Rollover Analysis of Sloshing Liquid Loads

Liquid loads are most commonly carried in tanker vehicles. When the tank is full, very little load movement is possible and the assumption of no load movement is valid. However, when the tank is only partially full, applying a lateral acceleration by cornering, for example, will cause the load to move sideways. This sideways movement causes the centre of gravity of the load to shift sideways which effectively narrows the track width of the vehicle and reduces its rollover stability. To reduce this effect, tanker vehicles are often compartmentalized and are loaded/unloaded one compartment at a time. Thus when partially loaded only a proportion of the total load is free to move and the negative effect on rollover stability is reduced.

The effect described above relates to the quasi-static situation of steady-speed cornering. However, there is also potentially a dynamic effect. All dynamic systems have a natural frequency or frequencies at which they resonate and liquids sloshing from side-to-side in a tank are no different. If the vehicle executes a dynamic manoeuvre such as an evasive maneuver to avoid a collision and the frequency of the side-to side movement of the vehicle coincides with the natural frequency of the side-to-side liquid slosh the movement will be magnified and this will impact negatively on the vehicle's stability. If the frequency of the liquid slosh is a multiple of the frequency of the side-to-side movement of the vehicle there will still be a magnification of the effect although it will not be as strong. A useful analogy is to consider pushing a child on a swing. If one provides a push every cycle of the swing the swing goes higher. If instead one provides a push every second cycle the swing will still go higher but the rate of increase is slower.

Now we consider the magnitude of these two effects, starting with steady-speed cornering or SRT. If the tank is full the load cannot move and the SRT can be calculated in the usual way. When the tank is not full the centre-of-gravity is lower which improves the stability of the vehicle. However, because the load can now move, the centre-of-gravity of the load moves laterally towards the outside of the curve which degrades the stability. The relative magnitude of these two effects depends on the cross-sectional shape of the tank. As the vehicle proceeds around a corner at a steady speed, the load is subjected to a lateral acceleration which gives rise to a lateral force while still being subjected to a vertical force due to gravity. The liquid moves until its free surface is perpendicular to the vector of the combined lateral and vertical forces. The effects of this phenomenon on stability were investigated by Lidstrom and Strandberg (1978) and their results, together with some additional information, are also presented in UMTRI (2001). Below we present a short summary of the key findings.

Figure 1 shows how the change in the orientation of the free surface of the liquid changes the centre of gravity of the load for different tank cross-section shapes. For the circular tank section the centre of gravity moves through a circular path as the lateral acceleration increases. For the rectangular tank section the path of the centre of gravity position is more complicated and is elliptical in character.

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Based on these paths the SRT can be calculated for different levels of loading for the two tank cross-section shapes. The results of doing this are shown in Figure 2. This illustrates that when fully laden the rectangular cross-section tank has superior rollover stability to the circular tank. However, when partially laden the circular tank section is superior. More importantly the change in rollover stability characteristics of the rectangular tank is counter-intuitive. Generally as load is removed from a vehicle the centre of gravity becomes lower and the rollover stability improves. However, with the rectangular tank section, the rollover stability deteriorates so that, for the particular example shown, the worst case rollover stability occurs when the vehicle is approximately 40% laden. For the circular tank, although the load movement when the vehicle is partially laden does result in the rollover stability being poorer than it would be if the load did not move, the rollover stability always gets better as load is removed. Clearly the behavior of elliptical and super-elliptical tank sections will lie somewhere between the circular section and the rectangular section.

