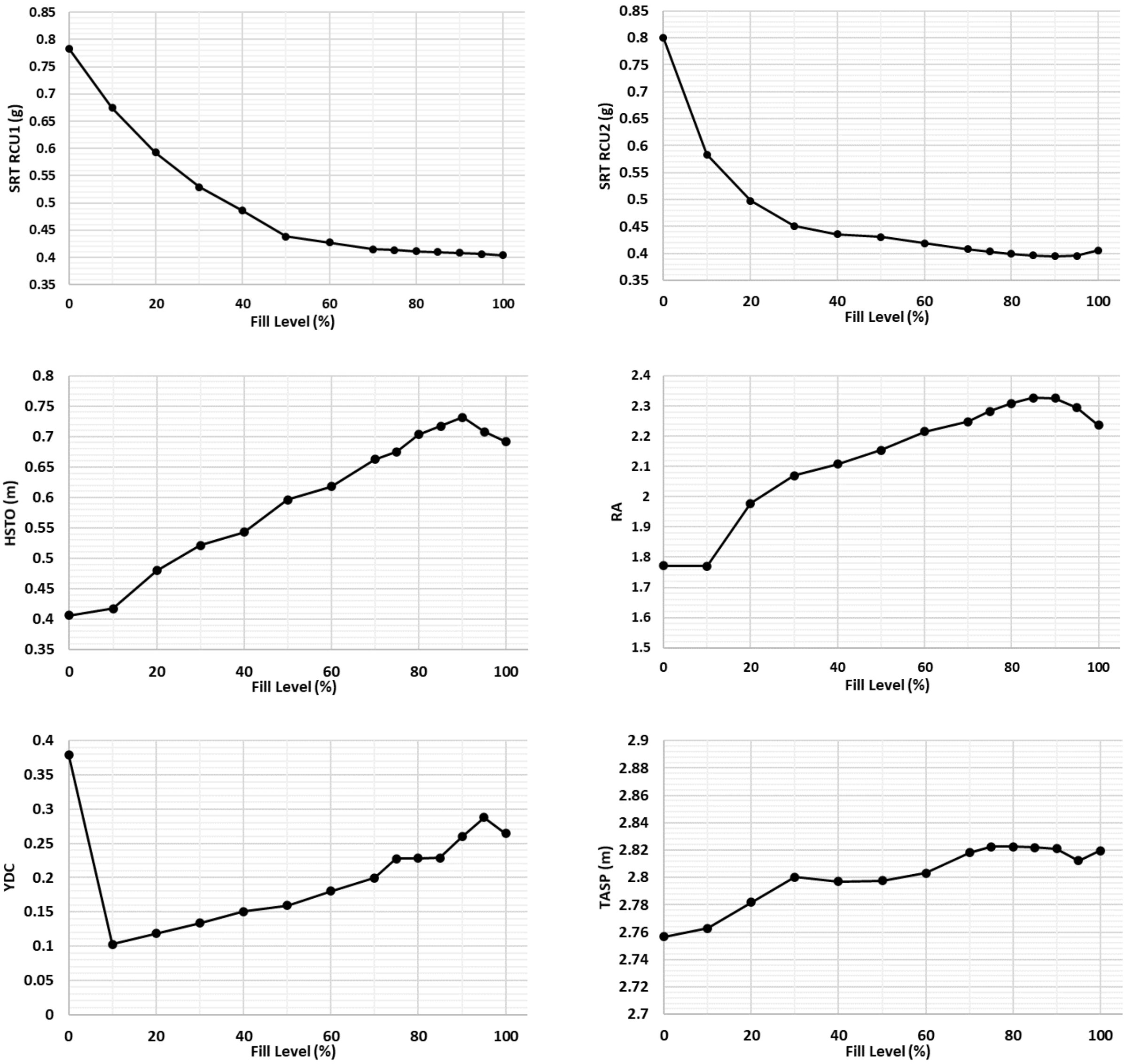

Figure 4: Results of PBS standards as a function of fill level with constant density

