HEAVY VEHICLE SPEED THROUGH CURVES

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ABSTRACT

Heavy vehicle rollover is an issue of concern in many countries In New Zealand and the Netherlands (and probably in many other countries) speed through curves is the cause of more than half the rollovers. In this paper we present the findings of three investigations into vehicle speed through curves.

Two of the studies involved measuring the curve speed behaviour of heavy vehicle drivers. In the first a line haul vehicle was instrumented to monitor its lateral acceleration, speed and location. Measurements were taken over several weeks of operation. Occurrences of high lateral acceleration were then identified and related back to location and speed. Sites of repeated occurrences of high lateral acceleration were identified. In the second study, heavy vehicle speeds were monitored on a number curves with advisory speed restrictions. These measurements have been repeated at intervals of approximately six months. The primary purpose of the survey is to look for changes in speed behaviour over time but we are also able to see differences between vehicle types and with different advisory speed levels.

The third study used a driving simulator to investigate ways in which the speed around curves could be managed through the manipulation of the visual cues that influence driver behaviour. This included determining the effectiveness of different road signs and markings in slowing down drivers.

From the findings strategies for improving the speed through curve behaviour of heavy vehicle drivers are proposed.

INTRODUCTION

A study undertaken in the Netherlands in 1997 (Hoogvelt et al., 1997) found that, based on the Police reports, 61% of heavy vehicle rollover crashes could be attributed to speed through curves, 26% are caused by the vehicle running onto the soft shoulder and 10% are related to evasive manoeuvres. In New Zealand the Log Transport Safety Council maintains a database of all log-truck rollover crashes. Analysis of these data shows that for log trucks in New Zealand, 55% of rollovers are from speed through curves, 21% from running onto the soft shoulders and 6% from evasive manoeuvres. The similarities between these two sets of figures are remarkable given the substantial differences in vehicle type, roading conditions and terrain. The New Zealand log-truck fleet consists primarily of truck and full trailer combinations; more than half the New Zealand highway network is classified as mountainous or hilly and the travel is almost entirely on two-lane roads with very little multi-lane divided highway. In the Netherlands the fleet is dominated by tractor semi-trailer combinations, the highway network is almost all flat and most of the travel is on multi-lane motorways. Although no data have been found from other countries on the cause of their rollover crashes, it would seem likely that the pattern would be similar.

Speed through curves does not mean that the driver was necessarily speeding in the regulatory sense (i.e. relative to the posted speed limit) but rather that he or she was travelling too fast for the stability of the vehicle and the geometry of the curve. In New Zealand we have already introduced legal requirement to ensure that heavy vehicles achieve a minimum level of rollover stability and a paper at this symposium (de Pont et al., 2004) describes the implementation of this measure. In this paper we discuss the driver's speed selection. It brings together the findings from three different projects which all looked at speed through curves but from different perspectives.

The first project involved the measurement of lateral acceleration on in-service heavy vehicles. The location of high risk events was recorded and locations where repeat events occurred were investigated further to see whether there were any identifiable common factors at these sites. The second project involved monitoring the speed of heavy vehicles through curves. A methodology for comparing results from different curves based on the advisory speeds was developed and this led to an investigation of the usefulness of advisory speed signs for heavy vehicle safety. The third study is based on a human factors approach and considers how drivers respond to various types of warning signs and other visual cues. It also looks at the effect of distractions on driver response.

IN-SERVICE LATERAL ACCELERATION MONITORING

Initially in this project, a refrigerated-van B-train operating on a line-haul route between Auckland and Christchurch was instrumented as follows:
- an accelerometer mounted on the front axle to measure lateral acceleration
- a Hall-Effect transducer on the driveshaft to measure vehicle speed
- a string potentiometer to the steering to measures steer input
- a GPS system to monitor vehicle location

The instrumentation was connected to a standalone data acquisition unit with in-built filtering and fitted with a cellular modem so that the data could be downloaded remotely. The system was configured to trigger acquisition of an event at a user-specified level of lateral acceleration and to record all the transducers for a specified interval straddling the event. More recently the instrumentation has been transferred to a log truck-trailer combination operating in the central part of the North Island.

