Curve Advisory Speeds in New Zealand

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An Important Note for the Reader

The research detailed in this report was commissioned by Transfund New Zealand.

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Executive Summary

This research project investigated the use of curve advisory speed signs in New Zealand. The main objectives of the research, carried out in 2000–1, were:

1. To study the current traffic behaviour at the location of curve advisory speed signs in New Zealand, to determine their effectiveness and compliance with them.
2. To assess the feasibility of using alternative methods for determining curve advisory speeds, e.g. road geometry data or accelerometer-based systems.
3. To assess the existing ball-bank criteria used for setting curve advisory speeds in New Zealand in light of the above findings.

A review of local and international literature on relevant topics revealed:

1. Driver compliance with curve advisory speed signs is historically poor throughout the world. Curve speeds adopted in New Zealand are generally less conservative than measures used elsewhere, such as most parts of Australia and the US.
2. There is little guidance or documentation available locally to inform road practitioners of the "correct" ball-bank survey procedure.
3. Posted advisory speeds may have modest effects on speeds, compared with equivalent curves that are unsigned or have only curve warning signs.
4. The safety effect of advisory speed signs is unclear.
5. Only about half of the signs locally have been found to have posted speeds matching those determined by ball-bank surveys, with some sites not warranting a sign at all.
6. Multiple ball-bank test runs are required to reduce random errors, with ideally at least one run very close to the true advisory speed.
7. Curves that pose dangers for less stable trucks may warrant specific signing.
8. No appreciable differences in curve speeds between dry and wet weather or between day and night have been observed in most studies.

Field surveys at 28 rural curves, recording vehicles' speed profiles, showed:

1. Posted speeds generally underestimate mean observed speeds by approximately 5–10 km/h and 85th percentile speeds by ~10–20 km/h.
2. Ball-bank derived speeds appear to provide a reasonable measure of observed mean speeds up to about 60 km/h, with a disparity of ~10–15 km/h above this.
3. Heavy vehicles were slower than light vehicles by 4 km/h on average, with no noticeable change in this difference as the mean speeds increased.
4. Driver compliance with posted advisory speeds and ball-bank speeds varied widely, from almost no compliance to almost total compliance.

Analysis of measurements taken during repeated drive-over surveys at four sites found:

1. Driver observation of the speedometer appears to be sufficient to ensure consistent vehicle speeds.
2. Advisory speeds calculated from an electronic gyro were generally less than the equivalent ball-bank speeds, by ~9% on average. “Smoothing” the automatically recorded gyro readings may produce less conservative values.
3. Ball-bank surveys provide a fairly consistent measure, irrespective of driver, vehicle, or test speed. The surveys carried out showed a range of up to 12 km/h between individual tests. When grouped, the differences between groups were still ± 3 km/h.
4. Speed values from road geometry data slightly underestimated measured ball-bank advisory speeds. Using a rolling average of 50–100 m produced a more accurate fit.

Consideration of the above findings in the context of existing procedures concluded:

1. Ball-bank speeds derived assuming a constant advisory ball-bank reading of 17° (irrespective of advisory speed) appeared to fit observed mean speeds very well. This suggests that drivers do not change their level of comfort for different curves.
2. Road geometry data can provide a reasonable alternative to field survey measures and appears to present no less accurate a method for assessing curve speeds.
3. Automated devices for determining curve speeds should be allowed in New Zealand, provided they can replicate a wide range of ball-bank derived speeds consistently.
4. Significantly changing the existing curve speed criteria to produce more realistic posted speeds would have a potential impact on safety. A possible alternative approach instead would be to change the standard subtly by very small increments over a long period of time.
5. The existing method for determining advisory speeds cannot be applied to unsealed roads, as driver discomfort is not likely to be reached before insufficient friction causes loss of control.
6. Sites at which less stable trucks experience problems but which do not meet the normal conditions for advisory speed signing should be considered for truck-specific warning signs.
7. Ball-bank surveys are not accurate enough to warrant allowing a curve advisory speed system with intervals of 5 km/h.
8. Alternative curve warning devices, including road delineation counter-measures and dynamic vehicle warning systems, could provide more effective guidance.

The following items are recommended for further investigation or action.

1. A standard methodology for carrying out ball-bank survey procedures correctly should be made available for local road practitioners, e.g. in the *Manual of Traffic Signs and Markings* [*MOTSAM*]*: Part I* (Transit New Zealand and Land Transport Safety Authority (TNZ/LTSA) 1999).
2. The relative safety benefits of curve advisory speed signs should be identified separately from those of curve warning signs, using local crash data.
3. The effect of changing curve signing on driver behaviour should be studied, using before and after surveys where a speed plate was changed, added or removed.
4. A documented road geometry method should be allowed as an alternative for deriving curve advisory speeds in New Zealand. Allowance should also be made for using properly calibrated automated inclinometer devices instead of ball-bank gauges.
5. Guidelines for curve advisory speeds on unsealed roads should be developed. Further research to observe traffic behaviour at a number of unsealed sites is also suggested.
6. Guidelines should be developed for truck-specific warning signs at sites where the combination of typical speed, radius and superelevation warrants it.
7. Changing the curve advisory speed system to round to posted speeds ending in zero should be considered. This could be done in conjunction with making a slight change in speed criteria.
8. Alternative curve warning devices, such as the road marking counter-measures investigated in Australia and dynamic warning systems, should be trialled in New Zealand.

