Stability Analysis of Liquid Tank Vehicle

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ABSTRACT

Dynamics associated with the bulk transportation of liquids is unique in that the dynamic interactions of the liquid with the moving vehicle significantly affects the stability and controllability of the tank vehicle. The influence of liquid motion within the tank, on the static stability behaviour of the vehicle, is investigated. The vertical and lateral shift of center of mass of the liquid is established as a function of tank tilt and centrifugal forces encountered during a steady turning manoeuvre. A static roll model of a tank vehicle employing partially loaded circular tank is developed to incorporate forces and moments arising from vehicular components as well as from the liquid cargo. The lateral shift of center of mass as a function of the tank shape and the influence of compartmenting the tank is also discussed.

INTRODUCTION

For reasons of economy, the trucking industry in Canada has indicated a continuing interest in increasing the vehicle size and load carrying capacity. A number of studies carried out for the trucking industry as well as the policy makers have established that changes in size and weight of heavy vehicles can cause significant variations in handling and control characteristics of the heavy vehicles. The rollover immunity levels of conventional highway articulated vehicles are well known to be so low that a moderately severe manoeuvre often leads to significant magnitude of lateral and roll instabilities of the vehicle. A vast majority of the studies on dynamics of heavy vehicles focus on stability and handling of heavy vehicles with rigid loads (1,2,3,4). Rigid loads, in general, are fastened to the trailer structure, thus the interactions due to the load are considered insignificant. However, in case of tank-vehicles, used for the transport of liquid loads, the dynamic interactions of the liquid cargo cannot be ignored. The roll stability characteristics of heavy vehicles with liquid loads is known to be significantly lower than that of other highway vehicles. The roll-over immunity and stability of the tank-vehicles is further deteriorated due to the interactions of the liquid cargo. The liquid slosh within the tank coupled with dynamics of articulated vehicles can lead to longitudinal and lateral instabilities, decreased controllability/manoeuvrability, and increased stresses on the container structure (5). Thus a greater safety consideration should be given to the operation of highway tank-vehicles, specifically due to the dangerous nature of the liquid loads.

Road accidents involving tank-vehicles pose unreasonable risks to health and safety or property in Commerce. A survey of the reportable incidents involving transportation of dangerous liquids reveals that 76% of the dangerous occurrences in Canada, during 1981-1983, are attributed to road mode of transportation and 45% of these occurrences resulted in overturning of the tank-vehicle. A number of single vehicle accidents reviewed revealed that 72% of the accidents occurred while negotiating a curve (7). This may be attributed to severe liquid surge associated with simultaneous turning and braking of the vehicle.

Dangerous occurrences of the tank-vehicle can be attributed to a number of casual factors, such as human factors, mechanical failure, lateral surge of the fluid, fluid-vehicle interactions, etc.. A number of investigations carried out in the past focus either on the dynamics of highway vehicles with liquid cargo being treated as rigid cargo (8) or only on the liquid slosh behaviour within the container (5). However, a complete understanding of the destabilizing effects of liquid in a tank-vehicle, requires a comprehensive interface between the heavy vehicle dynamics and liquid slosh phenomenon. While a comprehensive vehicle-fluid dynamic model may be of a highly complex nature, the rollover immunity levels of tank-vehicle can be established by interfacing steady-state fluid

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dynamics with the static roll model of the heavy vehicle. In this paper, static roll model of a tank-vehicle incorporating steady-state behaviour of the fluid within the tank is developed to establish the static rollover characteristics of the tank-vehicle.