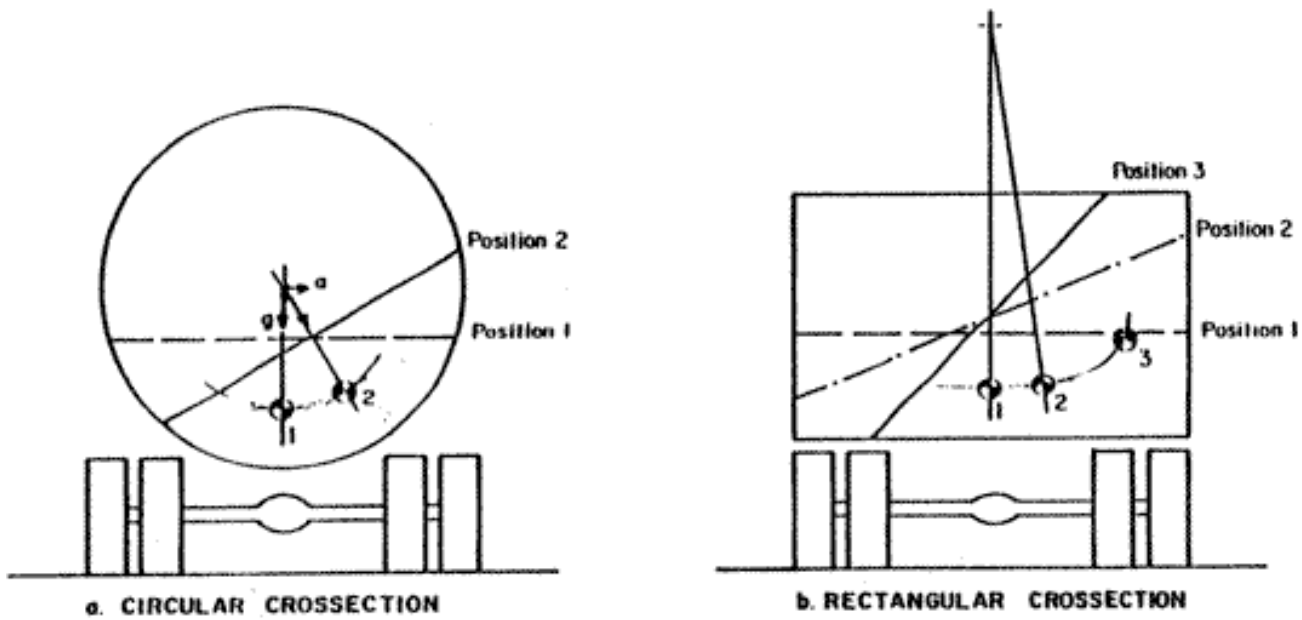

Figure 1. Illustration of liquid level during steady-speed cornering with different tank cross-sections (UMTRI, 2001).

As mentioned earlier, the rollover stability situation becomes more complicated when dynamic maneuvers are taken into account. Typically the side-to-side slosh of a half-loaded full width (2.5m) tanker has a natural frequency of 0.5Hz. This means that one cycle of slosh takes about 2 seconds. For narrower tanks the frequency increases slightly and thus the period reduces slightly. Studies of driver steering behavior (UMTRI, 2001) have shown that in demanding situations such as accident avoidance, there is a significant component of steer input that aligns with the natural frequency of the slosh. This will reinforce the sloshing and degrade the rollover stability.

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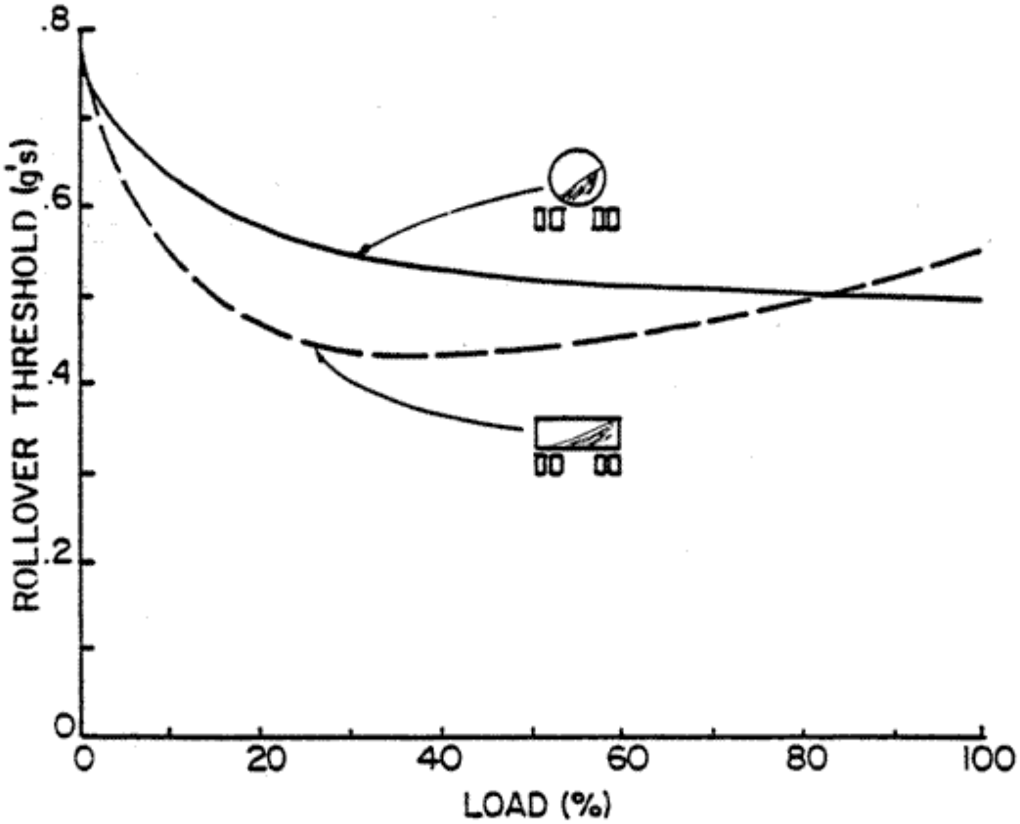

Figure 2. Static Rollover Threshold as a function of load during steady speed cornering (UMTRI, 2001).

