The mechanics of roll-over for logging trucks

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Introduction

"Truck terror, ready to roll" cries the cover of a popular magazine (Chamberlain, 2000). With splashy photographs of crushed cars and portraits of sad relatives, the chilling stories of logging trucks rolling onto family cars are told in detail. One can imagine the terror of the passengers, and the panic of the truck driver in the last few moments before disaster, and most drivers can recall at least one close call in their own experience.

Passenger car traffic and logging truck traffic don't mix very well, especially when there is a high proportion of tourists in the traffic stream. There is friction between the drivers of the vehicles associated with two of the country's most important industrial sectors. Tourists hate what they consider to be oversize, aggressively driven logging behemoths, and logging truck drivers become exasperated with what they consider to be the foolhardy antics of tourists buzzing around them. The recent publicity of accidents has only served to heighten anxiety and harden attitudes and perceptions.

But it need not be that way. A large part of the problem is perception, and education can soften attitudes. Beyond this, there are basic physical and mechanical causes for many of the accidents: if the mechanics[1] of the problem were examined and acted upon, the accident rate could be significantly reduced.

In many cases, the accident is initiated when a truck rolls over while negotiating a curve in the road. The combination of truck speed, curve radius, curve super-elevation (banking), and truck characteristics ensures that the truck *will* roll over, spilling its logs. Once the process is started, there is nothing the driver can do to avoid disaster.

Some have offered opinions on what should be done. Indeed, comments have been written in this journal's Recent Events section (NZJF, 2000). However, virtually none of the commentary recognises the basic mechanics of the problem, and it is unlikely that a satisfactory solution will be found until the mechanics are understood and then carefully addressed.

This paper first presents an outline of the generalities of the problem, then details the relevant mechanics, and ends with conclusions and recommendations based on the mechanical analysis of the problem.

We begin with a look at the legal limits on the mass and dimensions of heavy trucks.

"Weighing out" and "bulking out"

There are legal limits on the gross mass and the loads imposed by individual axles, and on the overall dimensions permitted for large, heavy vehicles using public roads. Consequently, at the limit, trucks can either "weigh out" or "bulk out", reaching their maximum permitted mass, or their maximum permitted length, width, or height.

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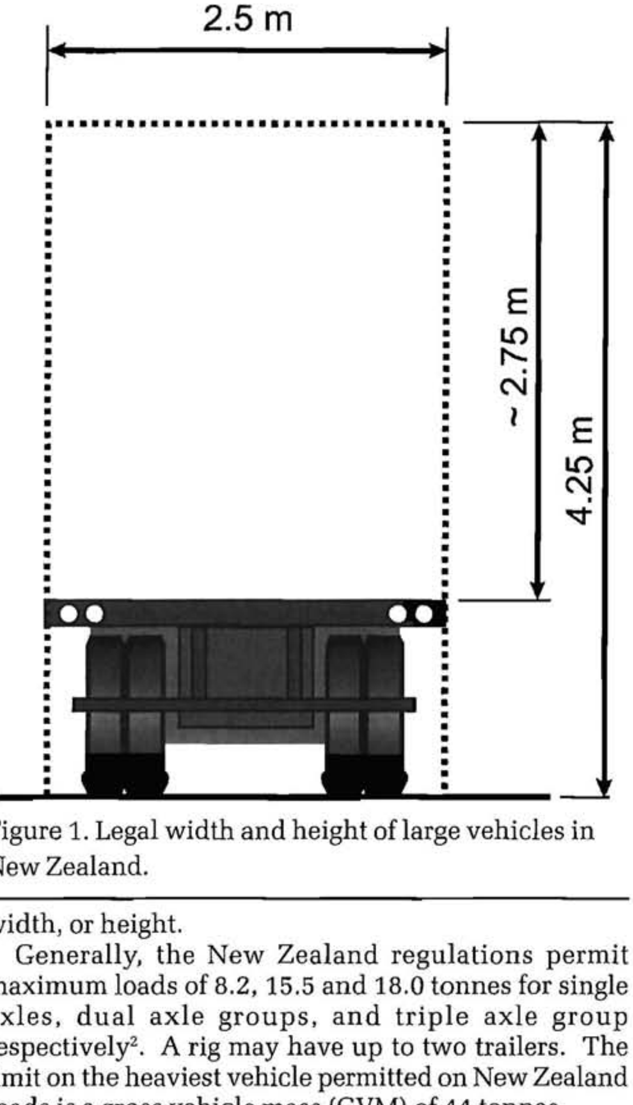

Figure 1. Legal width and height of large vehicles in New Zealand.