EFFECTS OF LIQUID MOTION

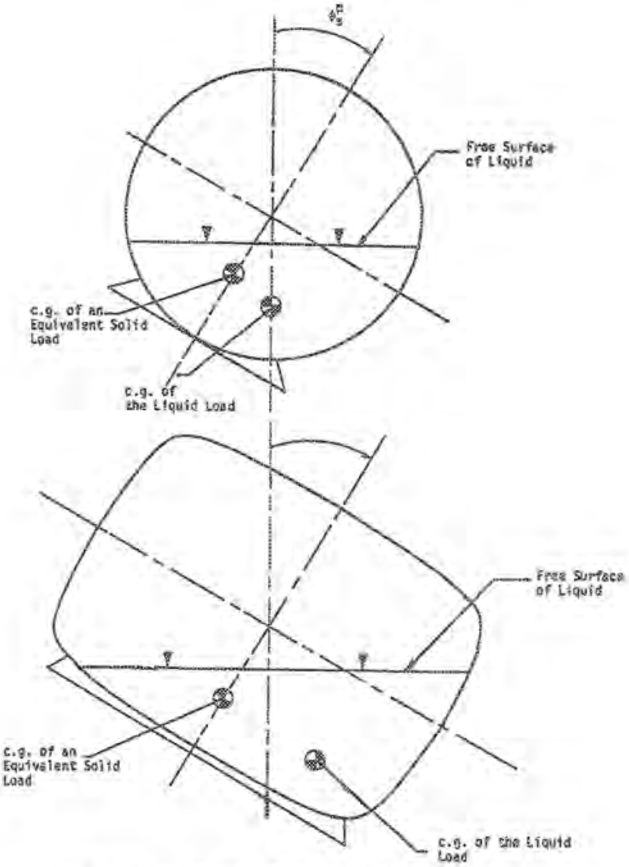
Safe transportation of bulk liquids in a highway tank-vehicle deals with factors other than normal trucking practices. Liquid tankers are considerably different from regular dry freight units in that the cargo hauled is not packaged before loading. Thus the liquid motion within the tank may cause excessive yaw, roll, pitch, longitudinal and lateral motions of the vehicle. Certain vehicle manoeuvres coupled with liquid slosh can lead to vehicle instabilities, and complexities in vehicle handling that are caused by fluid-structure interactions. The liquid slosh phenomenon together with dynamic characteristics of the vehicle can lead to poor tank-vehicle performance during braking and cornering manoeuvres. The sources of vehicle instabilities/rollover can be mainly attributed to: motion of the free surface of liquid; vehicle and liquid motion due to road roughness, cornering and due to wheel slip during braking.

In order to enhance the rollover immunity of tank-vehicles, it is essential to establish an understanding of the fluid motion during turning manoeuvres and the vehicle rollover process. During the turning manoeuvre, a conventional highway vehicle is subject to lateral tire forces which promote vehicle rollover. However, in the case of liquid tank vehicle, the center of mass of the liquid cargo experiences a lateral shift due to the roll of vehicle spring mass. The lateral shift of the center of mass is a function of the liquid fill level, tank geometry and tank roll angle. The lateral shift of center of mass of the fluid due to tank roll angle is shown in Figure 1. Figure 2 shows the lateral shift of center of mass quantitatively as a function of tank roll angle and liquid fill levels, from 2.03m (80 inches) diameter cylindrical tank, when lateral acceleration ay = 0. The vehicle is normally subject to a lateral acceleration during a turning manoeuvre. The lateral acceleration experienced by the tank structure imposes an equal and opposite acceleration on the fluid mass. For low speeds, under steady-state condition, the entire fluid bulk can be assumed to move as a rigid body. The centrifugal action due to the lateral acceleration causes a further shift in the center of mass of the load as shown in Figure 3. Assuming negligible viscous effect, and for small angle, the gradient of the free-surface of the fluid can be established from the following:

$$\theta = \frac{a_u + \phi_s}{1 - a_y\phi_s} \tag{1}$$

where ay is the lateral acceleration in g's, ϕ's is the tank roll angle and θ is the gradient of the free-surface of liquid measured in radians.

The gradient of free-surface and hence the lateral shift of the liquid mass is highly a function of the lateral acceleration and liquid fill level. Figure 4 shows the change in gradient of the free surface corresponding to change in lateral acceleration for various tank roll angles. The corresponding lateral and vertical shift in the center of mass of the liquid load are presented in Figures 5 and 6, respectively. It can be seen that partially loaded tanks with fill levels below 50% of the diameter can lead to a significant shift in lateral and vertical shift in



Translation of the center of mass of liquid loads in cylindrical and modified oval tanks