SRT results are in good agreement with the estimated SRT values by UMTRI (2001). The cross-sectional profile of a fuel tanker is a blended shape of rectangular and circular geometries as shown in Figure 5. This is reflected in the results as the trendline of both RCUs are located closely between, or in close proximity to the circular and rectangular profiles throughout all fill levels. Unlike, the rectangular profile in Figure 5, the stability of the vehicle did not worsen at reduced fill levels. It is hypothesized that the rounded floor of the container lessens fluid movement during turning, resulting in a reduced lateral centre of gravity offset and improved stability.

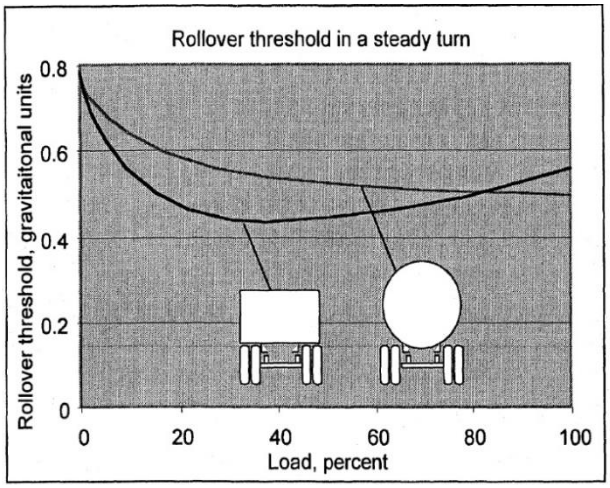

Figure 5: Effect of fluid movement on rollover threshold in a steady turn, (UMTRI, 2001)

RA and HSTO are generally improved with reduced fill levels. However, there is strong worsening of performance from 100% fill to 90%. At these fill levels, the model shifts away from a rigid body to a fluid model with pendulum movement and inertia is introduced into the model. Due to a proportionally small cross-sectional area at the top of the tanker, changes in fill level at small ullage leads to large shifts in fluid height, tanker fluid cg height, and therefore pendulum properties. For example, pendulum length of the trailer is almost doubled from 119 mm for 95% fill to 194 mm for 90%, resulting in greater fluid movement. Large fluid mass combined with pendulum movement at these fill levels causes a worst-case scenario for RA and HSTO. Therefore, the assumption of a 100% fill scenario for PBS assessments does not evaluate the vehicle at the most unstable loading condition.

YDC worsens with lower fill levels until the unladen case is reached and performance is greatly improved. Damping coefficients for the pendulum were directly sourced from Figure 2, so a similar trend in YDC was anticipated. The linear trend shown in Figure 4 was unexpected and is attributed to the increase of fluid movement with reduced fill levels. Greater fluid movement and inertial forces are likely to reduce dynamic stability of the vehicle during transient manoeuvres. This effect is shown to overcome counteracting influences of reduced fluid mass and increased damping (at lower fill levels) that would otherwise improve YDC. It should be noted that even at 10% fill the fluid mass in the trailer was 2680 kg which is comparable to the sprung tare mass of the trailer at 3248 kg, so the fluid mass is still a large percentage (45%) of the total trailer sprung mass.

Moreover, the empirical data shown in Figure 2 is only representative of fluid motion damping. The model employed in this study considers other aspects of damping such as tyre, suspension and vehicle effects that are likely to shift the trendline away from what is seen in an isolated experiment.

It is likely our result for YDC at the low fill levels is conservative because the model only considers viscous fluid damping and effects such as turbulence and flow separation were not modelled. These effects cannot be described by a pendulum model and will likely require a CFD model and/or field tests, which was outside the scope of this work. However, it would be interesting future work.

TASP is shown to marginally improve with decreasing fill levels. This was expected as TASP is mainly a straight-line manoeuvre, with some cross-fall and roughness, as such the fluid does not experience much lateral movement.