Abstract

This research project investigated the use of curve advisory speed signs in New Zealand. A literature review identified key issues to examine. Current traffic behaviour at the location of curve advisory speed signs was observed in order to determine effectiveness and compliance. Alternative methods for determining curve advisory speeds, using road geometry data or accelerometer-based systems, were compared with ball-bank surveys. The existing criteria and methods used for setting curve advisory speeds in New Zealand were assessed in light of the above findings, and changes suggested.

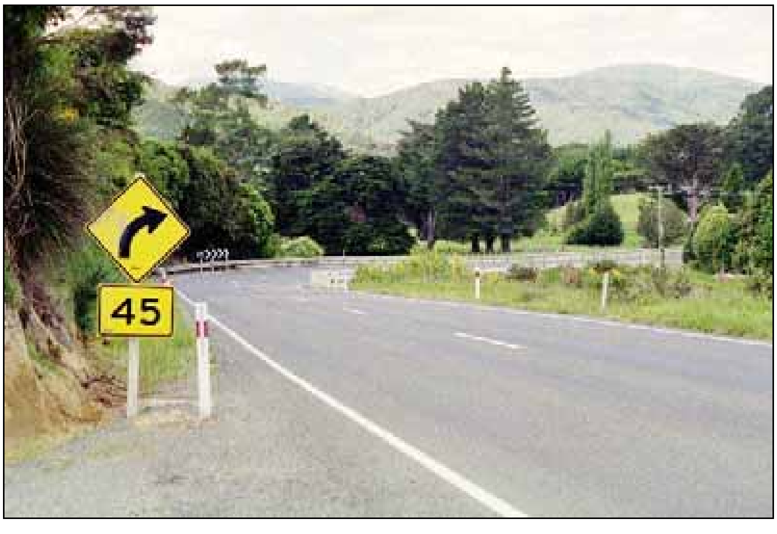
1. Introduction

Despite being a comparatively developed country, New Zealand has both a low population density and relatively difficult terrain. As a result, major roading expenditure is limited and the country continues to rely largely on two-lane highways of varying standard to link the major urban areas and provide access to rural centres. This has resulted in many sub-standard curves out of character with the surrounding environment that need to be identified and ultimately remedied.

As an interim safety measure, many curves are now posted with advance curve warning signs to indicate roughly the direction and severity of the following curve(s). In addition, many have a supplementary plate that shows a suggested "advisory speed" for travelling the curve(s). This is usually a speed ending in 5 between 15 and 95 km/h. Appendix A.1 shows the range of standard warning signs available in New Zealand for signing curves. Standards Australia (1994) defines the curve advisory speed as "the maximum speed at which a curve may be comfortably negotiated under good road and weather conditions".

In common with many countries, New Zealand relies on a "ball-bank indicator" (or "side-thrust gauge") as the standard way of determining the need for and appropriate value of advisory speeds (a detailed description of this device is given in Section 2.3). For more information about the specific methods used to establish curve advisory speeds, readers are directed to Appendix A3 of *MOTSAM: Part I* (TNZ/LTSA 1999). Figure 1.1 shows a typical application of this signage locally. As well as advance warning signs, chevron arrows (both with and without an advisory speed displayed) are also common practice to further delineate curves.

Figure 1.1 Typical curve warning signage in New Zealand.



However, road geometry data and electronic accelerometers are now readily available and may be practical for establishing and reviewing curve advisory speeds.

This research project investigated the use of curve advisory speed signs in New Zealand. In particular, it looked at both the instigation of these signs and their subsequent effects. The research was carried out in New Zealand during 2000–1, and the authors would like to acknowledge the valuable assistance received from Mike Jackett (formerly of the Land Transport Safety Authority) and Dave Wanty and David Petrie of Traffic Design Group.

The project set out to resolve two key questions:

1. Are the existing advisory speed criteria appropriate or do they need changing? If an updated method is considered necessary, the question of how the transition could be safely implemented will also arise.
2. Irrespective of the first question, are there more reliable and robust ways of determining/validating advisory speeds other than the existing ball-bank criteria?

In dealing with these questions, there was a need to consider the practicality of providing consistent and accurate measurement methods for roading practitioners in New Zealand.

1.1 Objectives

The main objectives of this research were:

1. To study the current traffic behaviour at the location of curve advisory speed signs in New Zealand, to determine their effectiveness and compliance with them.
2. To assess the feasibility of using an alternative method to the ball-bank indicator for determining curve advisory speeds, e.g. road geometry data or accelerometer-based systems.
3. To assess the existing ball-bank criteria used for setting curve advisory speeds in New Zealand in light of the above findings.

To meet these objectives, site surveys were conducted at curves to observe vehicle behaviour. The accuracy and repeatability of curve speed prediction using ball-bank indicators, road geometry data and an accelerometer device were also checked. These are discussed in more detail below.

The study concentrated on rural curve advisory speeds. Although some (generally low-speed) curves are signed in urban areas, they are relatively few. Driver behaviour is also more likely to be influenced by both urban speed limits and adjacent land uses, complicating the relative effect of curve warning signs.

1.1.1 Task 1: Site Surveys of Curve Speed Profiles

Site surveys were conducted at curves both with and without advisory speed signs. The effectiveness of advisory speeds was checked by comparing them with actual vehicle speed profiles through the curve. Ball-bank tests were also carried out at each site to assess the true theoretical curve speed. Other relevant site data was also noted to determine any localised effects.

1.1.2 Task 2: Surveys Using Alternative Methods

An accelerometer-based system was developed that can be fitted to a vehicle and connected to a data logger. This device was then used to record data (including lateral and longitudinal accelerations, body roll and travel speed) continuously as various vehicles traversed corners. Software on a connected laptop analysed the data and ultimately derived an advisory speed for the curve.

