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Stability Effects of Sloshing Liquids and Hanging Meat

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Introduction

In July, 2002 New Zealand introduced a minimum rollover stability requirement for most large heavy vehicles. This requirement specified that heavy vehicles must achieve a Static Rollover Threshold (SRT) of 0.35g or more. SRT is a performance measure which is the maximum lateral acceleration that the vehicle can withstand before the wheels on one side of the vehicle lift off the ground. Primarily SRT reflects the propensity for the vehicle to roll over during steady-speed cornering with a higher SRT implying greater stability. Although SRT is based on steady-speed cornering, a higher SRT also implies greater stability during dynamic manoeuvres such as high-speed lane change, or an evasive manoeuvre to avoid a collision.

SRT can be determined experimentally using either a tilt-table test or a cornering test with an instrumented vehicle fitted with outrigger to prevent rollover. However, it is more common to determine it using a computer-based calculation method. In New Zealand a relatively simple computer-based method known as the SRT Calculator has been developed and has been shown to have good accuracy. This is the most widely used method for determining SRT. However, the SRT Calculator does assume that the load is firmly secured to the vehicle and does not move relative to the vehicle. This assumption is commonly used in the other computer-based methods as well.

For most load types this assumption of a well-secured load that does not move relative to the vehicle is valid. However, for two specific load types: liquids in tankers and hanging meat, the assumption is clearly not strictly correct at least some of the time. The purpose of this review is to quantify the effect that sloshing liquids and swinging hanging meat have on the rollover stability of the vehicle. The differences in behaviour and magnitude of the effect between the two types of moving load will be compared and the effect on safety will be estimated.

There have been several recent crashes involving hanging meat loads and this has been a factor in the commissioning of this analysis. For this reason there will be a particular focus on hanging meat loads in this report.

Methodology

The main approach used in this study is a review of research literature of the effects on stability of sloshing liquid and hanging meat with the analysis considering how these reported effects apply to New Zealand operations.

Three transport operators and one trailer manufacturer were contacted and the normal practices for loading and transport of hanging meat were discussed. Three hanging meat loads were inspected and measurements were made of the floor height, the load height, and the clearances of the carcasses from the floor and the side walls as well as estimates of the carcass centre-of-gravity heights.

Sloshing Liquids

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 compartmentalised 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 manoeuvre 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.

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 behaviour of elliptical and super-elliptical tank sections will lie somewhere between the circular section and the rectangular section.

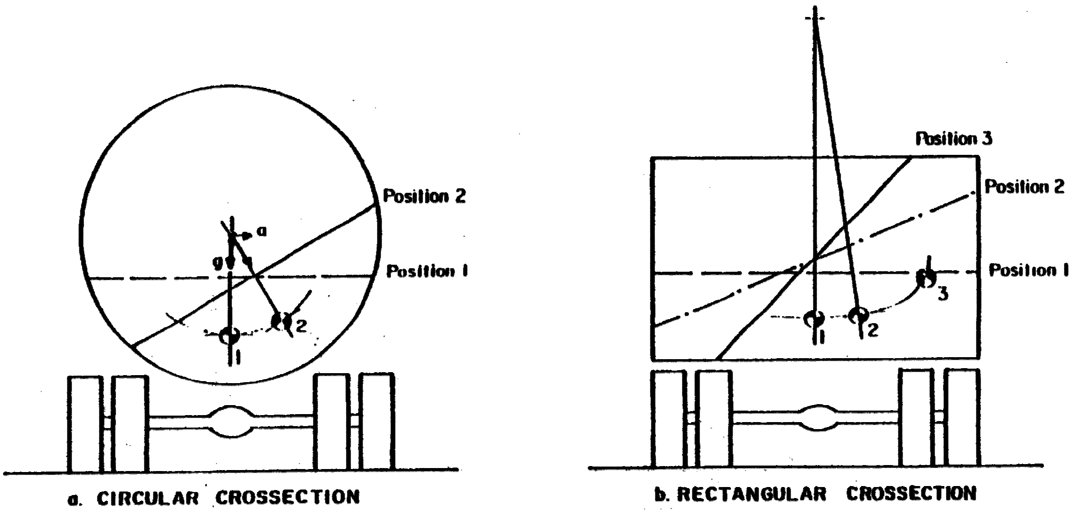

Figure 1. Illustration of liquid level during steady-speed cornering with different tank cross-sections (UMTRI, 2001).