FIGURE 1

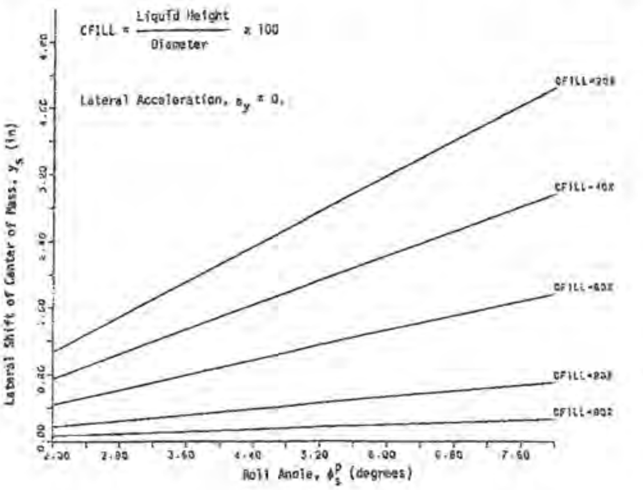
center of mass of the liquid. Thus a significant roll moment due to the liquid load is caused.

Although the trucking industry associated with transport of liquids makes all possible attempts to operate their vehicles with full loads only, the vehicle operation with partial loads is often encountered. Specifically, the steel tanks used for the transportation of various types of chemicals often carry partial loads due to variations in fluid density and to meet provincial limitations on the axle loads. The majority of these tanks are of cleanbore cylindrical cross-sectional design to facilitate cleaning, while the tanks used to transport gasoline are often compartmented, as shown in Figure 7. Certain compartments of such vehicles are often partially loaded during the local distribution of gasoline. Thus, the lateral surge behaviour due to lateral shift of the fluid mass is a significant contributory factor in determining the forces and rollover moment experienced by the tank-vehicle during a turning manoeuvre.

HEAVY VEHICLE STABILITY DURING STEADY TURNING

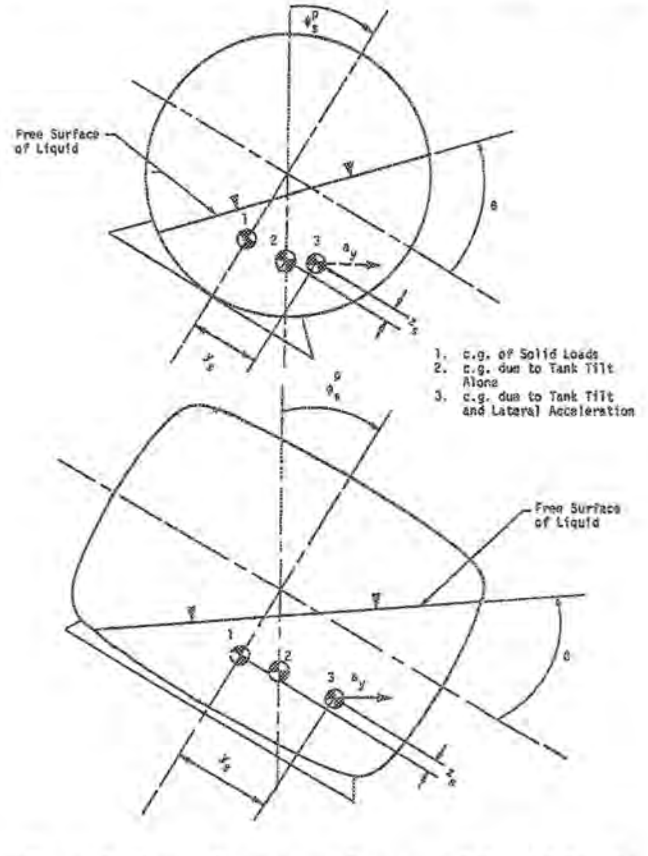
Heavy trucks, in general, begin to exhibit unstable behavior at lateral acceleration levels 0.3 - 0.4g (9). The likelihood that a certain vehicle manoeuvre can lead to the vehicle rollover is strongly correlated to the rollover threshold of the vehicle in steady turning. A vast number of studies have been carried out to establish the rollover threshold of heavy vehicles. Isermann (10) carried out an extensive study on the rollover threshold of heavy vehicles, and developed a roll-plane analytical model to compute vehicle rollover threshold.