An over-arching finding is that there is no clear worst case fill level, which is worst for all standards. For example, SRT-RCU1 was worst at 100%, SRT around 85-95%, RA and HSTO around 90%, TASP around 75-100% and YDC at 10%.

7.2 Part 1B

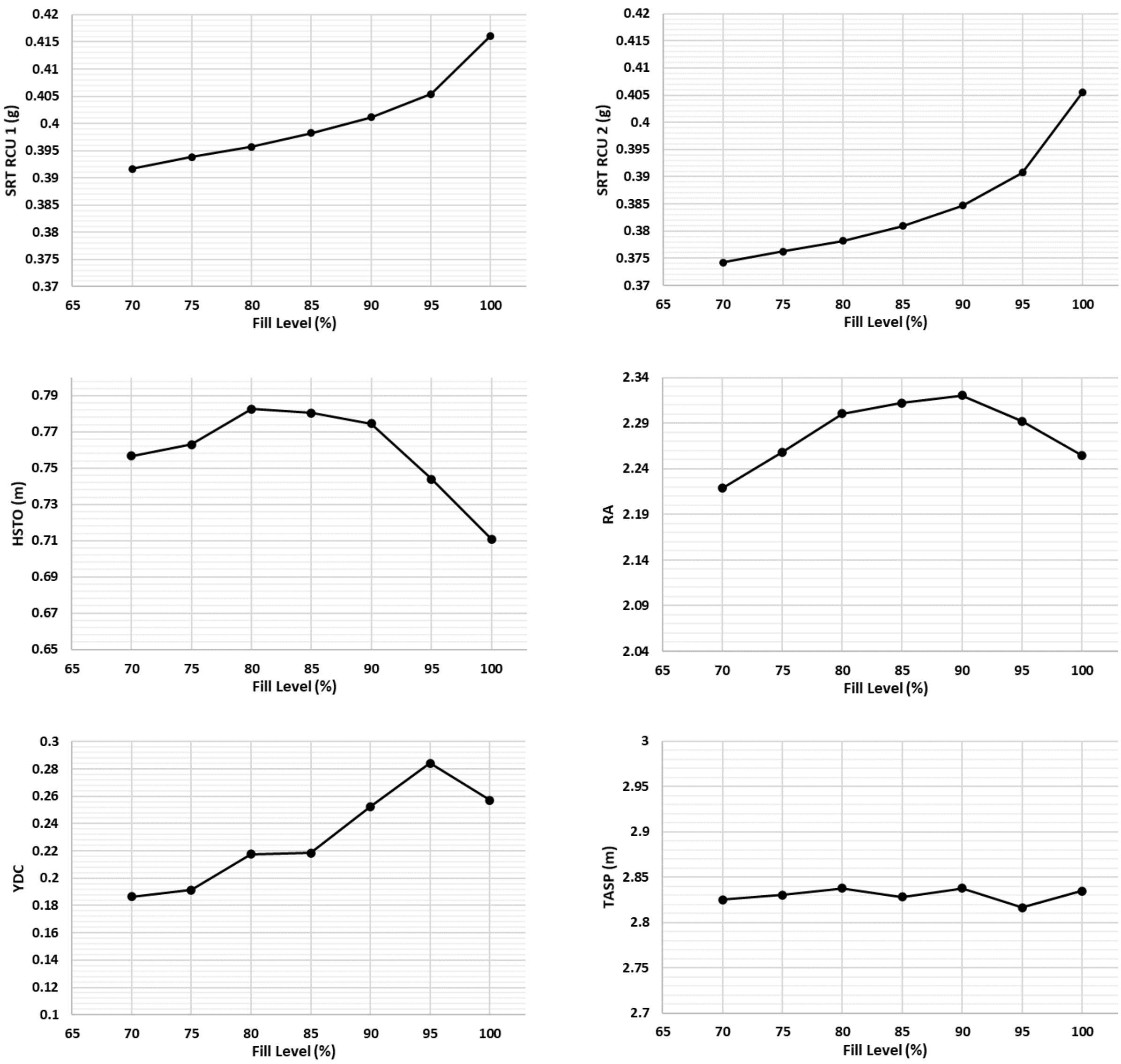

Figure 6: Results of PBS standards as a function of fill level with constant mass