In the initial set of measurements on the B-train the trigger level was set at 0.22g and the event length was 44.4 seconds consisting of 19.4 seconds pre-trigger and 25 seconds post-trigger. The vehicle was monitored over the period from July 2001 to January 2002. In January 2002 the vehicle rolled over but unfortunately the data acquisition had been removed from the truck for upgrading and so this event was not recorded. The data were processed and events with either an invalid GPS position or with a vehicle speed below 10 km/h were removed from the dataset. The remaining events were compared with all other events to determine their distance from each other. Events within a defined distance threshold were deemed to have occurred at the same curve.

After data conditioning there were 352 valid events recorded over a distance of between 146,000 km and 176,000 km. All the events were grouped depending on their location. Events were considered to have occurred at the same curve if they were within 465 m of a given location. This gave 147 unique locations where lateral accelerations above 0.22g were recorded. At some locations up to 24 events were recorded. The locations where multiple events occurred were plotted on a digital map of the New Zealand State Highway network.

The lateral acceleration for each event was plotted against time to ensure that each recorded event was genuine. This required that the duration of elevated lateral acceleration was sufficiently long for the vehicle to respond and be in quasi steady state conditions. Figure 1 is an example of one of these plots. The initial offset from zero in the graph is an indication of the super elevation (cross slope) on the road. In Figure 1 this is approximately 0.07g (4 degrees). The offset is predominately opposite in sign to the peak, indicating positive road camber (banking).

The highest lateral acceleration recorded was approximately 0.38g and this was recorded on two occasions at the same location. The plots of lateral acceleration for these two events were remarkably similar indicating, at least, consistent behaviour by the driver.
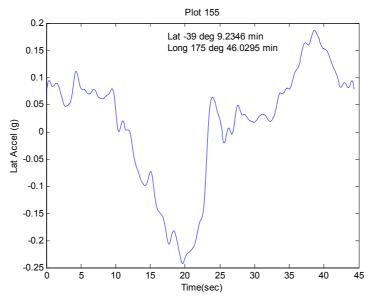
Figure 1. Lateral acceleration versus time for a curve on SH1.

CURVE SPEED MONITORING

In June 2002, the Land Transport Safety Authority (LTSA) approved an application by the Log Transport Safety Council (LTSC) to operate permitted log truck-trailer combinations at up to 22 m overall length (compared to the general length limit of 20 m). The basis of this departure from the size limits was that by increasing the allowed length, more log lengths could be loaded as two packets on the trailer rather than one with significant reductions in load height and improvements in stability. The approval came after a detailed performance analysis, an extended trial and considerable public consultation. A concern that was raised was that with improved vehicle stability, the vehicle speeds through curves might rise and thus the safety benefits from improved stability would be eroded. To ensure that this did not occur, the LTSA required that the LTSC conduct regular surveys monitoring the speed of log trucks through curves.

The first of these surveys was undertaken in July, 2002; before there were any significant numbers of 22 m log trucks operating. The purpose of this survey was to determine some benchmarks of truck speed in curves and to establish the analysis procedures for future surveys. A second survey was undertaken in April-May, 2003.

The survey equipment and personnel were provided by the LTSA. The first survey was taken in a brief period between other speed surveys and so was time-constrained by the availability of the surveyor. As there was no a priori knowledge of the speed distribution it was not possible to accurately determine the sample size needed to obtain statistics within reasonable confidence limits and there was no time to do a preliminary survey. So the surveyor was instructed to survey as many sites as possible within the time available. The data would then be used to establish analysis processes, hopefully estimate some baseline statistics, identify issues for site selection and determine the sample sizes for future surveys. The aim of the survey was to benchmark the speed of logging trucks through curves and to relate these to the speeds of the general heavy-vehicle fleet through curves. Thus routes with high densities of log-truck traffic were identified. The LTSA speed-survey procedures emphasise the need for the surveyor to ensure the safety of both himself and other traffic which means that survey sites must have adequate visibility and road space. It was not possible to identify suitable survey sites from map information and so the selection of the survey sites was left to the surveyor.