The rollover threshold of heavy vehicles is strongly related to vehicle geometry, suspension properties, and tire properties (11). The static rollover threshold of a rigid heavy vehicle (no suspension and tire deflection) can be estimated as the ratio of half of the effective track width to the trailer center of gravity height. The rollover threshold of such rigid vehicles is of the order of 0.6g (12). Introduction of compliant tires can lower the threshold value to approximately 0.5g. The rollover threshold value is further decreased to approximately 0.44g due to compliant tires and springs. Spring lash can lead to even lower valve (approximately 0.34g) of vehicle rollover threshold (12). Interactions due to fluid in a partially loaded tank vehicle can further reduce the rollover threshold value thus increasing the likelihood of tank vehicle rollover due to either manoeuvring or accident-induced forces. A typical tank-vehicle



Lateral shift of center of mass of liquid loads due to tank roll angle

FIGURE 2



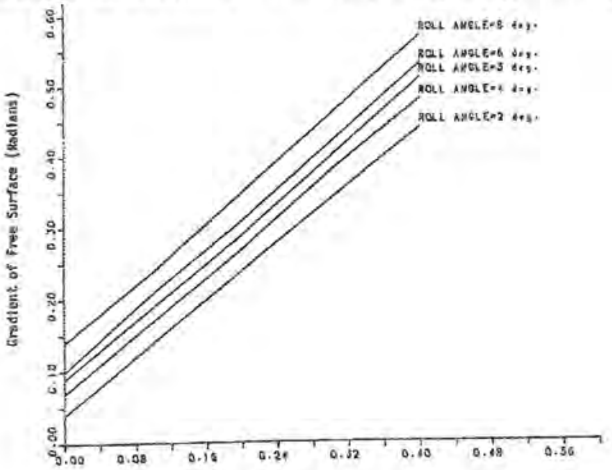
Translation of center of mass of liquid loads in cylindrical and modified oval tanks, due to tank tilt and lateral acceleration

FIGURE 3

with 50% loaded elliptical tank can rollover at lateral acceleration levels well below 0.2g during a lane change manoeuvre (12). Although a partial load in a tank provides low sprung mass center of gravity height and thus an improved value of rollover threshold value, when the load is considered to be rigid. However, the threshold value of the partially loaded tank vehicles is rather deteriorated due to the lateral surge of the liquid. A number of tests conducted on a cleanbore tank negotiating 40 m radius curve, by Fruehauf showed an increase in lateral forces for partial loads (13).

STEADY TURNING/STATIC ROLL MODEL OF TANK VEHICLES

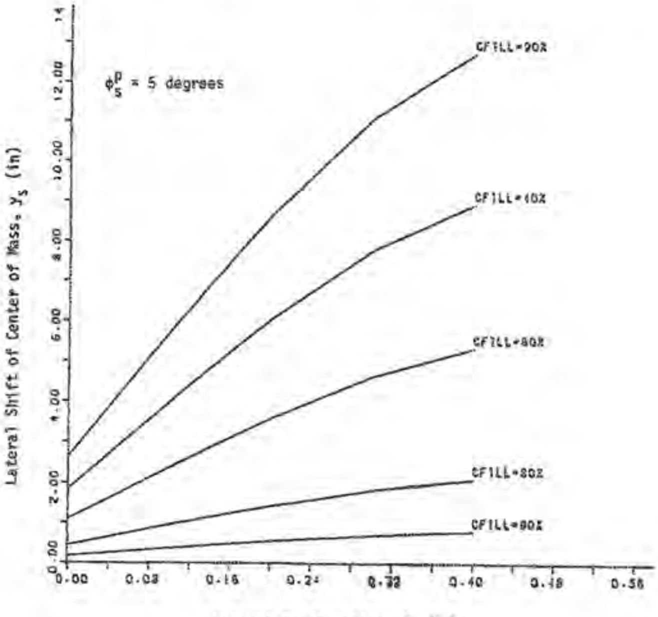
Tank vehicles with multiple axle suspensions are often approximated by grouping the axles with similar suspension properties such that the multiple axles are reduced to three composite axles. The lumped composite axles represent tractor front axle, a single tractor rear axle, and a single semitrailer axle (3,4). While the modeling of tractor tandem axle to a single composite axle may be quite reasonable, the single axle representation of wide spread tri- and quad- axle semitrailers may lead to significant modeling errors. However, the simplified model with a composite semitrailer axle can provide significant insight pertaining to the interactions of liquid motion during the steady turning manoeuvres. The spring weight of the tractor is modeled as two sprung weights supported by the front and rear composite axles, as shown in Figure 7. The two sprung weights are coupled through the torsional flexibility of the tractor frame.