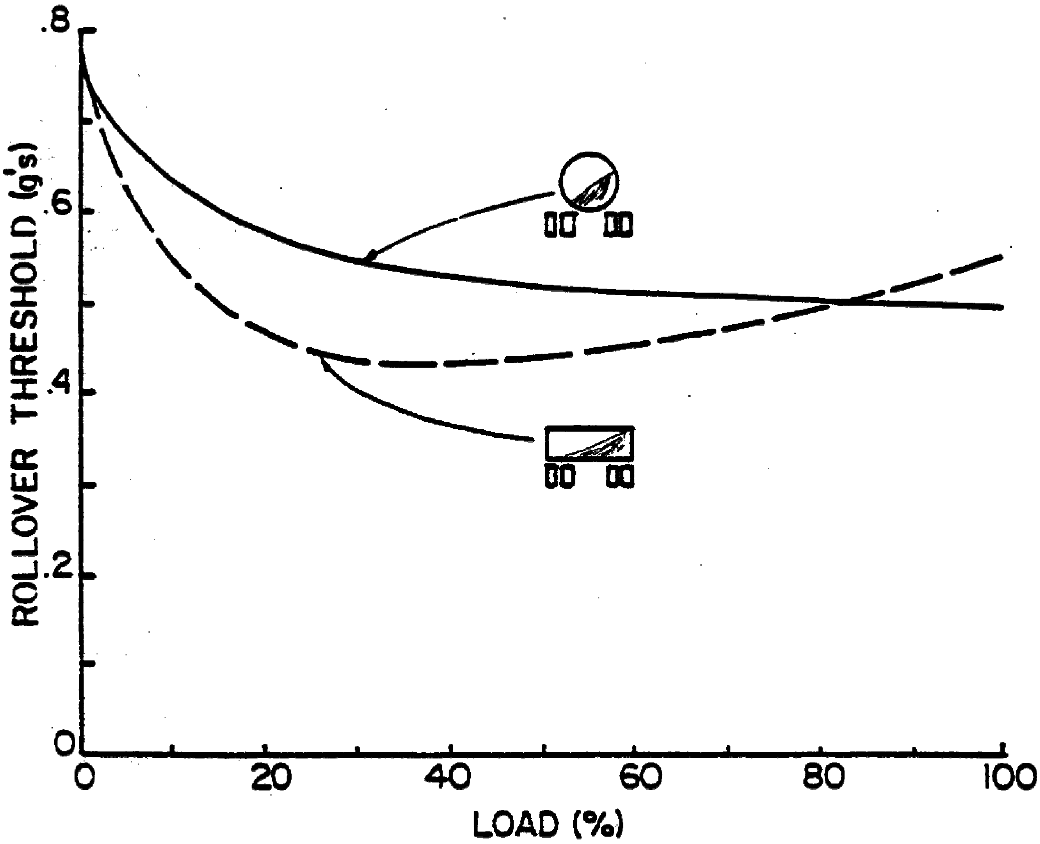

Figure 2. Static Rollover Threshold as a function of load during steady speed cornering (UMTRI, 2001).

As mentioned earlier, the rollover stability situation becomes more complicated when dynamic manoeuvres 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 behaviour (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.

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.

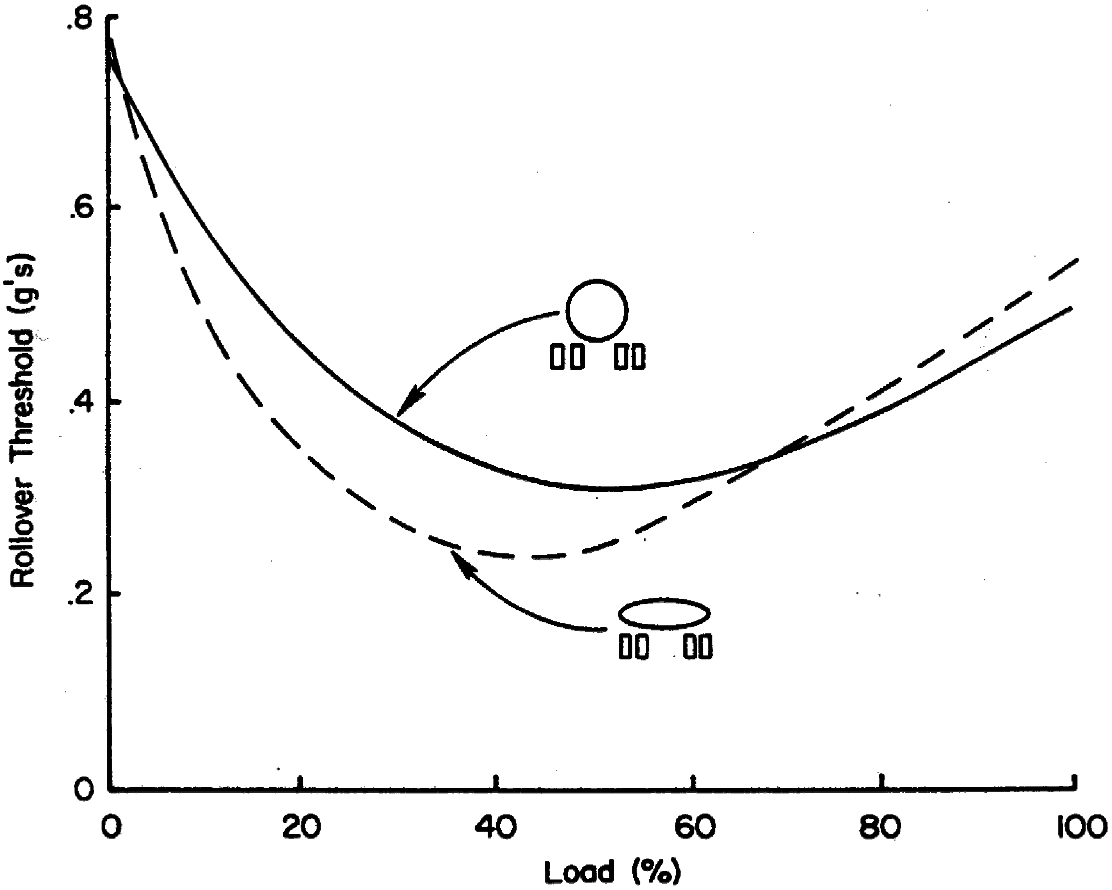

Figure 3. Rollover Threshold as a function of load during a 0.5Hz transient manoeuvre (UMTRI, 2001).