Road geometry data from curve sites was also used to derive curve advisory speed measures analytically. Existing theoretical relationships for speed profiles were related to the surveyed data collected in Task 1 to establish a sufficiently accurate method. The accuracy and repeatability of curve speed prediction using the road geometry data and accelerometer device were compared with the existing ball-bank indicator and site field data.

1.1.3 Task 3: Review of Existing Advisory Speed Criteria

In light of the findings above, and from literature around the world, the methods for determining appropriate advisory speeds used in New Zealand were reviewed. Possible options for change to New Zealand’s advisory speed criteria were identified and the consequences of these options considered. The practicality of using alternative measuring methods in New Zealand was also reviewed, and recommendations made.

1.2 Report Outline

Section 2 of this report summarises literature reviewed on curve advisory speeds, from New Zealand and around the world.

Section 3 then details the results of site surveys of curve advisory speeds.

Section 4 details the determination of curve speeds using alternative measurement devices.

Section 5 then reviews the existing criteria for determining curve advisory speeds and suggests changes to the current procedures.

Conclusions and recommendations from this report are summarised in Section 6, followed by a list of references and appendices.

2. Literature Review

This section reviews the literature on curve advisory speeds from New Zealand and around the world and identifies some issues for further consideration.

2.1 The Effect of Horizontal Curvature on Speed

Horizontal curves have long been recognised as having a significant effect on vehicle speeds because of the additional centrifugal force. The common curve design equation is:

$$e + f = \frac{v^2}{Rg} \tag{1}$$

where

e is the superelevation (or crossfall), in m/m
(positive when falling towards the centre of the curve)
f is the side friction factor of the road surface
v is the vehicle speed through the curve, in m/s
R is the radius of curvature, in m
g is the acceleration due to gravity, in m/s^2.

The equation can be rewritten as:

$$v = \sqrt{(e+f)Rg} \quad \text{(m/s)} \tag{2}$$

The above equation represents the maximum speed at which a vehicle can safely traverse a curve. This maximum speed depends on the radius of curvature, the superelevation and the side-friction factor. The radius and the superelevation are always fixed for individual curves (although they may vary somewhat through the curve), but different values for the side-friction factor may be employed to provide a margin of safety between the maximum speed and the "design speed".

The design speed was defined by McLean (1989) as:

> A speed selected for purposes of design and correlation of those features of a highway, such as curvature, superelevation and sight distance, upon which the safe operation of vehicles is dependent. It is the highest continuous speed at which individual vehicles can travel with safety upon a highway when weather conditions are favourable, traffic density is low, and the design features of the highway are governing conditions for safety.

Historically, minimum curve design standards were derived by researchers based on two criteria:

1. The side-friction factor demands were not excessive.
2. There was adequate sight distance.

Design guides specify side-friction factor values that decrease with increasing speed. The rate change in side-friction factor as a function of speed and the range of values varies significantly between countries. Table 2.1 lists the range of values for the side-friction factors employed in different countries, as summarised by Bennett (1994).

Table 2.1 Range of side-friction factors used in design guides.

Country	Range of side-friction factors
Australia/New Zealand	0.11 – 0.35
Germany	0.05 – 0.15
Papua New Guinea	0.22 – 0.44
Switzerland	0.11 – 0.22
United States	0.10 – 0.16
Recommended for developing countries	0.15 – 0.33

Side-friction factors for vehicles on curves and the tolerance level of motorists have been subjects for study since the original 1936–40 studies in the US (Merritt 1988). In those early studies it was assumed that there was a relationship between speed and a perceived "safe and comfortable" value for the side-friction factor.

While many design guides still limit the maximum side-friction factor based on the criterion of comfort, others like AUSTROADS (1989) have suggested much higher side-friction factors than would arise from comfort considerations. McLean (1989) found that on lower-standard alignments drivers operated at speeds requiring friction factors in excess of the limiting values traditionally assumed for design. On high-standard alignments (>90 km/h) the side-friction factors used by drivers were within the traditional limits defined by the comfort criterion. In other words, on low-standard curves drivers were prepared to accept much higher side-friction factors, and thus much lower levels of comfort, than had traditionally been assumed.

Chowdhury et al. (1991) noted that modern cars on dry pavements are capable of generating friction coefficients of 0.65 and higher before skidding, with coefficients of 0.40 and higher typical on wet pavements. Lay (1984) indicated that professional racing drivers on public roads have had average side-friction factors of 0.8 recorded, with a peak of 1.02. He argued that "design values of f only become the coefficient of friction if the vehicle is about to slide. Otherwise f is simply the indeterminate part of a force-equilibrium equation".

Bennett (1994) concluded from these findings that the side-friction factor is an outcome of the speed selected by the driver, rather than being a factor governing speed. Given the wide variety of f values used around the world, however, not all of them are evidently based on observed practice.

2.2 International Curve Signing Practice

Signing sub-standard curves is a common international roading measure, but the practice varies quite considerably from country to country. The variety of approaches world-wide deserves further investigation to determine whether New Zealand's current system is the most appropriate.

Donald (1998) provides a comprehensive overview of methods used throughout the world. While curve warning signs are used in many countries, there appear to be three different approaches to the use of curve advisory speeds.

- No curve advisory speeds are provided (e.g. Austria, Belgium, Hong Kong, Hungary, Poland, Sweden).
- Curve advisory speeds are provided on curves where warranted (e.g. United States, Australia, New Zealand, South Korea, South Africa, Canada).
- Curve advisory speeds are not used but regulatory speed limits (or speed zoning) are applied to curves where warranted (e.g. Israel, France, Germany).