The guidelines he was given were:
- to meet all safety requirements
- to select sites with posted advisory speeds spread across the range from 35 to 85 km/h
- the sites should be relatively flat and certainly should not have a significant uphill gradient
- to spend no more than one hour continuously at any site
- to be as inconspicuous as possible
- the surveyed vehicles should be free running, i.e. not have their speed restricted by a vehicle in front.

The basic principle was that the surveyed drivers should be selecting their speed in the curve on the basis of their perception of its severity alone.

In the first survey, data were collected over a period of three days from six different sites. At four of those sites readings were taken in two travel directions. All sites were at curves marked with advisory speed signs, three at 85 km/h, two at 75 km/h and one at 55 km/h. At these curves the speed of 159 trucks including 33 loaded log trucks was measured. Empty log trucks were considered to be part of the general fleet.

Because the number of samples at any one site was relatively small it is desirable to be able to combine the data from different sites and so the data need to be normalised in some way. Three approaches were tried. The first was to normalise the data by the posted advisory speed. The second was to normalise by the advisory speed squared. This approach is based on theoretical considerations because lateral acceleration is proportional to steady-state speed squared and so this is effectively normalising by lateral acceleration. The third approach was to normalise by the average speed for the curve by the whole fleet. This method is useful for comparing log-truck speeds with the rest of the fleet but does not provide any information on how the fleet is behaving.

The first approach seemed to work reasonably well in that the distribution of normalised speeds both for logging trucks and for the fleet as a whole appeared to be approximately normally distributed as expected. The mean normalised speed for the fleet was 1.05 (std error 0.009) and the mean for logging trucks was also 1.05 (std error 0.014). That is, on average vehicles were travelling at 5% above the advisory speed. Further investigation showed that speeds through the 85 km/h curves were lower than for other curves. On reflection this was not surprising. The open-road speed limit for truck-trailer combinations is 80 km/h while that for rigid trucks and fifth-wheel coupled combinations is 90 km/h (in practice the speed for the two categories of heavy vehicles are similar). Thus, on 85 km/h curves the advisory speed is close to the speed limit. The driver's speed selection will be affected not only by the severity of the curve but also by the overall speed limit and for many vehicles the capability of the vehicle as well. Unfortunately the survey included a significant number of 85 km/h curves and again in hindsight this is not surprising. The safety requirements for the surveyor included visibility and space to park the survey vehicle on the shoulder. These characteristics are much easier to find on higher speed curves. On removing the 85 km/h curves from the dataset, it was found that for the lower speed curves, the general fleet (excluding logging trucks) was travelling at 11% (std error 1.6%) above the advisory speed while logging trucks were travelling at 6% (std error 1.4%) above advisory speed. For the 85 km/h curves both groups were travelling at 99% (std error 1.2%) of the advisory speed. An advisory notice from the LTSA to log transport operators in 1999 recommended that, because of their poorer rollover stability, log trucks should go around curves at 10% or more below the advisory. Although log trucks are travelling more slowly than other trucks they are not anywhere near complying with this recommendation.

Using advisory speed squared as the normalising terms rather than advisory speed also worked but did not offer any significant advantages. While using the average speed through the curve of all heavy vehicles except logging trucks as the normalising term showed that, on average, logging trucks were 3.5% (std error 1.2%) slower than other trucks and this result did not change much when the 85-km/h curve data was removed.

For the second survey, a much more comprehensive set of routes was selected. The surveyor was instructed that all sites should have an advisory speed of 75 km/h or less, that he should try to achieve a reasonable spread from 35-km/h curves to 75-km/h curves and, wherever possible, that sites from the first survey were to be surveyed again.

The survey was conducted in April and May 2003. A total of 15 sites were surveyed in the North Island. Speeds were recorded for 381 trucks including 76 laden log trucks. Two of these sites were repeat sites from the first survey. Of the 15 sites, there were five with an advisory speed of 75 km/h, five at 65 km/h, two each at 55 km/h and 45 km/h and one at 35 km/h. In the South Island there were five sites surveyed with 89 trucks recorded including 12 logging trucks. The five sites consisted of three at 75 km/h and one each at 65 km/h and 55 km/h.