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 manoeuvres.

Compartmentalising the tank can significantly reduce the effect of slosh by allowing the compartments to be unloaded one at a time. Only a proportion of the load is free to slosh at any one time and so the effect is reduced. It has been shown (UMTRI, 2001) that if no more than 20% of the total load is free to slosh at any one time the rollover stability of the partially loaded vehicle will always be greater than that of a fully loaded vehicle.

Current New Zealand regulations for hazardous goods transport require compartments of less than 10,000 litres if fitted with baffles (these are transverse baffles) or less than 7,000 litres if not fitted with baffles. In practice this means that typical petrol tanker semi-trailers have more than five compartments and thus, provided they are unloaded correctly, will always have better rollover stability when partially laden than when fully laden. This is not necessarily the case for tankers not carrying hazardous goods. To facilitate cleaning, milk tankers are generally not compartmentalised. They are usually fitted with baffles but only in the transverse direction. In their favour most of their travel distance is done with the tank either empty or fully laden.

Hanging Meat Loads

In hanging meat loads, the meat is suspended by hooks on rails suspended from the ceiling or walls of a refrigerated van body. In New Zealand there are two basic types of vehicle configuration used for transporting hanging meat. The first of these is a dedicated vehicle in which case the rails run longitudinally along the length of the vehicle with, typically, five rails across the width of the vehicle. These vehicles are typically a little over 2m from floor to ceiling because the driver has to be able to reach the rails to take carcasses on and off. Two of the vehicle/loads we inspected were of this type (see Figure 4 and Figure 5). In both these cases the floor-to-ceiling height was 2.1m. The alternative is a general-purpose vehicle in which case removable cross-beams are fitted with slots that act as transverse rails. A single longitudinal rail is used as a feeder to the transverse rails. The third load we inspected was of this type as shown in Figure 6. The feeder rail runs along the left hand side of the vehicle. General-purpose vehicles typically have a greater internal height to allow for other high volume loads but the hanging meat rails are hung at a height where the driver can reach them and so there is relatively little difference in payload height between these vehicles when carrying a hanging meat load. In the particular example shown in Figure 6 the transverse beams are 2.25m above the floor.

Broadly speaking, the transport of hanging meat can be categorised as involving one of two freight tasks; the line haul task where meat is moved from a meat processing facility to a cool store or distribution centre and the local delivery task where meat is moved from a distribution centre to retail outlets such as supermarkets or butchers' shops. The line haul task generally involves full vehicle loads of a single species while local delivery vehicles may carry a mix of species and may make multiple stops so that, at least some of the time, they are only partially loaded. In practice this distinction is not so clear cut. Line haul loads may involve multiple drop-off points so that significant parts of the journey are done with part-loads. Local delivery operations are not limited to urban driving and may involve open-road speeds with high-speed cornering so rollover stability is important for these loads as well. Figure 4 shows a line haul load of pig carcasses which was transported from the South Island to Auckland. In the case parts of the load were delivered to several North Island centre en-route so that the load as photographed is only a part-load. Figure 5 shows a typical local delivery hanging meat load showing the less tight packing and the mixture of species, while Figure 6 is also a line haul part load.

Figure 4. Line haul load of pig carcasses - not fully loaded.

Figure 5. Typical local delivery hanging meat load.

Figure 6. Line haul load in a general-purpose refrigerated van with removable transverse rails.

With line-haul operations best-practice loading requires that the carcasses are packed tightly to minimise movement. For the dedicated vehicles with longitudinal rails, the hooks are slid as far forward as possible and the carcasses packed together. With the transverse beams, the beams are packed fully from the front of the vehicle. For the example shown in Figure 6, the pig carcasses are packed in pairs with 14 carcasses on each beam. According to the operators and the trailer manufacturer virtually no movement of the carcasses should be possible. In practice there is a gap between the carcasses and the side walls which is typically about 100mm with a maximum gap of 200mm observed. Thus some side-to-side movement is possible.

In the case of sheep/lambs, a full semi-trailer load consists of approximately 550 carcasses with an average weight of up to 20kg. Thus a full load is about 11 tonnes which is considerably less than the weight capacity of the vehicle. The vehicle shown in Figure 4 is a 3-axle tractor 3-axle semi-trailer combination which has a GCM of 39 tonnes. The tare weight of the two vehicle units is 18.2 tonnes so the payload capacity is 20.8 tonnes. With pig carcasses, the individual carcasses are significantly heavier (60kg+) and it is possible to achieve a maximum weight load without completely filling the load volume.

For dedicated vehicles with longitudinal rails the standard practice is to pack the load tightly and then to rotate the hooks of the rearmost carcass on each rail by 180 degrees. This prevents the hook from sliding more than one hanger spacing in the fore-and-aft direction. These hangers are clearly visible in Figure 4. Thus a small amount of movement of the last row of carcasses is possible but most of the load is not free to move. One of the drivers spoken to during the load inspections said that his practice was to lock off the load (by rotating the hooks) in sections to reduce the possibility of fore-and-aft movement even further.

With general-purpose vehicles and the removable transverse rail system no fore-and-aft sliding is possible. For the load inspected a retaining bar was used to prevent fore-and-aft swing. For this loading system best practice requires that the number of partially loaded rails should be minimised (there should not be more than one).