In contrast to Part 1A, the SRT results for Part 1B show a reduction in stability with reduced fill level from 100% full to 70%. For the stability to be reducing with decreasing fill level, it indicates that the lateral displacement of cg has a greater effect on stability than the vertical reduction. Unlike Part 1A, the mass is not reduced in Part 1B. Therefore, the vertical cg of both units lowers at a much faster rate in Part 1A than in Part 1B. Additionally the higher mass in Part 1B causes higher deflection in compliant vehicle systems, such as tyres and suspension. Current PBS assessment requirements, modelling the SRT as a solid mass without lateral cg displacement, are too optimistic and would not capture the SRT results obtained in this test.

HSTO and RA show a similar trend to Part A, initially worsening from 100% to around the 90% mark before beginning to improve. However, HSTO reaches a worse value than Part 1A at maximum by around 50 mm. In the context of PBS this is not negligible and on tipper vehicles for example it would mean a several hundred millimetres difference in load height and/or the removal of multiple tyre options, to counteract poorer HSTO. The results for RA were similar between the two methods.

Within the test range, YDC worsens with reduced fill as in Part 1A with similar performance between the two methods. Due to the limited test range, the mass difference between Part 1A and 1B remained relatively close. Additionally, considering the dynamic nature of the test it can be concluded that fill level enabling a greater sloshing influence has a greater impact on damping than mass reduction.

TASP also remains relatively constant and is slightly worse than in Part 1A, but the difference is negligible. The slightly worse result can be attributed to the higher mass and higher cg.

Again, there is no clear worst case fill level, which is worst for all standards. SRT was worst at 70%, HSTO at 80%, RA at 90% and YDC at 70% (TASP showed negligible difference).

No comparison was done in Part 1 against the PBS requirements, the main aim of Part 1 was to obtain trends in the data and to compare the results of the reduce mass method (Part 1A) vs constant mass method (Part 1B).

7.3 Part 2

The four models in Part 2 were designed to resemble existing truck and dog combinations and comply with PBS permitted HML masses and axle loading conditions, including the ullage requirements in the codes of practice for dangerous goods vehicles. Table 6 shows the results for each model alongside the PBS limits for the chosen combination and demonstrates that vehicle performance is strongly dictated by payload type. The most influential factor differing the results of diesel and petrol tests is density, which leads to a variance in fill levels as shown in Table 3. As discussed in Part 1, a lower fill level results in a reduction in overall vertical cg but a greater lateral cg offset during roll.

Table 6: Comparison of PBS results between the solid body and pendulum models

Model	TASP (m)		SRT (g)				HSTO (m)		RA		YDC	
	Result	L2 limit	Result-RCU1	Result-RCU2	Min (DG)	Min (non-DG)	Result	L2 limit	Result	Limit	Result	Min
Diesel Case 1	2.827	≤3.0	0.399	0.386	-	≥ 0.35	0.719	≤0.8	2.153	2.19	0.192	≥0.15
Diesel Case 2	2.816	≤3.0	0.397	0.386	-	≥ 0.35	0.726	≤0.8	2.131	2.20	0.208	≥0.15
Petrol Case 1	2.827	≤3.0	0.404	0.390	≥ 0.40	-	0.752	≤0.8	2.298	2.22	0.270	≥0.15
Petrol Case 2	2.823	≤3.0	0.404	0.391	≥ 0.40	-	0.754	≤0.8	2.300	2.22	0.263	≥0.15
Solid	2.835	≤3.0	0.415	0.405	≥ 0.40	≥ 0.35	0.711	≤0.8	2.264	2.30	0.247	≥0.15