In many cases, curve signs are put up only in response to perceived safety problems, rather than proactively. Others apply a criterion based on the relative difference between the safe curve speed and either the operating approach speed or speed limit. Hong Kong discontinued the use of curve advisory speeds in the 1980s after deciding that advisory speeds were not meaningful because of the different performance of different vehicle types, and even of the same vehicle in different weather conditions.

In those countries where curve advisory speeds are used, they are set using a number of different methods. The most common are:

- driving on the curve a number of times before selecting a "safe" speed,
- applying a formula, look-up table or nomograph based on curve geometry,
- using a ball-bank indicator to measure an appropriate advisory speed.

Where ball-bank indicators are used, the graphs used to convert ball-bank readings into advisory speeds are commonly assumed to be based on comfort, rather than safety, owing to the conservative nature of advisory speeds gained via this method.

In contrast to New Zealand, some countries give more precise advisory speeds in multiples of five (although in some cases these are in mph), or they round speeds to the nearest whole ten. In most cases, practitioners report that drivers are able comfortably to exceed the posted speeds, although the Netherlands applies a quite strict safety margin and encourages drivers not to exceed the posted speeds.

2.3 Ball-Bank Criteria for Setting Curve Advisory Speeds

The most common device used to establish curve advisory speeds is the ball-bank indicator. This was developed from use in the aircraft industry to provide a simple and inexpensive instrument for that specific purpose. A steel ball sealed in a curved glass tube is free to roll transversely under the influence of the forces acting upon it. The glass tube is graduated from a centre zero point outwards to the ends of the tube in degrees of a full circle. When the vehicle is exactly horizontal and on a perfectly level roadway, the ball-bank reading should be zero. When the vehicle traverses a curve, the centrifugal force on the vehicle will cause the ball to roll out to a fixed position. Figure 2.1 shows a typical ball-bank indicator ready for survey.

Figure 2.1 Typical ball-bank indicator attached to a vehicle dashboard.

The ball-bank test runs are usually made by a driver and an observer. After checking to ensure that the ball is on the zero position when the vehicle is horizontal and that tyre pressures are all equal, the vehicle is driven around the curve at a constant speed and parallel to the centre line. Usually a number of runs at different speeds are made for validation. As driving speeds increase, side-friction forces acting inwards react on the vehicle. If it were not for the body roll of the vehicle and the superelevation of the curve, the ball-bank angle in degrees would have a direct relationship with this side-friction value. The ball-bank reading in degrees is the sum of the centrifugal force angle plus the body roll minus the superelevation angle. It is a measure, therefore, of the difference between centrifugal and gravitational forces on the vehicle and driver.

The difference between the superelevation angle and the body roll angle is commonly taken to be fairly constant, at around 3° (Preisler et al. 1992). From this, it can be demonstrated that the side-friction value, f, can be approximately related to the measured ball-bank angle:

$$f = \tan(b+3) - e \tag{3}$$

where

b = ball-bank angle (degrees)
e = superelevation (m/m).

A commonly accepted criterion for setting advisory speeds is ball-bank readings of 14° for speeds below 35 km/h, 12° for speeds between 35 and 55 km/h, and 10° for speeds of 55 km/h or greater. These criteria are based on “comfort” tests conducted in the 1930s that were intended to represent the 85th to 90th percentile curve speed (Merritt 1988). Apparently they corresponded to side-friction values of 0.21, 0.18 and 0.15 respectively, although the above side-friction relationship would suggest otherwise.

Some literature on the subject (Merritt 1988) suggests that the existing ball-bank criteria used in setting curve advisory speeds have essentially not changed in over 50 years. Certainly, New Zealand’s original system dates back to local trials carried out in the 1950s (Palmer 1962). In 1992, with the introduction of international symbolic road signs, the criteria were reviewed and a slightly less conservative policy, based on the New South Wales (NSW) standard, was adopted (Jackett 1992). However, the NSW relationship does not appear to be based on anything more recent than surveys in the 1970s (Preisler et al. 1992). More recent major field surveys of vehicle behaviour do not appear to have been undertaken in Australasia. If so, then the NSW relationship is not likely to represent current vehicles’ performances and drivers’ behaviours either. For example, road safety practitioners have been concerned about the stability and handling of recent popular vehicles such as four-wheel-drive “family” vehicles and utility vans.

Chowdhury et al. (1991) suggested replacing the existing criteria (10°/12°/14°) with a higher range that would better reflect observed or average curve speeds. The suggested new criteria were ball-bank readings of 20° for speeds below 30 mph (48 km/h), 16° for speeds between 30 and 40 mph, and 12° for speeds greater than 40 mph (64 km/h). It should be noted that many local ball-bank gauges do not provide so wide a range, often extending only to 18°.

The mechanical nature of the ball-bank indicator also brings into question its reliability for assessing curve advisory speeds. Donald (1998) listed practical problems that have been identified with the ball-bank method:

- Repeatability is poor when the chosen test speed differs markedly from the resultant advisory speed.
- The ball-bank indicators are imprecise, relying on manual observation and being subject to disturbances from the road and vehicle.

McLean (1974) suggested that equipment errors are a leading contributor to the inconsistency of posted advisory speeds, with previous studies showing that some ball-bank indicators are giving erroneous readings. Griffiths-Jones & Locke (1995) also suspected a speed dependence in the current measurement methods, i.e. driving the curve at different speeds produced different advisory speeds.