Beef carcasses are quartered before transport with the individual quarters being relatively heavy (like pigs). Again it is usually possible to achieve a maximum weight load without occupying all the vehicle space.

It is difficult to establish the centre of gravity of carcasses exactly but it appears that for a headless carcass it is about midway along the carcass length while for carcasses with heads (pigs) it is closer to the head end. With larger pig carcasses (those that are too long and would reach the floor) it is common practice to remove the head and stuff it inside the chest cavity. Again this means that the centre of gravity is significantly closer to the head end of the carcass. Based on observations of actual loads it would appear that the centre of gravity of pig carcasses is well below the mid-height of a 2.1m van body. Beef hind quarters have a centre of gravity that is lower but this is offset by beef fore quarters which have a centre of gravity that is somewhat higher. Sheep and lambs have shorter carcass lengths and hence their centre of gravity is somewhat higher but as noted earlier they cube out the load space and hence a load of sheep is much lower weight. For the example loads we have observed we would estimate the centre of gravity of a beef load (equal weight of hind and fore quarters) to be about 1.3-1.35m from the floor; for pigs the centre of gravity is less than 1m off the floor and for sheep about 1.2m.

For local delivery operations such tight packing is often not possible. The load may well consist of a mixture of different species. It is common to have multiple delivery points and so the driver needs to be able to access all of the components of a particular order. Thus a significant degree of carcass swing may be possible.

The side-to-side swing of the carcasses has a number of effects on the rollover stability of the vehicle. While the carcass is swinging freely its only point of attachment to the vehicle is through the roof of the van body. Thus the lateral forces generated by cornering are reacted through the roof of the van rather than through the centre of gravity of the payload. Thus the load behaves like a load with a much higher centre of gravity. Once the carcass comes into contact with the side wall of the van (or with other carcasses that have come into contact with the side wall) the line of action of the lateral forces drops to the load centre of gravity. This impact causes a disturbance to the lateral acceleration experienced by both the tractor and the trailer in a semi-trailer combination and particularly to the yaw rate of the tractor. As the tractor yaw rate provides an important cue to the driver for steering, this disturbance may well affect the driver's steering behaviour. When the carcasses come into contact with the van wall, the centre of gravity of the payload has moved towards the wall. This is equivalent to having an offset load which degrades the rollover stability.

This effect was investigated in UMTRI (2001) using a computer simulation model to consider the effect of a step-steer input on a hanging meat load with a 100mm gap to the side walls of the van. Figure 7 shows the calculated lateral accelerations for the two vehicles while Figure 8 shows the yaw rate response. From these two graphs it is clear that the swinging carcasses contact the side walls after about 0.75s. This causes a pulse in the lateral acceleration history which is in a favourable direction from a stability point of view. The effect on the yaw rate of the tractor, in particular, is quite significant.

During the load inspections some informal discussions with the drivers were held. These were not structured or planned and do not constitute a scientific study in any way, particularly as the inspections were undertaken at different stages of the research and so the nature of the discussion was affected by the findings at the time. The two drivers of the last vehicle inspected were asked whether they could feel the effect of the carcasses hitting the side wall during cornering on the vehicle handling. Both felt the effect was small but did say that the handling was different from that of a fixed load like pallets of product. They both indicated that you adjust to the load and hence that experience with this type of load was important.