As with the first survey, the measurements were normalised by the curve advisory speed so that data from different curves could be combined and compared. In the first survey this approach worked well once the 85 km/h curves were removed from the dataset with the other curves all having similar average normalised speeds. However, for the second survey this methodology did not work as well. Figure 2 shows the average normalised speed compared to advisory speed for all the survey sites. The trend line shows the best straight line fit to these data. Although the r^2 statistic is not high it does improve significantly (to 0.59) if the two main outliers are removed from the dataset.
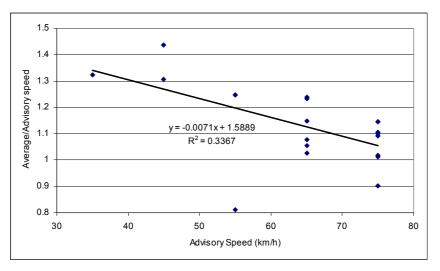

Figure 2. Average of (speed/advisory speed) versus advisory speed, by site.

The speed values on advisory speed signs in New Zealand increase in 10 km/h increments and always end in 5. Thus, for example, a 65 km/h advisory sign covers theoretical advisory speeds from 61 km/h to 70 km/h, a range of 15%. If the driver's speed selection is governed primarily by his (or her) own assessment of the severity of the curve rather than by the sign it would not be surprising to see a range for the average normalised speed of 15% for 65 km/h curves. In fact the range is a little higher than this. However, of more concern is the apparent trend for the average normalised speed to be higher on lower speed curves. This led us to investigate the basis for determining the appropriate advisory speed sign in more depth, with some disturbing findings.

The fundamental basis for setting advisory speeds in New Zealand is passenger car comfort. This also seems to be the case in most other jurisdictions. The basic process is that a passenger car fitted with a relatively simple mechanical lateral acceleration meter, the ball-bank gauge, is driven around the curve and a reading taken. From this reading, a theoretical advisory speed is calculated and if the traffic conditions warrant it the appropriate advisory speed sign is installed. From the equation for theoretical advisory speed, the underlying relationship between lateral acceleration and advisory speed can be extracted. This is as shown in Figure 3. As can be seen, passenger car occupants will accept a higher level of lateral acceleration at lower speeds. Other jurisdictions use a different relationship but have the same trend.

If we then try to use curve advisory speeds as a safety guide for truck drivers we have a serious problem particularly at low speeds. A 31-km/h theoretical advisory speed implies a lateral acceleration of 0.3g. However, this curve would be signposted at 35 km/h and at this speed the lateral acceleration would be 0.38g. In New Zealand we now have a requirement that heavy vehicles achieve a minimum Static Roll Threshold (SRT) of 0.35g. So a vehicle at the lower end of the stability spectrum would roll over at the

advisory speed. Other countries do not have a minimum stability requirement and do have vehicles with SRTs below 0.35g operating on their roads.
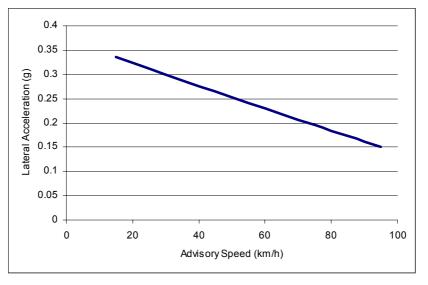

Figure 3. Relationship between lateral acceleration and curve advisory speed.

Compounding this problem, it has been found that in many cases the advisory speed signs are not correct. A survey conducted in 1997 (LTSA, 1998) found that only 53% of advisory speed signs were at the correct speed. Fortunately, most of those in error were on the low side but 17% were posted too high.

Relating these findings back to the survey data (see Figure 2) highlights some major issues. At least two of the survey sites appear to be incorrectly signposted, the lower speed of two 55 km/h sites and the higher of the two 45 km/h sites. The 45 km/h site was, in fact, re-surveyed and found to warrant a 55 km/h sign. Much more concerning was the fact that relative curve speeds seemed to increase as the advisory speed decreased even though lower advisory speeds represent higher lateral accelerations.