During a nation-wide Land Transport Safety Authority (LTSA) survey on advisory speed signs, the average difference in calculated ball-bank speed between the first and second run over 322 curves was 1.88 km/h, with a standard deviation of 1.82 km/h (Jackett 2001). The range was 0 to 16.4 km/h, but there were very few runs with more than 6 km/h difference. This finding contrasts with the previous concerns about ball-bank reliability.

The need to have this specialised device available is obviously also compromising the undertaking of some surveys, where subjective assessment only is being used instead. In recent times, however, LTSA has endeavoured to increase the supply of ball-bank gauges throughout New Zealand. It is also not clear whether operators understand the proper usage, such as damping using water-filled tubes, and varying driving speeds. It is notable that no information is currently provided in *MOTSAM* on the correct procedure for ball-bank tests, nor in any other local standard guideline. However, AS 1742.2 (Standards Australia 1994) describes a survey methodology designed to minimise the measurement error when using the ball-bank indicator.

2.3.1 Current New Zealand Ball-bank Derived Speeds

The current method for determining curve advisory speeds in New Zealand is based on formulae summarised by Preisler et al. (1992), and these are presented below. It should be noted that the simplifications they present for removing "tan *x*" terms are not strictly correct, as tan *x* can be approximated to *x* only for very small *x* when the angular units are in radians and not degrees (requiring a scale factor of π/180). The end result is still correct, however, as it involves a ratio that allows these factors to cancel one another out.

A linear equation is derived for the relationship between the ball-bank reading, b_A (degrees), and the true curve advisory speed, V_A (km/h):

$$b_A = 20.4 - 0.125V_A \tag{4}$$

This equation is used in NSW, and differs slightly from the Australian standard equation of $b_A = 17.5 - 0.1V_A$.

The above relationship alone could be used to determine advisory speeds by carrying out a series of test runs at different speeds until the test speed produced the correct relationship with *b*, at which point the true advisory speed would be known. However, Preisler et al. found that a more efficient technique can be achieved by noting the following relationship:

$$\frac{b_T + K}{b_A + K} = \frac{V_T^2}{V_A^2} \tag{5}$$

where

b_T = ball-bank angle (deg) at test speed
b_A = ball-bank angle (deg) at advisory speed
K = constant for effect of superelevation and body roll, usually taken as 3°
V_T = test speed (km/h)
V_A = curve advisory speed (km/h).

The two equations can then be combined to form:

$$(b_T + 3)V_A^{\,2} + (0.125\ V_T^{\,2})V_A - (23.4\ V_T^{\,2}) = 0 \tag{6}$$

Solving for V_A, using the quadratic formula, produces the formula found in *MOTSAM*:

$$V_A = \frac{V_T\left[\sqrt{V_T^2 + 6000(b_T + 3)} - V_T\right]}{16(b_T + 3)} \tag{7}$$

2.4 Calculating Curve Advisory Speeds from Road Geometry

Another method used to determine the advisory speed is to derive it from known road geometry data. On New Zealand state highways, for example, regularly collected data is available at 10 m intervals for:

- horizontal curvature (expressed as radius or 1/radius),
- gradient,
- superelevation or crossfall.

Combining these data with the design value for side friction (*f*), it is possible to calculate the design speed of a road section, as discussed in Section 2.1. Simplifying Equation 2 to use more familiar speed units, it becomes:

$$V^2 = 127\,R \times (e + f) \tag{8}$$

where

e = superelevation (% crossfall)
f = coefficient of side friction
V = design speed (km/h)
R = radius (m).

As discussed in Section 2.1, research has shown that the value of the coefficient of friction (*f*) used in the design equation is not a factor that governs traffic speed, but rather an outcome of the speed selected by the driver. Rawlinson (1983), in determining advisory speeds from the Australian Road Research Board's road geometry data acquisition system (RGDAS), used the following simple relationship to derive this:

$$f = 0.30 - 0.0017\,V \tag{9}$$

Substituting this in the previous equation, *V* can be solved for using the quadratic formula. On this basis, an alternative speed formulation which is independent of friction was adopted by Wanty et al. (1995). This was termed the "RGDAS advisory speed function" (*AS*), which is defined as:

$$AS = -\left(\frac{107.95}{H}\right) + \sqrt{\left(\frac{107.95}{H}\right)^2 + \left[\frac{127{,}000}{H}\right]\left[0.3 + \frac{X}{100}\right]} \tag{10}$$

where

AS = RGDAS advisory speed (km/h)
X = % crossfall (sign relative to curvature)
H = absolute Curvature (rad/km) = (1000 m / R).

Using this relationship, the road geometry data can be used to generate a speed measure over the state highway network. This approach is specified as an alternative method for determining curve advisory speeds in Australia (Standards Australia 1994).

A relationship between the observed 85th percentile speed of passenger cars and the RGDAS advisory speed was derived (Wanty et al. 1995) based on observations of 34 curves (Bennett 1994). This indicated that the RGDAS advisory speed is generally more conservative than the 85th percentile speed and matches the mean traffic speed.

If necessary, gradient effects can also be incorporated into the *AS* by using a simple formula to limit speeds (derived from Bennett 1994):

$$AS \leq 125 - G \times 5 \tag{11}$$

where

G = % gradient (positive = uphill).

This helps to dampen speeds on steep uphill slopes where the curve is not the most limiting factor. For example, on an 8% uphill grade, the *AS* cannot exceed 85 km/h. The above factor applies to car speeds; for truck speeds, a different calculation can be derived, and applied to steep downhill grades as well.