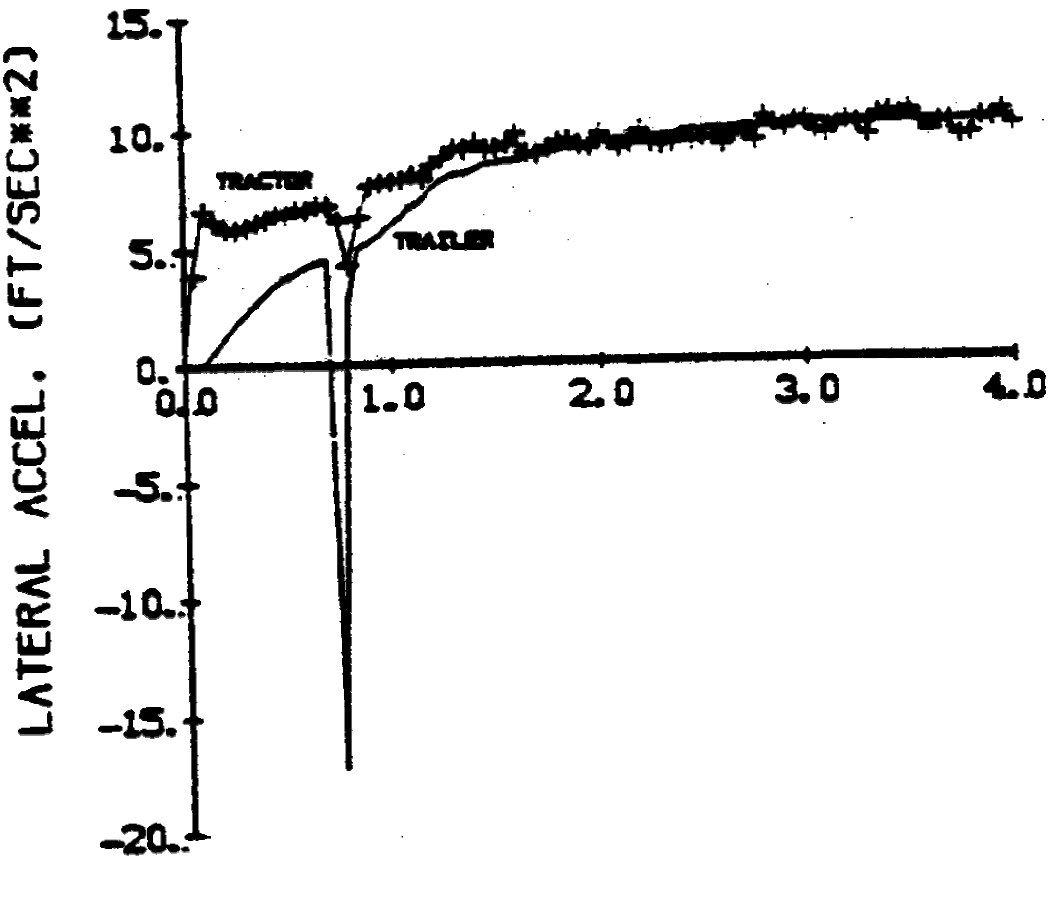

Figure 7. Lateral acceleration response to a step-steer of a tractor-semi carrying hanging meat (UMTRI, 2001).

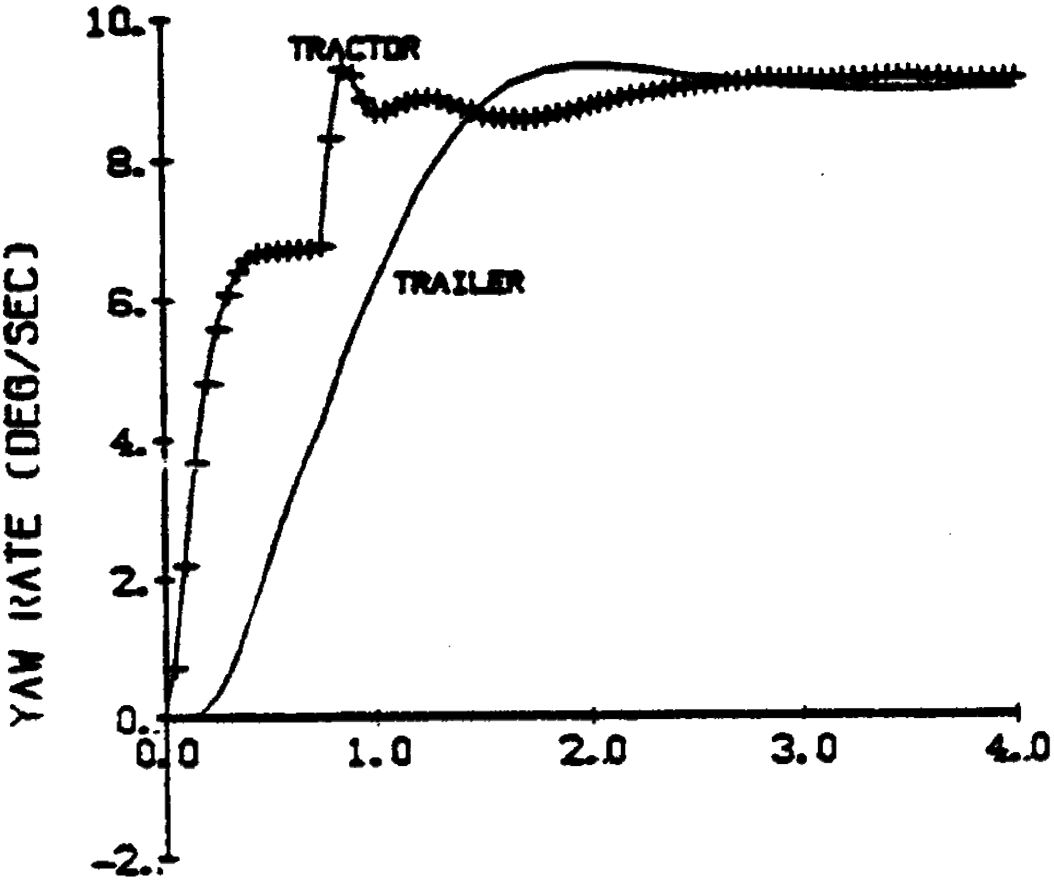

Figure 8. Yaw rate response to a step-steer of a tractor-semi carrying hanging meat (UMTRI, 2001).

UMTRI (2001) also presents the results of an analysis investigating the effect on rollover stability of the gap between the carcasses and the side wall of the van as well as the effect of suspension lash. These results are shown in Figure 9 below. This shows that if the carcasses are loaded so that 0.3m (12 inches) of swing is possible before the carcasses hit the side wall the SRT will be about 0.06g or 15% lower than if there was no gap (i.e. the carcasses were not free to swing). Note that 0.3m of swing on a 1.5m long carcass corresponds to a lateral acceleration of 0.2g so that in all the cases shown in Figure 9 the carcasses have contacted the side wall well before rollover.