** Shaded cells indicate a fail against PBS requirements.*

It is difficult to assess which of the two fluid types performs better overall. Diesel appears to perform better in TASP, HSTO and RA while petrol displays better results in SRT and YDC. Due to the lower density of petrol resulting in higher fill levels in partially filled compartments, the fluid movement is restricted and results in improved YDC values. Similarly, SRT for petrol cases is improved due to less lateral offset of the fluid cg as the vehicle rolls. Diesel cases perform better in TASP simulations because the cg height is lowered, and the combination does not experience high lateral acceleration which would otherwise produce large lateral offsets. The reason for better performance in HSTO and RA for the diesel cases is unclear. Potentially, the reduction in overall cg height due to lower fill levels overcomes limitations incurred by more fluid movement, improving dynamic stability of the vehicle. Additionally, due to the HML loading conditions and higher density of diesel, there is a smaller sloshing mass in the partially loaded compartments for the two diesel cases. However, it is not possible to state that this phenomenon will be consistent across tanker combinations with varying dimensions.

Both Petrol Case 1 and Petrol Case 2 do not comply with the minimum SRT requirement for dangerous goods (DG), despite meeting the ullage requirements in the codes of practice for dangerous goods vehicles. Additionally, RA values for the two cases exceed the PBS limit of ‘no more than 5.7x SRT of the rear RCU’. These results would not be captured if the combination were modelled with a solid payload as shown in Table 6.

Whilst HSTO did not fail, the results were up to 40 mm worse for the pendulum model vehicles. If the overall HSTO performance of all models was slightly worse, the pendulum models would have failed, and the solid body model would still have passed.

The complex nature of vehicle dynamics, when coupled with fluid dynamics, produces an array of physical characteristics that govern the mechanics and behaviour of the vehicle. It is not possible and valid to accurately predict the performance of a combination without considering all physical aspects including fluid slosh. This is further exemplified within the findings of the literature review discussing the different methods for simulating fluid slosh which found that at least the mechanical analogy method is required to simulate dynamic effects. For static tests such as SRT, a quasi-static (cg offset) method is valid and reliable (see part 5). However, for dynamic tests such as HSTO, RA and YDC, a static cg offset model is not able to simulate the transient effects created by fluid slosh on the system such as frequency and damping.

Fluid slosh is not currently addressed sufficiently within the current PBS assessment rules that simply state that load cg height and lateral offset are the major parameters to consider for SRT standards and are also a high-priority parameter for HSTO and RA. The rules do not explicitly state that fluid slosh needs to be modelled and assessed. Therefore, assessors are given the opportunity to disregard fluid slosh in simulations. Time and financial pressures are likely to discourage assessors from incorporating a fluid slosh model if they have not already done so. Furthermore, as shown in Table 6, integration of fluid slosh into simulations may lead to a worsening of assessed vehicle performance. Ultimately, resulting in further load restrictions and/or less flexibility in the vehicle design for the customer. Without regulation by the NHVR, it is likely that this issue will persist, allowing vehicles to be passed that would otherwise fail to meet PBS safety requirements if tested in accordance with the intent of the rules.

7.4 Part 3

As expected, all dynamic tests showed a better performance at higher viscosity. The results in Figure 7 show that results did not vary significantly when compared to adjustments such as variations in mass and fill level. Only changes in order magnitude will amount to noticeable differences in vehicle performance. Additionally, due to the consistency in trends, the assessor can also be confident that the lowest viscosity would produce the worst-case results.