Various speed measures can be calculated from road geometry data using the above formulae. The calculated speeds from section to section often vary quite erratically due to the recorded changes in road geometry, and this does not represent vehicle speed profiles. Therefore, some kind of smoothing algorithm is usually required. For example, “local operating speed” can be taken as the average speed over the 100 m length surrounding the 10 m section of interest, while “approach speed environment” can be approximated by the average speed over the previous 500 m. A 100 m length for local speed “irons out” any irregularities in the data and approximates the actual changes in speed that a vehicle will make. The resulting analysis can then identify any sections where local speed is significantly less than the speed environment, warranting intervention (Koorey & Tate 1997).

Other systems around the world assume different values for friction, resulting in marked variation in suggested speeds. Chowdhury et al. (1991) noted that the commonly used US nomograph assumes a friction value of 0.16, irrespective of speed. It was suggested that values of 0.3 at low speeds and 0.2 at high speeds would provide more realistic determination of safe speeds.

Bennett (1994) took a slightly different approach from the mechanistic one outlined above. Noting that superelevation also did not appear to significantly affect observed curve speeds, he derived curve speed prediction models of the form:

$$S_c = a_0 + a_1.S_a + a_2/R \tag{12}$$

where

S_c = predicted curve speed (km/h)
S_a = approach speed (km/h)
R = curve radius (m)
a_0, a_1, a_2 = coefficients to be determined.

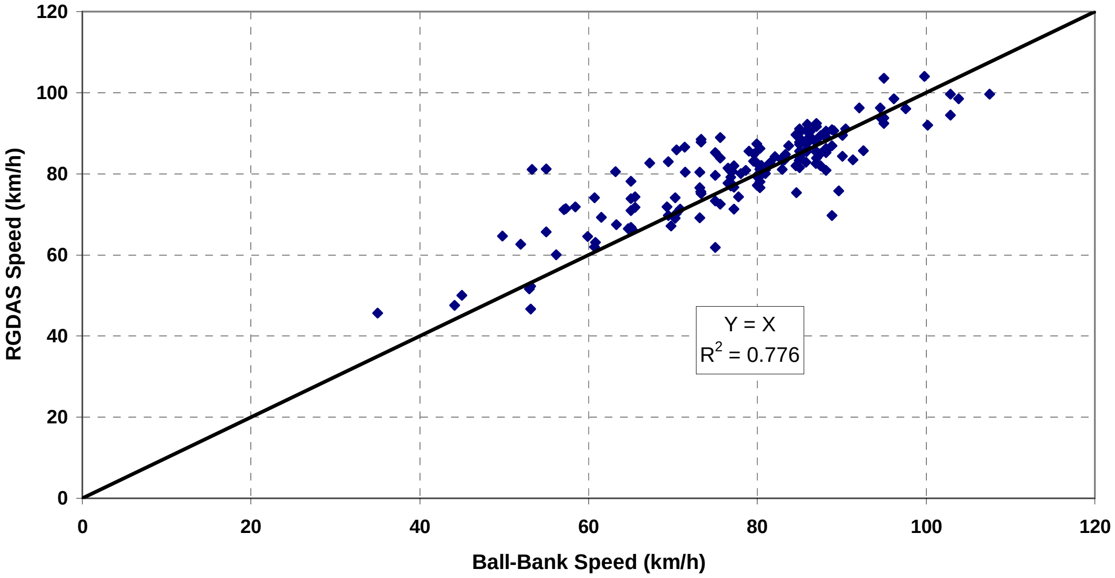
By using different percentile approach speeds, relationships for different percentile curve speeds were fitted with good ($R^2 > 0.8$) explanatory power. This approach appears to merit further investigation.

2.4.1 Local Application of Road Geometry Derived Speeds

Opus International Consultants (Opus) used road geometry data to undertake a desk-top analysis of sites requiring advisory speeds as part of an overall review of signs on state highways in Otago/Southland (Opus 1999). Curvature values were used first to identify the location of "curves" within the geometry data. The RGDAS advisory speed function was then used to derive measures for local curve speeds and approach speed environments. From these, locations that warranted advisory speed signs could be identified and compared with those recorded in the Road Assessment and Maintenance Management system (RAMM) signs inventory. The anomalies between the two lists were then field-tested using traditional ball-bank surveys to confirm any changes in signing.

Figure 2.2 shows the comparison between calculated and measured advisory speeds for the Central Otago network. The data showed that the advisory speeds calculated by RGDAS were close to the survey results obtained using a ball-bank gauge. If it is assumed that the RGDAS speed is equal to the speed surveyed via ball-bank gauge, this relationship fits the data fairly well, with an R^2 value of 0.776. The Southland network showed a similar relationship; however, the data collected from Coastal Otago was not as good. This may have been caused by inconsistent operation of the ball-bank method, given that different surveyors were used in each network.

Figure 2.2 Comparison of ball-bank surveys and RGDAS advisory speeds (Central Otago).



Some of the biggest inconsistencies appeared to be at tight curves with very low speeds; RGDAS was not producing values quite as low. However, this appears to be a consequence of the way the original RGDAS road geometry data was produced. A smoothing function produced curvature values as a rolling average of a number of values, and this tended to mask the true extreme values found at short curves of small radius. The more recent road geometry data does not have this problem.

The correlation appears very promising. Certainly, as a “first sieve” desk-top exercise prior to field surveys, the approach enabled the number of field surveys to be greatly reduced. However, the suitability of these approaches for general use needs to be confirmed with further field data.