Gradient of free surface of liquid due to lateral acceleration, for various tank tilt angles
FIGURE 4

The tank-trailer weight is modeled as five sprung weights; weight due to the tank and trailer structure Wtk and weights due to liquid in each of the four compartments W_{l1}, W_{l2}, $W_{l3}$and W_{l4}, as shown in Figure 7. The sprung weights due to the tank-trailer are coupled to the tractor sprung weight through a torsional element. The torsional element represents the compliance due to the tank structure and the fifth wheel coupling. The roll plane representation of the tank-trailer is shown in Figure 8. The center of mass due to tank and trailer structure is located at p, while the floating center of mass due to the liquid weight is located at p'. The coordinates of p' with reference to the body fixed point p (y_s and z_s) represent the vertical and lateral shift of liquid weight under the actions of the sprung weight roll and centrifugal forces.

The suspension springs are assumed to translate along the vertical direction only, parallel to the ku axes of the unsprung weights, while the relative motion of the sprung weights with respect to the axles is assumed to occur at the roll centers, which are located at fixed distances beneath the sprung weights. The nonlinearities arising from suspen-



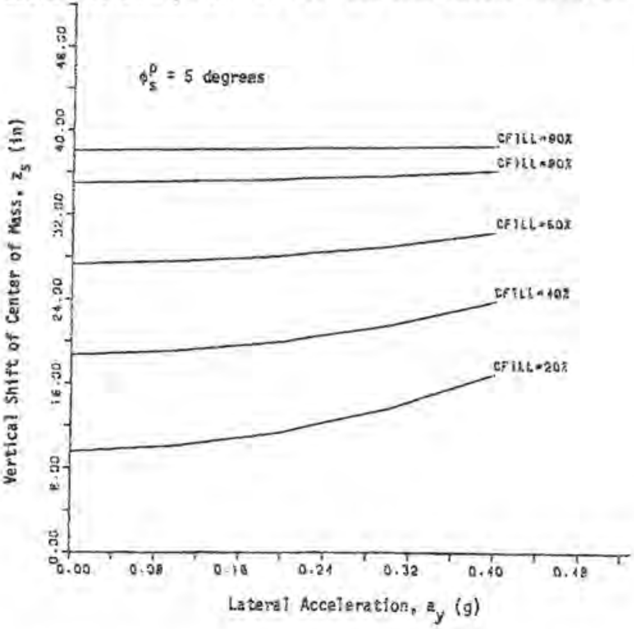
Lateral shift of center of mass due to tank tilt (ϕ p/s = 5°) and lateral acceleration
FIGURE 5

sions, fifth wheel coupling and torsional compliance of the tractor frame are incorporated in the simulation model. The lateral translation of the tires and the lateral forces due to the camber angle are also modeled as described in reference (14).

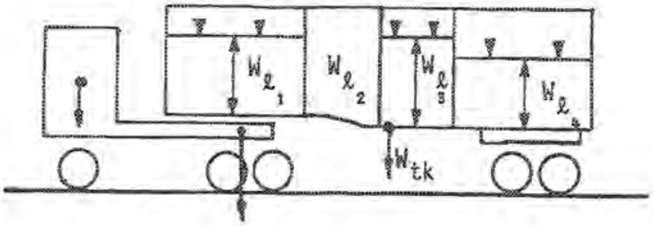
The static roll equilibrium of the tank vehicle is defined by balancing the rolling moments acting on the sprung and unsprung weights, the vertical forces acting on the suspensions and tires, and the lateral forces acting on the tires. The above force and moment balance leads to 15 equilibrium equations. An additional eight equations are derived to compute the vertical and lateral shift of liquid center of mass within the four compartments of the tank, thus leading to a total of 23 equations. The roll equilibrium equations are written in the matrix form as:

$$[A]\,\{\Delta x\} = \{B\}\,\Delta\,\phi\,p/s \tag{3}$$

where the matrix [A] is a (23 x 23) coefficient matrix and {B} is (23 x 1) vector. Vector {Δx} defines the change in vehicle response parameters such as lateral acceleration (a_y), roll angles of the sprung weights, roll angles of the unsprung weights, translation of the roll centers with respect to the unsprung weight center of mass, tire vertical and lateral deflections, and center of mass of the liquid, caused by varying the roll angle of the sprung weight of the tank and trailer structure (Δ φ p/s). Equation (3) is solved to compute the variations in vehicle response parameters due to a change in the roll angle of the tank-trailer weight. The response parameters and thus the coefficient matrices [A] and {B} are updated for every increment in Δ φ p/s . The rollover threshold of the vehicle is the value of lateral acceleration, a_y at which the tires on the tank-trailer composite axle as well as on the tractor rear composite axle are lifted off the road.



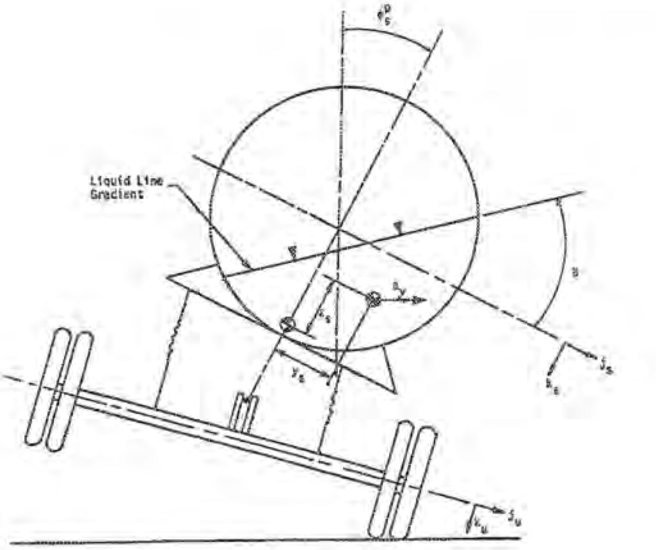
Vertical translation of center of mass of liquid due to constant tank tilt (φ p/s = 5°) and varying lateral acceleration
FIGURE 6



Schematic of a four compartment cylindrical tank vehicle
FIGURE 7

RESULTS AND DISCUSSIONS

Equation (3) is solved to establish the rollover threshold acceleration levels of a triaxle tank



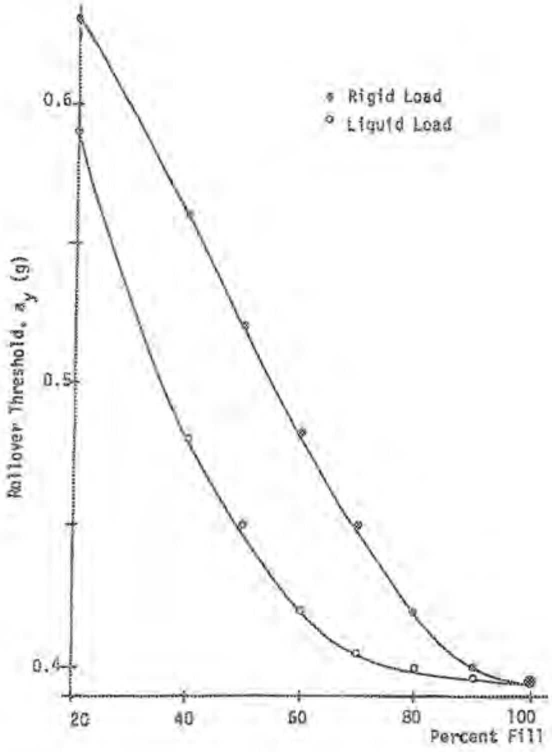
Roll plane model of the tank vehicle
FIGURE 8

Table 1 — Parameters/specifications of the simulation vehicle (15, 16)