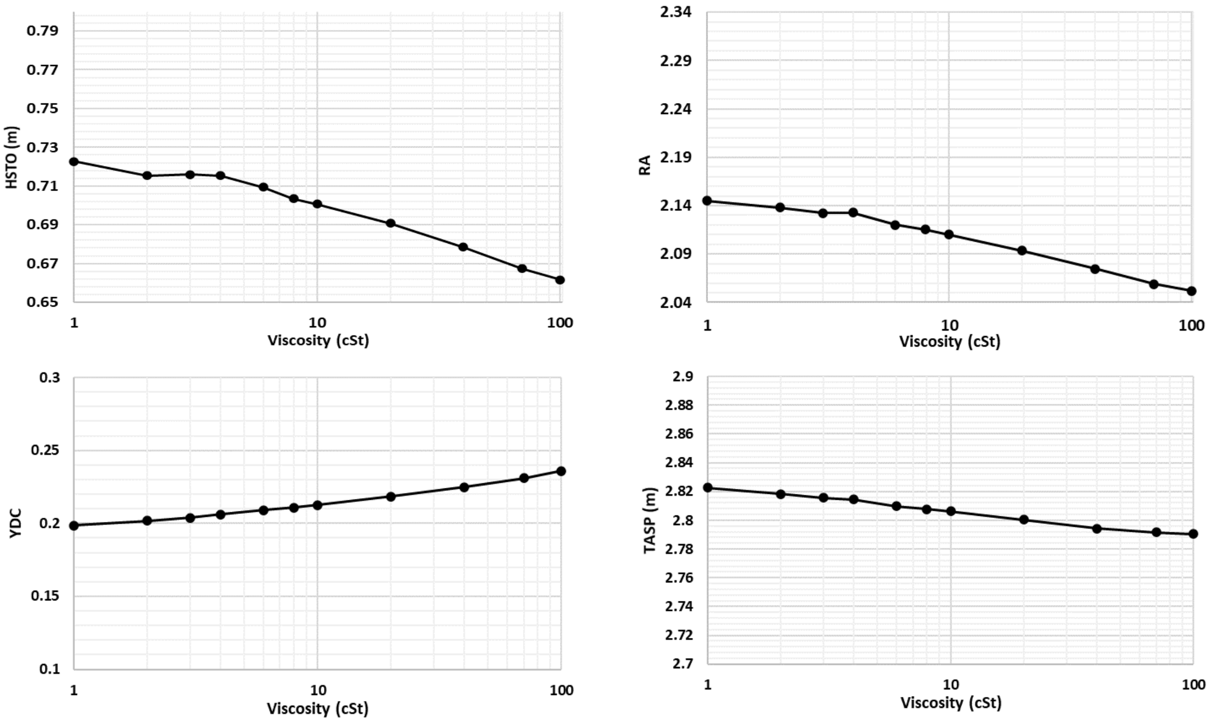

Figure 7: Results of PBS dynamic standards as a function of fluid viscosity

7.5 Part 4

Based on the results in Figure 8, there is no clear evidence to suggest that a particular location of a partially loaded compartment will lead to an idealised worst-case scenario for all manoeuvres. However, the following trends were observed:

- TASP: For the truck, shifting the partially loaded compartment to the rear improves stability. This contrasts to the trailer, where rearward migration of the partially loaded compartment worsens stability.
- RA, HSTO: Rearward migration of the partially loaded compartment improves stability. However, results regarding the trailer are inconclusive.
- YDC: Rearward migration of the partially loaded compartment worsens stability. Conversely, rearward migration on the trailer improved stability.
- For SRT the position of the partially loaded compartment makes negligible difference on the truck but on the trailer SRT gets worse as the partially loaded compartment is moved to the rear. The latter is possible due to the compliance of the ballrace coupling, causing the front of the trailer to roll more than the rear, assuming both have identical axle loads. This difference in the roll angle would increase as more mass is put on the front axle group due to the partially laden compartment being moved to the rear.

The findings do not give a clear conclusion regarding the optimal location of partially filled compartments that lead to best vehicle performance. The ideal compartment location depends on both the unit of the vehicle and manoeuvre being assessed. Therefore