2.5 Alternative Methods for Determining the Curve Advisory Speed

Various commercially available products have been touted as “hi-tech” alternative methods for determining suitable curve speeds. Generally they work by incorporating accelerometers to determine the forces acting on the vehicle carrying them, and from these derive suitable speed measures. One regularly mentioned product was Valentine Research’s “G-Analyst”, but these are no longer on the market. Other more complicated devices are often developed more specifically for the car-racing market.

HMR Communications in the US claims that its equipment is able to obtain highly accurate “Advisory Curve Speeds” (HMR 2000). The kit includes two electronic ball-bank sensors, interface cables and the software for performing curve advisory speed measurements. HMR states that the advantage of this equipment over the traditional ball-bank gauge is that users have to drive on the curve only once at any speed to determine the proper curve advisory speed. Quite how this allows for driving or vehicle variation is unclear, and it would seem that making multiple runs is still a prudent approach.

A search of Internet sites produced other similar products, typically from the US. For example, as well as supplying manual ball-bank indicators, Rieker Inc. also produces an electronic version (Rieker 2001). Vericom Computers Inc. has a range of accelerometer devices, including its flag-bearer VC2000 single-axial product (Vericom 2001).

The key advantage of these devices over manual ball-bank measuring methods would appear to be their accuracy in recording the correct lateral forces at the actual speed driven, rather than relying on observation for both of these measures. The associated software also has the further advantages of being able to record these measures and automatically determining the appropriate curve speed, although similar tools could easily be derived for ball-bank surveys using (say) a spreadsheet on a laptop. The cost of these items is often the sticking-point, as the above products typically retail for about US$500.

2.6 Safety Effects of Curve Warning Signs

Previous research (Matthews & Barnes 1988) has shown that crash rates increase significantly where the difference between local curve speeds and the approach speed environment is large (e.g. >15 km/h). This can be explained by the element of “surprise” affecting driver performance, e.g. an unexpected tight curve at the end of a long straight.

Between 1995 and 1999, there were 819 head-on/lost-control injury crashes on rural roads with “severe” curvature, costing New Zealand an estimated $41.6 million a year. Of these, 492 were on curves with no existing curve advisory speed (cost: $23 million a year), while 327 were on curves with an existing advisory speed sign (cost: $18.6 million a year). Clearly, curve speed warning signs will not eliminate all crashes. In fact, given that in New Zealand curve warning signs are typically present on only about 25–30% of “tight” curves, these sites appear to be over-represented in the crash data. However, it must be remembered that such signs are generally placed on the most “dangerous” curves (in terms of the relative speed change). As Jackett (1992) found, in New Zealand these curves typically have crash rates 1.5 to 4 times higher than curves requiring only minor speed reductions.

Although, intuitively, the safety benefits of advisory speed signs seem apparent, little research has directly identified the likely crash savings. Palmer (1962) intimated that the signs reduced crashes when introduced to New Zealand, but no specific details were provided. Rutley (1972) found an average 20% reduction following the installation of advisory speed plates to curve warning signs in three UK counties, albeit on limited data.

Previous Australian research has indicated that higher crash savings (at least 30%) are likely for the installation of curve warning signs with curve advisory speeds (Sanderson et al. 1985, Kneebone 1964). However, little data is available on the relative contribution of the warning sign itself and of the advisory speed plate. There are also the questions of whether some crashes “migrate” to subsequent curves, and whether sites chosen because of high crash records would have experienced falling crash numbers anyway (“regression to mean”).

2.7 Driver Compliance with Curve Advisory Speeds

An important factor when considering a curve advisory signing system is the likely effect on driver behaviour. Several studies have attempted to observe driver speeds on curves. Not all have involved curves with advisory speed signs, but they still have some relevance to the overall problem.

2.7.1 Overseas Studies

Chowdhury et al. (1991) used both ball-bank and standard US curve nomograph methods to derive the recommended speeds on 28 curves with advisory speeds posted. Both methods provided the same results at 15 sites. At the remaining sites, the differences in recommended speeds were still within 5 mph (8 km/h).

Speeds were collected on the 28 curves using radar and compared with the posted advisory speeds. The results indicated that compliance with the posted limits ranged from 43% to 0% depending on the advisory speed (see Table 2.2). Driving speeds did reduce on approaching the curves, but only by half (on average) of the expected drop according to the posted advisory speed (see Table 2.3).

Table 2.2 Percentage compliance with advisory speeds.

Advisory speed (mph)	% compliance
15–20	0
25–30	8
35–40	5
45–50	43

Table 2.3 Observed average speed reduction.

State	Posted speed drop (mph)	Actual speed drop (mph)
Virginia	15.8	4.6
Maryland	18.7	10.4
West Virginia	7.9	4.9
All curves	15.1	6.1

The survey revealed that the 85th percentile friction value observed (0.29) was almost twice the assumed value of 0.16 applied in the existing advisory speed-setting techniques.

The authors established that observed 85th percentile curve speeds were considerably higher than posted advisory speeds, irrespective of the method used to determine the advisory speed. Further, they suggested that the posted advisory speeds had little relevance to motorists because the frictional basis for the criteria was too conservative.

These findings led the researchers to question the relevance of the existing criteria for setting advisory speeds. Drivers may be setting their speeds according to the perceived road conditions rather than the posted advisory speed. It should be noted, however, that comfort rather than safety is generally used as the basis for setting advisory speeds, and the implications of this need to be considered.