Figure 3 shows the static rollover threshold for two tank cross-section shapes during a 0.5Hz transient manoeuvre for different states of load. As can be seen the reinforcing of the slosh leads to a significant reduction in rollover stability in this situation and the worst case rollover stability occurs at a partial load somewhere between 40% and 60% depending on tank shape.

All of the discussion so far has related to tankers without internal restraints. In practice it is common for tanker vehicles to be fitted with baffles or compartments. The most common form of baffles is in the transverse direction. These have no effect in preventing lateral slosh. Well designed longitudinal baffles significantly improve the rollover stability during transient maneuvers.

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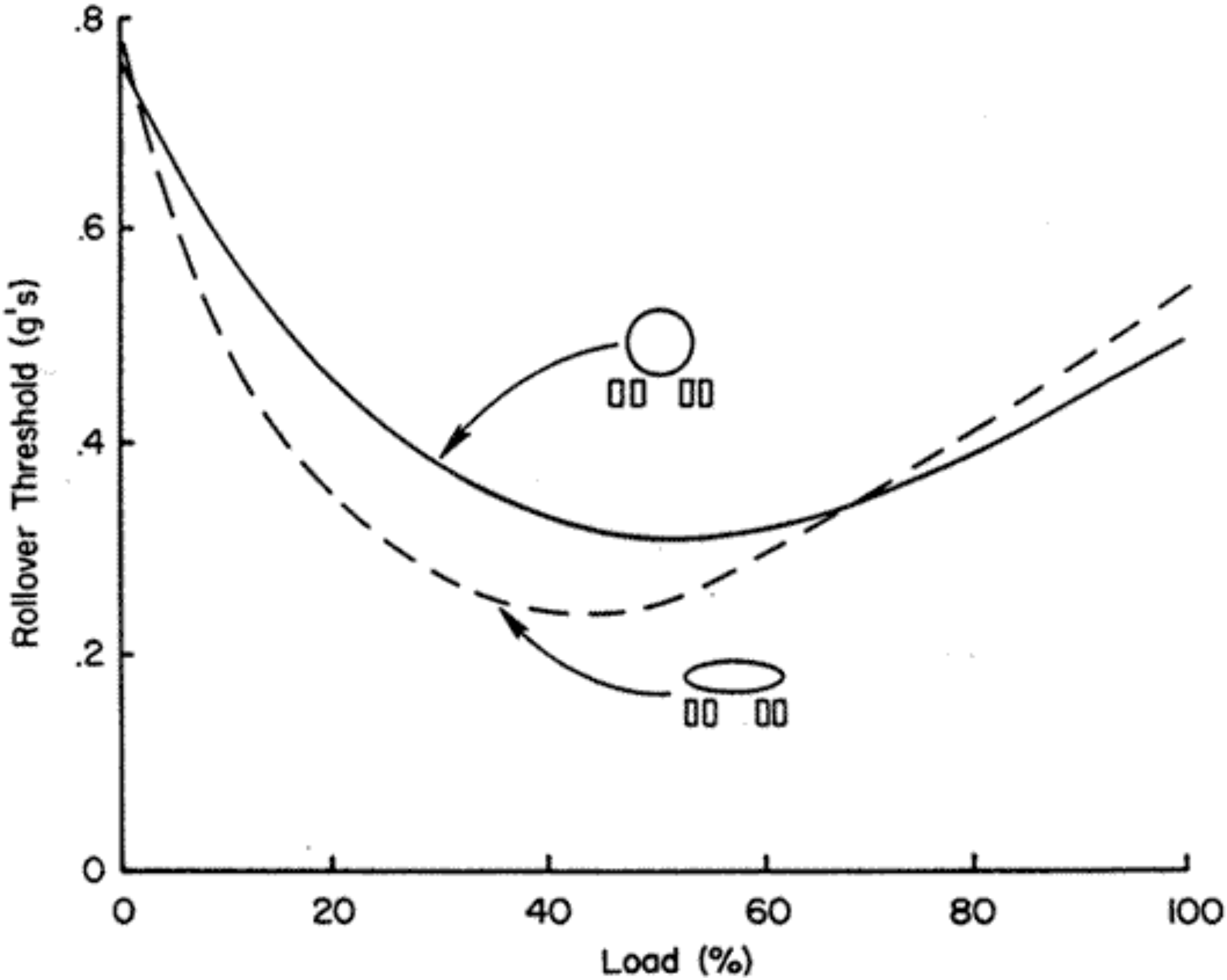

Figure 3. Rollover Threshold as a function of load during a 0.5Hz transient manoeuvre (UMTRI, 2001).

From a report on:

Stability effects of sloshing liquids and hanging meat

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