Tractor	
Type	Three axle
Sprung weight	5,335 kg (11,740 lb)
Unsprung weight	
Front axle	955 kg (2,100 lb)
Rear axle	2,270 kg (5,000 lb)
Front axle suspension rating	9,100 kg (20,000 lb)
Rear axle suspension rating	10,000 kg (22,000 lb) Hendrickson Rte. 440
Wheelbase	4.45 m (175 in)
Tank and trailer	
Type	Tri-axle
Sprung weight (empty)	8,450 kg (18,600 lb)
Tank length	12.2 m (480 in)
Tank diameter	1.83 m (72 in)
Axle rating	10,000 kg (22,000 lb) Reyco 21B
Weight density	0.0068 N/m3 (0.025 lb/in3)
Tires	
Type	XZA 11R225, Radial
Vertical spring rate	7,880 N/cm (4500 lb/in)
Lateral spring rate	8,755 N/cm (5000 lb/in)

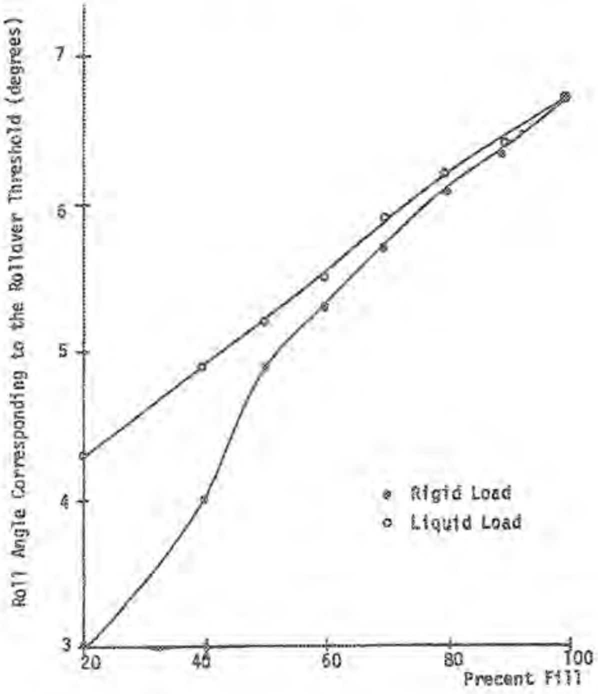
vehicle for various fill levels. The fill level is defined as the ratio of liquid height to the tank diameter. The rollover threshold values are computed for a clean bore cylindrical tank by assuming identical fill level in each compartment. The vehicle parameters/specifications are listed in Table 1.

The rollover threshold values of the identical vehicle are also established for equivalent rigid loads, using RTAC (Road and Transportation Association of Canada) simulation package (14). The rollover threshold acceleration limits of the tank vehicle are compared to those obtained for the rigid load as shown in Figure 9. It can be seen that for 100% fill level, the rollover threshold limit of the tank vehicle is identical to that of a heavy vehicle with equivalent rigid load. The rollover threshold values of the tank vehicle starts to deviate from those of equivalent rigid load, as the fill level is decreased. The rollover threshold value of the tank vehicle approaches that of the heavy vehicle with rigid load, as the fill level approaches zero. The rollover threshold value of the liquid tank vehicle corresponding to 50% fill level is significantly low when compared to that of the equivalent rigid load vehicle. The rollover threshold value is reduced by approximately 15% corresponding to 40% fill level, 13.5% at 50% fill



Comparison of rollover threshold values of vehicles with rigid and liquid loads

FIGURE 9



Comparison of tank roll angles for rigid and liquid loads

FIGURE 10

level, and 12.5% at 60% fill level. The tank/trailer sprung weight roll angle corresponding to the rollover point for various fill levels is shown in Figure 10.

The static rollover behaviour of the tank vehicle is significantly influenced by the tank shape and tank geometry. The lateral shift of liquid load in an oval shaped tank is significantly large as compared to the lateral shift within a circular cross section tank. The lateral motion of the liquid and thus the roll moment due to the liquid load is also a function of the tank diameter. Table 2 presents a comparison of the rollover threshold values of the tank vehicle for various values of tank diameter. The rollover threshold value of the vehicle with 50% liquid load within a 1.83 m (72 in) diameter, tank is reduced by 13.5% as compared to the rollover threshold value of a heavy vehicle with equivalent rigid load. The reduction in threshold value approaches 20% for tanks of diameter 2.03 m (80 in).