Generally, the New Zealand regulations permit maximum loads of 8.2, 15.5 and 18.0 tonnes for single axles, dual axle groups, and triple axle group respectively[2]. A rig may have up to two trailers. The limit on the heaviest vehicle permitted on New Zealand roads is a gross vehicle mass (GVM) of 44 tonnes.

The dimensional regulations in New Zealand[2] limit trucks to a length, width and height of 20.0, 2.5, and 4.25 metres, respectively. These dimensional limits constrain the practical volume of the truck's payload (Figure 1).

When considering logging truck stability, the concepts of weighing out and bulking out are crucial. The extremes are illustrated in Figures 2(a), (b), and (c). A truck hauling steel beams (Figure 2(a)), for instance, is clearly one which will weigh out. Given the heavy mass of its payload, it will reach the limit on GVM long before it approaches the limit on load height. On the other hand, trucks hauling light payloads, for instance groceries

[1] "mechanics" in its formal sense is used here: it is the "science which describes and predicts conditions of rest or motion of bodies under the action of forces" (Beer and Johnston, 1972).

[2] Land Transport Safety Authority. Web site www.ltsa.govt.nz/resources/index.html, Fact Sheets, Vehicle Standards, No. 13. Posted July, 2000.

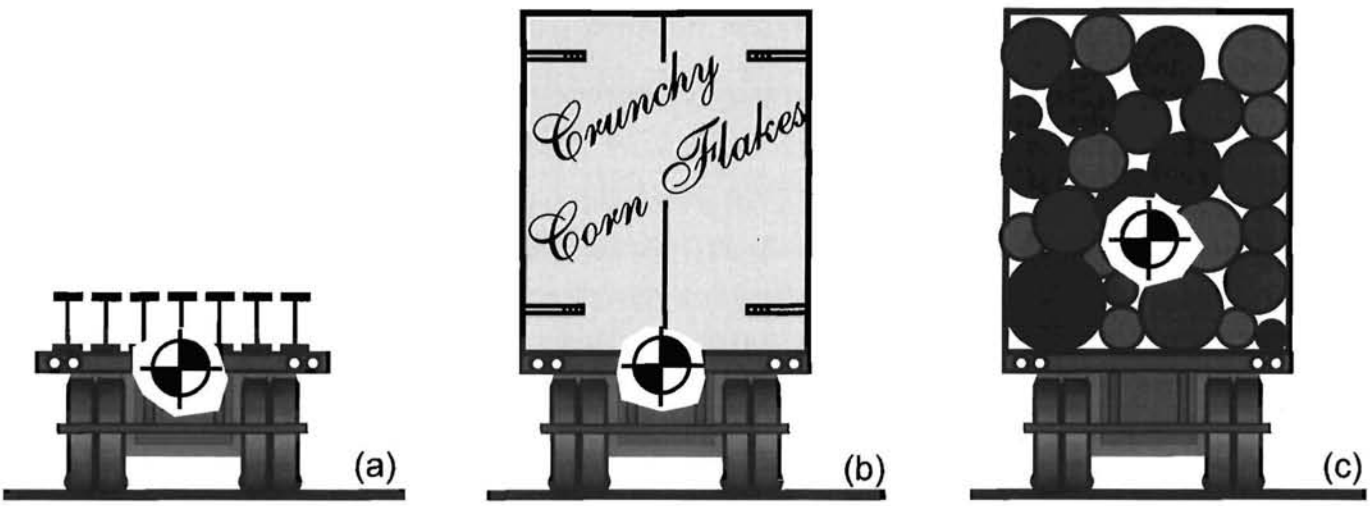

Figure 2. Truck configurations: (a) an example of a truck which "weighs out" — a flat bed truck carrying heavy steel beams, (b) a truck which "bulks out" — a truck carrying groceries. Both have low centres of gravity, at the locations indicated by the symbols. In (c) the logging truck "weighs out" and "bulks out" simulataneously, resulting in a high centre of gravity.

(Figure 2(b)), will bulk out, with the payload completely filling the space available, as set by the dimensional limits.

In both cases, it can be seen that the centre of gravity of the truck with its load secure will be relatively low to the ground, either because the load is heavy and relatively close to the ground, or because the payload is not very dense, and the weight of the truck itself keeps the centre of gravity relatively close to the ground. In both cases, the result is a comparatively stable arrangement, when curves are being negotiated. It comes as no surprise that we don't hear of many fatal accidents caused by corn flake trucks.

The situation is dramatically different for logging trucks (Figure 2(c)), and also, incidentally, for tankers hauling such products as milk or petrol. Typically these trucks reach the limits on weight *and* volume, simultaneously, with the result that they are comparatively less stable configurations.