The discussion so far has considered SRT which reflects steady speed cornering. As with the sloshing liquids, the hanging carcass has a natural frequency. In simple terms it can be regarded as a pendulum with a length equal to the distance from the point of attachment of the hook to the centre of gravity of the carcass. The period of a simple pendulum is given by $2\pi\sqrt{(l/g)}$ where l is the length and g is the acceleration due to gravity. The period of a 1m long pendulum is 2 seconds and so the natural frequency of swinging carcasses is similar to that of sloshing liquids. Thus the same reinforcement mechanism that was described for sloshing liquids could occur for hanging meat. However, the lateral movement of the carcasses is usually limited because of their proximity to the side walls (or neighbouring carcasses) and resonance will only occur for small amplitudes of motion. Larger amplitudes are possible when the vehicle is more sparsely loaded but in this case the quantity of mass swinging from side to side will be quite small and so the impact on the rollover stability will be small.

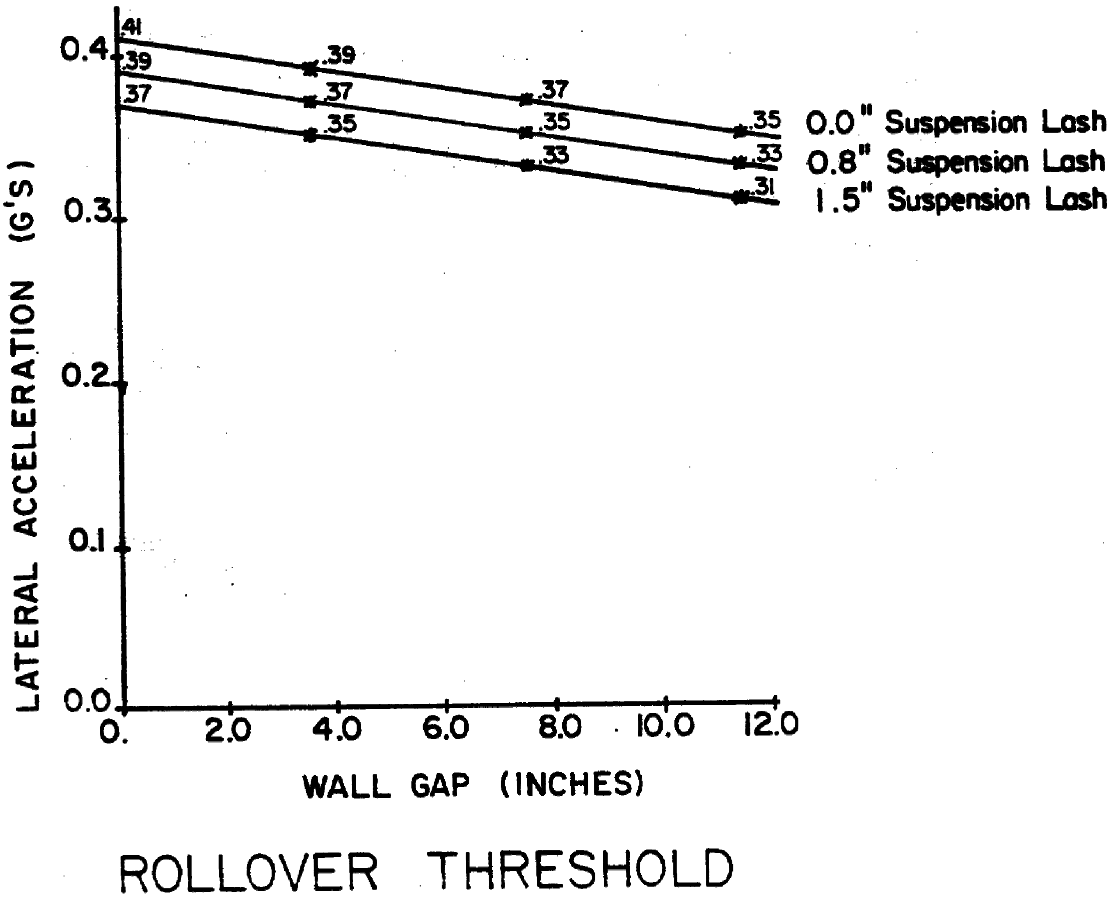

Figure 9. SRT of a hanging meat semi-trailer with different wall gaps and suspension lash (UMTRI, 2001).

If the SRT Calculator is used to calculate the rollover stability of the vehicle, there are two load categories that might be used for determining the SRT of a hanging meat vehicle. These are "uniform density" or "other".

The simplest load category to use is "uniform density" which assumes that the centre of gravity of the payload is midway between the floor and the roof of the load space. For the typical hanging meat refrigerated van this is 1.05m-1.10m above the floor. As discussed earlier for pig loads this is a conservative assumption, but for beef and sheep it is probably lower than the actual centre of gravity height. For sheep meat loads, the payload weight is typically much less than the legal maximum and this weight reduction will offset the higher centre of gravity height to give acceptable stability. The alternative load category to use is "other". In this case the certifier (or other user of the SRT Calculator) must calculate the centre of gravity height of the payload and enter the number explicitly. Using the basic parameters of the semi-trailer from Figure 4 and load category "other" we can use the SRT Calculator to determine the SRT for various payload centre-of-gravity heights for different suspension configurations. For a semi-trailer only the loads on the rear axle group are considered. For this analysis we assume the tare weight on the rear axle group is 6 tonnes, the maximum gross weight on the rear axle group is 18 tonnes and the load bed is 1.4m above the ground. The results of doing these calculations are shown in Table 1.

Table 1. Calculated SRT for a semi-trailer with different payload Cg heights and suspensions.