PERCEPTION AND ATTENTIONAL EFFECTS ON CURVE SPEED SELECTION

The third study included in this paper is a human factors study which was undertaken using a medium fidelity driving simulator. The work has been published by Charlton (2003) and the presentation here is only an outline summary.

The driving simulator used for the study can use digital photographs and measured road geometry data to generate its driving scenario and so it is graphically quite realistic. The vehicle models in the simulator are AutoSim generated multi-body dynamics models and it can be set up to simulate a passenger car, a rigid truck or a tractor semi-trailer combination. However, it has no motion feedback to the driver.

For this study a passenger-car model was used. The driving scenario was a 28.5 km section of actual road which was then modified to include twelve 45-degree curves of varying radii. Apart from the start and finish sections the road was 2-lane open road with a speed limit of 100 km/h and contained a representative mix of oncoming traffic. Thirty subjects (13 male, 17 female) ranging in age from 17 to 68 years were tested. Each curve was posted with one of the three advisory speed signage options illustrated in Figure 4 or not signposted at all.

The purpose of the test was to determine which style of sign was most effective in reducing drivers' curve speeds. The effect of driver distraction through secondary tasks was investigated. Each driver undertook the test three times each separated by no less than 24 hours and no more than 48 hours. On one of the tests there was no secondary task, on one there was a secondary task where on 16 occasions during the test a simulated cell phone call would occur and the driver would be required to repeat back a sequence of five rhyming words, while in the third test scenario the cell phone calls presented the driver with one word and required him or her to reply with five rhyming words. The order of taking the three tests was randomised. Finally, the

relative conspicuity of warnings presented at different locations in the driver's visual field was assessed by instructing drivers to report on detecting specific signals on roadside signs, on the road surface or on the dashboard. All subjects also completed a survey which included demographic information, driving habits and a standard driver behaviour questionnaire.

Figure 4. Three curve speed advisory options.

Although a number of performance measures were evaluated, the main measure of interest was speed through curves. The first style of advisory sign can be classified as attentional only while the other two have perceptual elements. (Although it may not be clear in the picture in Figure 4, the third style of marking has transverse white lines painted across the lane with the spacing between them reducing as the driver approaches the curve. This creates a perception of speed.)

Participants did reduce speed for the unmarked 45 km/h curves in the baseline scenario (no cell phone tasks) presumably due to the perceptual properties of the curve. The effect of the cell phone tasks was to increase curve speeds particularly for unmarked 45 km/h curves. All three advisory methods worked reasonably well for severe curves (45 km/h) regardless of the demands of the cell phone task. For the higher speed curves (65 km/h and 85 km/h) the diamond signs (first style) were ineffective in the presence of the additional attentional demands from the simulated cell phone tasks. Both of the signs with perceptual features were more effective in reducing curve speeds on the 65 km/h curves with the chevron style marking being most effective on the 85 km/h curves. Other analysis in the study related the driver performance to their characteristics as identified from the questionnaire.

CONCLUSIONS

Curve speed selection was investigated through three quite different approaches. In the first two studies, the curve speeds of truck drivers were monitored and it is likely that most of them were regular travellers on the routes in question and thus had some familiarity with the severity of the curves. It is not known to what extent they used the warnings provided by the curve advisory speed signs in making their speed selection. In the third study the drivers were not familiar with the route and used whatever cues were available to select their curve speed.

Key findings are:
- even when drivers are familiar with a route they do not necessarily select the appropriate speed for the curve as shown by the repeat occurrence of high lateral acceleration events at particular locations in the first study. Lateral accelerations of up to 0.38g were measured.
- the basis upon which the posted speed on advisory speed signs is determined does not make them suitable as a guide for truck safety particularly on lower speed curves.
- truck drivers in New Zealand do not appear to have a good understanding of the stability limits of their vehicles and travel too fast through curves, particularly on more severe curves
- the conventional diamond speed sign used in New Zealand is not very effective when the attentional demands on the driver are increased.

Further work is required to improve truck-driver understanding of the relationship between safety and curve speed and to develop advisory speed warning systems that reflect truck safety rather than just passenger-car comfort.

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