Logging trucks

For a tractor semi-trailer arrangement, the volume of logs carried is the length of the logs times the permitted width, times the height available between the trailer deck and the maximum height. Such a rig would likely be carrying long logs, typically about 5.6 metres long. As shown in Figure 1, the maximum permitted width is 2.5 metres, and the payload could be as much as 2.75 metres high. A payload volume of 38.5 cubic metres is calculated. If the density of wood is taken as about 1 tonne/cubic metre, and the ratio of the solid volume of wood to the volume occupied by the loose pile (the packing ratio) is about 0.8, the payload would be about 30 tonnes. It has been shown that over a very wide range of GVM for logging trucks, from 25 to 170 tonnes, payload represents a very consistent proportion of GVM, about 70 per cent (Douglas, 1992). Thus, if the payload filled the available volume and was about 30 tonnes, the GVM would be expected to be about 43 tonnes.

A legal 3S3 configuration in New Zealand has a maximum permitted GVM of 40.7 tonnes. Thus it can be seen from these rough calculations that for this very common configuration, filling the permitted volume with logs easily brings the truck to its maximum permitted GVM. The truck weighs out and bulks out, simultaneously. With the trailer filled to the maximum permitted height with a comparatively high density payload, the truck will have a high centre of gravity.

Conventional curve design

It is self-evident that having a high centre of gravity is a liability when it comes to stability on road curves. It is surprising, however, that conventional highway curve design does not take this into account.

Conventional curve design is based on the desire to avoid causing a passenger car to slide laterally off the road surface. Consideration of the equations of lateral equilibrium of a passenger car negotiating a circular curve results in the equation:

$$R_{min} = \frac{V^2}{127(e_{max} + f)} \quad \dots (1)$$

where:

R_{min}	=	minimum radius of circular curve [m]
V	=	speed of vehicle [km/hr]
e_{max}	=	maximum superelevation (banking) of road surface [m/m]
f	=	coefficient of lateral friction between tyres and [unitless] road surface

Designers must consider the lowest value of f that could reasonably be expected to occur. Usually appropriate values for wet asphalt are adopted.

Most modern highway engineering texts do not delve very deeply into roll-over. The standard reference texts usually just note in passing that roll-over is a possibility. The venerable text by O'Flaherty (1986) even includes a sketch of a double-decker bus (Figure 3), but it pursues roll-over no further.

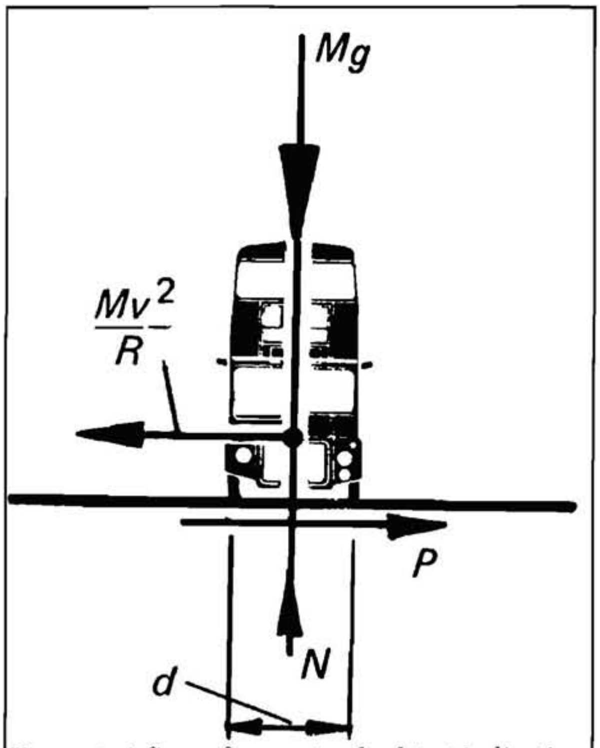

Figure 3. A figure from a standard text indicating forces affecting vehicle stability on curves (O'Flaherty, 1986).

The mechanics of roll-over

As shown by Figure 4, it is the "centrifugal force" mV^2/R resulting from the lateral acceleration acting through the logging truck's high centre of gravity which tends to roll it over when going around a circular curve.

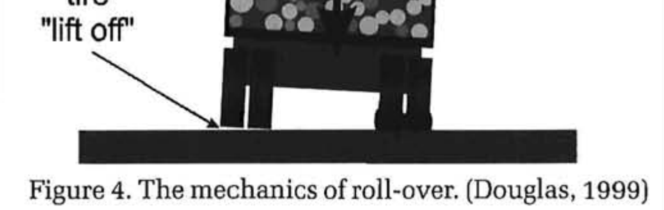

Figure 4. The mechanics of roll-over. (Douglas, 1999)

El-Gindy and Woodrooffe (1990) tested a broad spectrum of logging truck configurations and found that the lateral acceleration needed to initiate roll-over ranged from 0.22 g to 0.33 g (g being the acceleration due to gravity, 9.81 m/s²). For a vehicle on a circular curve, the lateral acceleration is V^2/R, where V is the truck speed (m/s) and R is the radius (m) of the circular curve.