Payload centre of gravity height (m)	SRT		Reduced load on rear axle group for SRT > 0.35g (steel suspension case)
	Generic steel suspension	Generic high roll stiffness air suspension	
0.9	0.39g	0.43g	N/A
1.0	0.37g	0.41g	N/A
1.2	0.34g	0.38g	17 tonnes
1.4	0.31g	0.35g	14.7 tonnes

These results show that if the load movement is not taken into account and a higher roll stiffness suspension is fitted to the vehicle, the calculated SRT meets the legal minimum requirements for all the payload centre-of-gravity heights considered. In fact, even with the less roll-stiff generic steel suspension, the SRT is sufficient for all cases except possibly beef carcasses where the load may achieve maximum weight and have a relatively high centre of gravity.

Referring back to the UMTRI analysis results shown in Figure 9 we see that the effect of hanging load is to reduce the SRT. Provided the gap between the carcasses and the side wall of the van is kept small (ideally less than 100mm on average) and high roll stiffness suspensions are used on the vehicle the SRT should be adequate for all practical loads. However, the disturbance to the vehicle's handling that occurs when the swinging carcasses contact the side walls may be disconcerting to the driver and he needs to be aware of this effect.

Safety Implications

Earlier research (de Pont et al, 2000) has shown a relationship between SRT and the risk of a rollover or loss of control crash. The relationship found is illustrated in Figure 10. This relationship implies that as the rollover stability (as indicated by SRT) of the vehicle declines the risk of a rollover or loss-of-control crash rises and at low SRT values rises rapidly. This finding is the basis of the current SRT requirement for large heavy vehicles in New Zealand. The required minimum level of 0.35g is a trade-off between safety and productivity. Setting a higher target would improve safety but would also reduce the payload capacity of a significant number of vehicles.

Tankers for carrying liquid loads generally have a relatively low centre of gravity and hence a relatively high SRT. The recent amendment to the dangerous goods transport regulations requires petrol tankers to have an SRT greater than 0.45g. In steady speed cornering, although the effect of slosh is to reduce the SRT, for circular and elliptic tanks, the SRT of a partially laden tanker is greater than that of a full tanker. Thus generally the effect of slosh on the steady speed cornering stability of liquid tankers is small and there is little change in relative crash risk. For evasive manoeuvres, however, if the steer input coincides with the natural resonance of the side-to-side slosh of the liquid the degradation in rollover stability can be substantial. In extreme cases a 40%-50% loaded tanker may have a rollover stability that is only half its fully loaded stability. Fortunately, evasive manoeuvre rollover crashes represent less than 10% of all rollover crashes (de Pont et al,

2004) so this effect is only relevant in a small proportion of cases. Well-designed longitudinal baffles can substantially reduce this effect while compartmentalisation can virtually eliminate it.

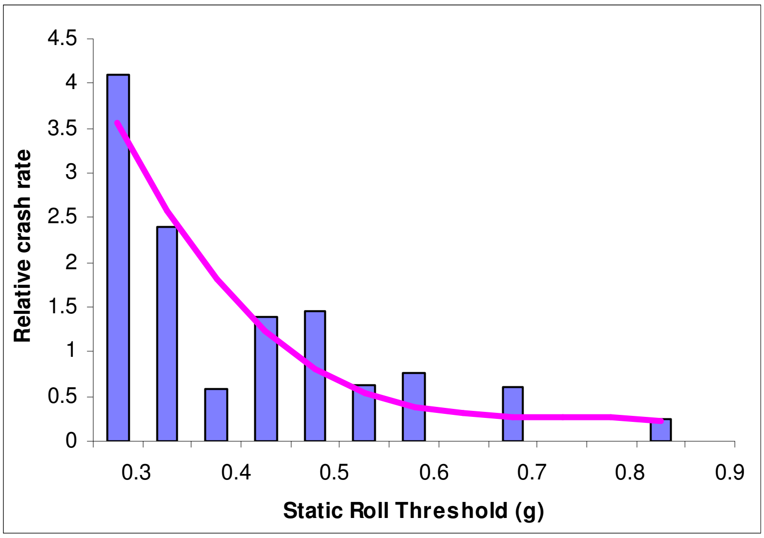

Figure 10. Relative rollover and loss-of-control crash risk against SRT.

Most hanging meat loads also have a relatively low centre of gravity or low weight and hence the vehicles have relatively good rollover stability. Although the industry seems to have the view that a well-loaded line haul load cannot move it appears that in practice some side-to-side swing is usually possible. On the loads inspected 100mm is typical. Based on the UMTRI research this would be expected to reduce the steady-speed cornering rollover stability by about 0.02g or 5%. If the SRT without swing is 0.4g this represents a 17% increase in crash risk, but the rollover stability would still be better than the statutory minimum. This effect is entirely predictable and drivers should be able to adjust their speed behaviour through curves to offset it. Note, however, that the results in Figure 10, which show that crash rate increases as the vehicle stability gets worse, indicate that drivers do not moderate their behaviour sufficiently to eliminate all the additional risk.

When a lateral acceleration is applied to a hanging meat load, initially it swings freely until it hits the side wall of the vehicle. When this occurs there is a disturbance to the vehicle's handling and behaviour. This should not have any significant safety impact but an inexperienced driver may react inappropriately to this disturbance. It is impossible to quantify the safety impact of this effect.

For dynamic manoeuvres, hanging meat has a natural frequency that is comparable with sloshing liquids. However, the side walls severely restrict this motion and so it is not expected to have the same negative safety implications that it does for liquid slosh.