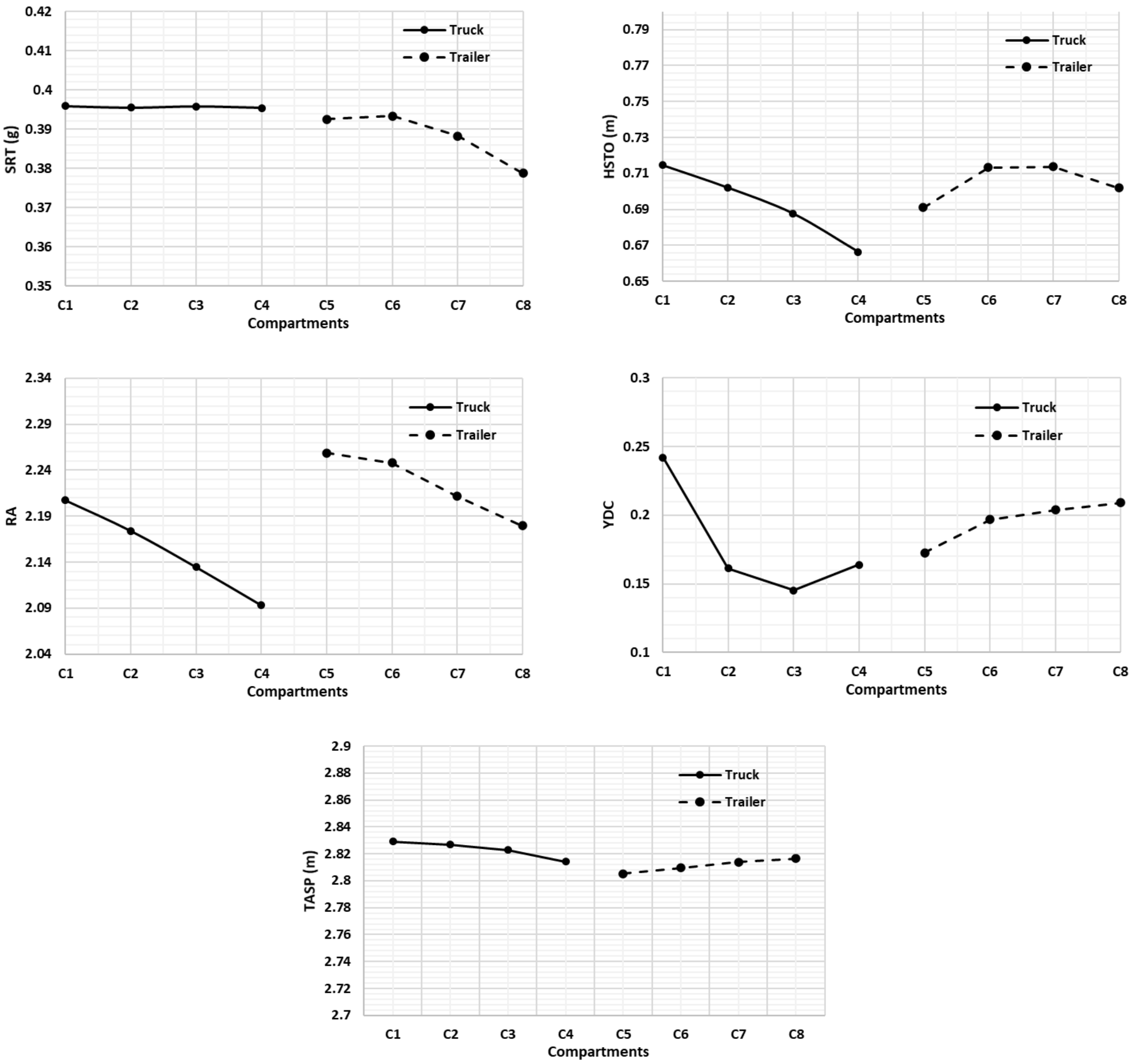

Figure 8: Results of PBS standards as a function of partially loaded compartment location

7.6 Part 5

Figure 9 shows the truck and dog combination at HML mass undergoing an SRT test and the different results obtained from modelling it as a solid mass, using load offset and with a pendulum method. The static cg offset and pendulum methods produced reasonably similar results and both display a far worse vehicle performance than using a solid mass model. The pendulum produces slightly worse SRT results, and it is expected to be the most accurate. However, if an assessor does not have access to a mechanical analogy model (pendulum or mass-spring-damper) then a static cg offset model provides a reasonable estimate.