Of course some lower value of lateral acceleration should be used in design: bringing trucks to incipient roll-over is obviously undesirable. A reasonable value to adopt might be approximately 0.15 g (Douglas, 1999). Assigning this value for the lateral acceleration V^2/R permits the calculation of acceptable curve radii set

Table 1
Minimum radius of curvature for roll-over criterion, based on maximum lateral acceleration = 0.15 g

Design speed [km/hr]	*Design speed* [m/s]	*Minimum radius of curvature** [m]
30	8.33	45
40	11.1	85
50	13.9	130
60	16.7	190
70	19.4	255
80	22.2	335
90	25.0	425
100	27.8	525

* rounded to nearest 5 m

to avoid logging truck roll-over, (Table 1).

It is crucial to observe that the minimum curve radii shown in Table 1 are greater than the minimum radii shown in standard tables for curves designed from the sliding criterion point of view in the more severe cases (comparatively high speed, tight radius, steep superelevation). The implication is that some highway curves, designed using the standard approach, may be tight enough to ensure that a truck with a high centre of gravity will roll over on them, even if not exceeding a posted speed based on the sliding criterion. Engineers could, in good faith, be inadvertently setting unsafe curve radii.

Potential solutions

Against this background, what are the potential solutions to the problem of roll-over of logging trucks, with their high centres of gravity? At first glance, there are two:

- increase the radius of tight curves; and,
- lower the centre of gravity of the trucks with their loads.

However, neither of these two is likely to lead to practical solutions.

To systematically go over the complete network of highways and roads in the country, searching for those where the roll-over criterion (i.e. Table 1) actually controls over sliding, would be an enormous task. It could be shortened by examining accident records to identify those curves were the problem seemed acute. But the subsequent step – acquiring the necessary land beside the road and reconstructing all those curves to larger radii, could be extremely expensive. The solution could be implemented incrementally, as opportunities arise in road upgrading and rehabilitation, but it is not going to happen across the country in a short time.

Attempting to find ways to lower the centre of gravity of logging trucks is also not likely to be very fruitful. Rigs with smaller wheels, which would permit the lowering of the frame, could be contemplated, but the small tyres associated with small wheels wear out proportionately more quickly, and are not robust enough to withstand the conditions on forest roads, where the hauls originate. New trailer frames with drop-down bellies could be considered, but as it turns out, they would not necessarily be compatible with the log form, specifically the length of the logs, prevalent in New Zealand operations. In addition, ground clearance could become a problem. And in any event, the centre of gravity needs to be lowered a very significant amount, perhaps a metre or more, not a few millimetres or centimetres, and these measures could not accomplish that.

The key to the solution is to recall that the stability depends on the lateral acceleration developed as the truck negotiates the curve, V^2/R. It is dependent on the square of the truck's speed. A driver entering a curve "just a little" over the recommended speed, even if that recommended speed was set according to the roll-over criterion rather than the sliding criterion (which it is unlikely to have been in the first place), will run considerable risk of rolling over. To travel at 110 km/hr on a curve posted for 100 km/hr is to be 10 per cent over the design speed, but to be 21 per cent less stable (1.10 ? 1.10 = 1.21) in the sense that the square of the speed determines the lateral acceleration and thus stability. To travel at 120 km/hr is to be 44 per cent less stable.

It thus appears that the most sensible solution is to focus on truck speed.

Drivers need to be made well aware of the part speed plays in instability. Payment systems need to recognise the dangers in the pressure drivers are under to get "just one more load in for the day". Curves need to be posted for safe truck speeds. That speed should be based directly on the roll-over criterion, rather than just some arbitrary amount less than the speed limit, or some fraction of the limit, because truck stability is related to the square of the speed.

In addition, enforcement efforts need to be focused on speeds, and stepped up at the sites of notorious curves.

Conclusions

Logging truck stability is a very serious issue but while many have commented on the problem, few have examined the basic mechanics in play. When the mechanics are studied, it becomes clear that the problem is linked to the high centres of gravity that logging trucks have, as a result of the fact that they "weigh out" and "bulk out" at about the same point. An analysis of the mechanics of the situation leads to the conclusion that the roll-over accident rate could be significantly reduced if speeds taking into account truck roll-over were posted, if logging truck drivers were to become better educated as to the effects of speed on truck stability, if the economic pressure on them to exceed safe speeds was reduced, and if speed enforcement efforts were stepped up.

Acknowledgment

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