Local delivery loads appear to be loaded so that considerably greater movement is possible than for line haul loads, but generally these loads weigh much less. The additional movement possible will severely degrade the stability but the low weights mean that the stability is inherently high. Drivers need to be aware that the stability of their vehicle is not as good as it would be if the low could not move.

Conclusions and Recommendations

For both sloshing liquids and hanging meat the effect of the load movement is to lower rollover stability of the vehicle during steady speed cornering. However, with liquids, there is no movement when the vehicle is fully laden while with meat the degree of movement depends on how the vehicle is loaded and can still occur when the vehicle is fully loaded.

With sloshing liquid loads the magnitude of the stability degradation depends on the shape of the tank. For the fully laden condition, a rectangular tank section provides the best rollover stability. However, when less than full, the degradation in rollover stability due to slosh for a rectangular tank is greater than the gain in stability from a reduced load height. This means that the worst case steady speed rollover stability occurs at less than full load which is undesirable. Generally drivers expect vehicles to become more stable as load is removed. For circular and elliptic tank sections, the gain in steady speed rollover stability from payload height reduction is greater than the reduction in stability from liquid slosh. Thus the worst case rollover stability occurs when the vehicle is full.

For dynamic manoeuvres such as collision avoidance, the steer inputs can coincide with the natural frequency of the liquid slosh (this typically has a period of about 2 seconds). When this occurs the rollover stability of the vehicle may be substantially reduced. In a worst case the rollover stability of a half laden vehicle during a 2 second lane change manoeuvre may be as little half the value it would be for a fully laden vehicle with no slosh. This effect can be substantially reduced with well-designed baffles and can be virtually eliminated by compartmentalising the tank and ensuring that only a small proportion of the load is free to slosh. Fortunately evasive manoeuvre rollover crashes are relatively rare.

With hanging meat the basic principles are similar but the situation is more complicated. When a lateral acceleration is applied during cornering the load moves laterally which move the centre of gravity laterally and effectively narrows the vehicle track width and reduces the stability. However, with hanging meat, initially the meat is attached to the ceiling of the load space and not to any other part of the vehicle body. Thus the lateral force on the payload arising from cornering acts at the height of the ceiling rather than the payload centre of gravity. As the carcasses swing laterally and come into contact with the side walls of the vehicle the line of action of this force move down from the ceiling to the payload centre of gravity so there is a sudden change in the rollover force. This disturbance also affects the yaw rate response of the tractor which is part of the feedback used by the driver to determine the steer input requirements. Once the carcasses are in contact with the side walls of the vehicle it behaves normally with the lateral movement of the payload centre of gravity causing a reduction in rollover stability. If this movement is not large this effect will not be large although the impact on crash risk is larger. For the inexperienced driver the disturbance to the handling that occurs when the carcasses hit the side walls may lead to an inappropriate steering response and have safety implications.

For dynamic manoeuvres, hanging carcasses are like a pendulum and have a natural frequency that is similar to that of sloshing liquids. However, if the carcasses are reasonably close to the side walls (or neighbouring carcasses) this resonance will only occur at low amplitudes and should not cause any problems.

The LTSA has produced a document titled "Heavy Vehicle Stability Guide" which provides advice to drivers and operators on the rollover stability of heavy vehicles and how to minimise the rollover crash risk. This briefly mentions load movement as a factor that reduces stability and highlights bulk liquids and hanging meat as examples. When this document is next revised it would be useful to expand on this issue by including a paragraph or two to explain:

1. How sloshing liquids affect dynamic stability and particularly that, if the load is not compartmentalised, the dynamic rollover stability of a partial load may be worse than that of a full load.
2. With hanging meat, the load should be packed to minimise movement but some movement will inevitably be possible. There is a change in handling response, which drivers need to understand, when the load transitions from swinging freely to being restrained by the sidewall.
3. In both case the load movement degrades the rollover stability over what it would be if the load did not move. Additional caution and lower speeds are required.

During the discussions with operators and drivers, the crashes that have occurred were often attributed to inexperienced drivers. Experienced drivers do appear to have adjusted their driving behaviour to match the changed handling characteristics of the vehicles but do not have a good understanding of how the handling characteristics have changed. These comments apply only to hanging meat loads because no liquids loads were inspected. Furthermore the discussions were very informal and unstructured so this is an anecdotal observation rather than a scientific finding. Nevertheless it would appear that there is some value in operators providing some training to drivers of these types of loads and in making them aware of the specific effects that load movement causes.

References

de Pont, J. J., Mueller, T. H., Baas, P. H. and Edgar, J. P., 2000. Performance measures and crash rates, in *6th International Symposium on heavy vehicle weights and dimensions*(Ed, Borbely, C. L.) Saskatoon,Saskatchewan, Canada.

de Pont, J. J., Charlton, S, Latto, D, and Baas, P. H., 2004. Heavy-vehicle speed through curves, in *8th International Symposium on heavy vehicle weights and dimensions* Gauteng, South Africa.

Lidstrom, M. and Strandberg, L., 1978. Influence from liquid load motion on the lateral stability of road vehicles, in *17th International Congress papers - FISITA*, Vol. 3 Budapest, June 1978, pp. 1727 - 1735.

UMTRI, 2001. *The Mechanics of Heavy-Duty Trucks and Truck Combinations.* The University of Michigan Engineering Summer Conferences, Ann Arbor, Michigan.

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