CONCLUSIONS

The lateral shift of liquid within the tank of a tank vehicle combination is investigated as a function of the roll angle of the sprung weight and the centrifugal forces encountered during steady turning manoeuvre. The roll moments caused by the fluid motion are incorporated in the steady turning model of a tank vehicle to investigate the unique steady turning characteristics of tank vehicles. Although the simulation package is capable of computing the steady turning characteristics of a compartmented tank vehicle with varying fill levels, the results and discussions in this paper are limited to a partially filled clean bore cylindrical tank. This is attributed to the fact that cylindrical steel tanks, used in the industry, are often clean bore and quite often they are forced to carry only partial loads due to variations in the weight density of various liquid chemicals. It is established that the rollover threshold limit of tank vehicles with partial loads can be 20% below the rollover threshold limits of other heavy vehicles carrying an equivalent solid load.

Table 2 — Influence of tank diameter on the rollover threshold values of liquid tank vehicles

Tank diameter m (in)	Rollover threshold (g) (50% load) Equivalent rigid load	Liquid load	% reduction in rollover threshold
1.83 (72)	0.52	0.45	13.50
1.93 (76)	0.51	0.42	17.65
2.03 (80)	0.50	0.40	20.00
2.13 (84)	0.48	0.39	18.75

REFERENCES

1. Miller, D.W.G. and N.F. Barter, "Roll-Over of Articulated Vehicles", I. Mech. E. Conf. on Vehicle Safety Legislation, Paper No. C203/73, 1973.

2. Ervin, Robert D., "The Influence of Size and Weight Variables on the Roll Stability of Heavy Duty Trucks", SAE Paper No. 831163, 1983.

3. Fancher, Paul S., "The Static Stability of Articulated Commercial Vehicles", Veh. Sys. Dyn., 14, pp. 201-227, 1985.

4. Mallikarjunarao, C., R.D. Ervin and L. Segal, "Roll Response of Articulated Motor Trucks During Steady-Turning Manoeuvres", ASME Winter Ann. Meeting, Nov. 1982.

5. Bauer, H.F., "Dynamic Behaviour of an Elastic Separating Wall in Vehicle Containers: Part 1", Int. J. of Veh. Design, Vol. 2, No. 1, 1981.

6. Transport Dangerous Goods, "Dangerous Occurrence Reports 1981-1985, Summary of Reports on File", Evaluation and Analysis, Transport Dangerous Goods, Report TP5695E, Aug. 1984.

7. Sankar, S., and S. Rakheja, "Summary of Tank Vehicle Accident Reports", Dept. of Mechanical Engineering, Concordia University Report, Mar. 1985.

8. Ervin, R.D., et al., "Future Configuration of Tank Vehicles Hauling Flammable Liquids in Michigan", Final Report, UM-HSRI-80-73-I, Dec. 1980.

9. Nalecz, A.G. and J. Genin, "Dynamic Stability of Heavy Articulated Vehicles", Int. J. of Vehicle Design, Vol. 5, No. 4, 1984.

10. Isermann, H., "Overturning Limits of Articulated Vehicles with Solid and Liquid Loads", MIRA Trans. No. 58/70, 1970.

11. Gauss, F., et al., "Calculation of the Overturn Resistance of Tractor-Semitrailer Combinations", MIRA Trans. No. 22/76, 1976.

12. Bechtold, James C., "Vehicle Stability and 102", Modern Bulk Transporter, pp. 65-69, Sept. 1983.

13. "Fruehauf Tank Test", Fruehauf Report, 1962.

14. RTAC, "Computer Simulation of Heavy Vehicle Dynamic Behaviour. Users Guide to the UMTRI Models", Vehicle Weights and Dimension Study, Interim Technical Report, No. 3, June 1985.

15. Billing, J.R., "Personal Communication", Ministry of Transportation and Communications, Ontario, 1986.

16. Personal Communication - Canadian Liquid Air, Sept. 1985.

SESSION 4
PAVEMENT RESONSE TO HEAVY VEHICLES 2

Chairman:

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SHRP Program
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