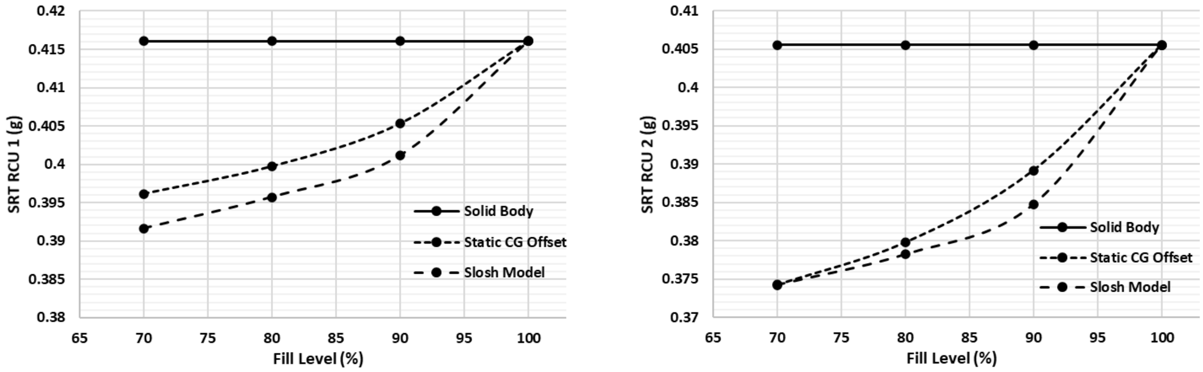

Figure 9: Comparison of PBS SRT results using various models

8. Conclusions

There have been numerous studies conducted to analyse and predict the slosh motion of fluids in containers. However, little research has been done to analyse the impact of slosh on vehicle dynamics within a PBS framework. Some of the common methods used to model slosh include quasi-static, mechanical analogy and CFD simulations. For this study, a pendulum - mechanical analogy model was used as the primary method to model fluid slosh enabling a reliable and accurate way to test both static and dynamic manoeuvres.

Fluid viscosity was shown to have minimal effect on the dynamics standards however viscosity estimates within an order of magnitude should produce reasonable results. There was no clear worst-case compartment to partially fill, as it depends on manoeuvre and the vehicle unit. A load offset method was considered and found to be reasonable for the static SRT tests.

A lateral and/or vertical cg offset method was not assessed for the PBS dynamic manoeuvres because this was found from the literature review to not be suitable for simulating dynamic manoeuvres. The review indicated that static method does not accurately predict the behaviour of slosh in dynamic manoeuvres such as a lane-change. Additionally, a static model fails to address fluid damping incurred by slosh movement and therefore cannot accurately predict performance in YDC. In theory, it is possible to determine a conservate offset that is large enough to cover all reasonable fill levels, tank shapes and vehicle specifications. Alternatively, a vertical cg offset could be incorporated to address the asymmetry of lateral loading which may lead to invalid results in dynamic tests. It is likely, that these two approaches will be extensive to determine, conservative in nature and will limit the vehicle capacity more than if a mechanical analogy or CFD method were employed. However, future work could be done to explore the suitability of these modelling approaches within a PBS framework.

Slosh was shown to have the greatest effect on YDC, HSTO, RA and SRT standards. Assuming a solid load led to the performance in these standards being under-estimated. When the same vehicle combination was assessed by more realistic models (such as a pendulum model) the vehicle was shown to perform worse in YDC and HSTO and even fail RA and SRT. Considering the subject vehicle used realistic specifications, it is likely that other PBS approved tanker vehicles will exhibit similar outcomes.

Currently, modelling of slosh is not a requirement of PBS assessments submitted to the NHVR. When left to the discretion of each individual assessor, inconsistencies are likely to occur, both within simulated vehicle performance, and ultimately the PBS scheme itself.

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