The above study does not identify whether drivers were actually travelling more slowly after the introduction of the signs. Kneebone (1964) found on 10 curves along the Hume Highway in Australia that mean speeds dropped by an average of 2.3 mph (3.6 km/h), with a maximum mean reduction of 6 mph (10 km/h). The 85th percentile speeds also dropped by a similar amount.

At least two overseas studies have suggested that driver speeds could in fact go up after the installation of advisory speed signs (Ritchie 1972, Rutley 1972). These findings may be explained by increased driver confidence because of the additional information provided. Additional curve chevron markings may produce similar effects.

Some research suggests that advisory speeds have a modest to negligible effect on driver speeds, particularly for drivers familiar with the road (TRB 1998, Zwahlen 1987). It is also suggested that advisory speed signs are no more effective at slowing speeds than curve warning signs on their own. One likely reason for the poor compliance is that posted advisory speeds are often set unrealistically low; the current US criteria for setting advisory speeds on curves, for example, are based on vehicles and tests from the 1930s (Chowdhury et al. 1998).

2.7.2 New Zealand Studies

Barnes & Thomson (1984) conducted similar surveys on 11 curves with posted advisory speed signs ranging from 30 km/h to 70 km/h. The compliance was poor too, with very few cars not exceeding the posted speed and most exceeding them considerably. Table 2.4 summarises the findings.

Table 2.4 Compliance of cars with curve speeds in New Zealand.

Advisory speed posted (km/h)	Number of curves	% compliance with posted speed	% compliance with speed + 10 km/h	% compliance with speed + 20 km/h
30	2	4%	73–88%	100%
40	1	0%	19%	78%
50	3	0–1%	19–41%	78–93%
60	2	0–5%	8–39%	54–77%
70	3	5–15%	24–61%	58–95%

Barnes & Thomson found that the mean observed speeds increased 1.12 times faster than the posted speeds, suggesting that motorists were prepared to exceed the posted speeds by greater margins at higher speeds. In comparing these with additional sites that had no posted speeds but similar true advisory speeds, they found no significant difference in mean speeds, although it appeared that standard deviations were slightly greater at the unposted sites.

Barnes & Thomson also compared their data with earlier New Zealand speed data by Palmer (1962). They concluded that modern motorists negotiate curves at far higher speeds than did their counterparts 25 years earlier. It is interesting to speculate whether this trend has continued to the present day.

An evaluation of the application of AUSTROADS horizontal curve design standards to New Zealand (Bennett & Dunn 1994) included a curve speed survey. Observations from 23 curves in the North Island indicated that at only 39% of sites were 85th percentile speeds below the design speed. At the 13 flat curves with advisory speed signs, Bennett (1994) found that all the 85th percentile curve speeds were between 10 and 28 km/h higher than the posted advisory speed. Drivers were not observed to have difficulties in negotiating the curves at these speeds. Bennett suggested that drivers were simply increasing the advisory speed by a fixed amount and traversing the curves at this higher speed. Therefore, an increase of advisory speeds to more "appropriate" levels could lead to an increase in accidents, since drivers have already altered their behaviour to account for the low posted speeds.

2.8 Accuracy of Posted Speeds

Curve advisory speeds can provide a safe and credible traffic measure only if the posted speeds are considered accurate. Many concerns, from both the public and the roading industry, relate to apparent inconsistencies in the speeds used. There is also some anecdotal concern about the use of values ending only in five, which suggests a greater precision (to the nearest 5 km/h) than is actually calculated (to the nearest 10 km/h).

In New Zealand, a recent LTSA survey (LTSA 1998) found poor compliance by road controlling authorities in setting the most appropriate curve advisory speed. Almost half were at least 10 km/h out, with some up to 30 km/h different from the recommended advisory speed. Twenty percent of the signs were also not warranted, based on either the approach or the curve speeds determined. This has significant safety implications and confirms the anecdotal evidence about inconsistencies in posted speeds. Because of the divergence between practice and policy in sign size and location, the report recommended that guidelines should be reviewed.

Some roading authorities have expressed concerns about the consistency of measurements (Donald 1998) and have taken various steps to "standardise" survey techniques. For example, the South Australian Department of Transport has a ball-bank device fitted within a test vehicle that is used for all curve assessments, which are made by the same personnel.

McLean (1974) identified several possible sources of error when measuring advisory speeds:

- instrument precision errors, due to inaccuracies in reading off ball-bank angles and vehicle speeds,
- short-term variations, due largely to vehicle vibrations and roughnesses in the road surface,
- instrument biases, due to built-in errors in the measuring equipment and vehicle (e.g. body roll), particularly if uncalibrated.

McLean determined that observed speeds are likely to introduce the greatest errors. For test speeds 10 km/h lower than the actual advisory speed, on a curve with 8% superelevation, the computed speed from a single run could be 6 km/h higher than the true speed. With a test speed 10 km/h higher, the computed speed was 3 km/h lower than the true speed. These findings confirm the need to have at least one run driving at close to the true advisory speed, and for multiple runs to reduce the likely error.

2.9 Effectiveness of Curve Signing

Advisory speed signs have evidently been effective in reducing vehicle speeds and the severity of accidents. However, there is good reason to believe that the effectiveness of road signing depends on a driver's attentional and visual search behaviour (Hughes & Cole 1984).

Summala & Naatanen (1974) and Hughes & Cole (1984) tested attentional conspicuity and demonstrated that drivers' motivation and expectancy levels influenced the perception of highway signs. Moreover, the amount of importance attached to advisory signs in general also affected driving performance (Summala & Hietamaki 1984).

Several studies have investigated the factors determining search conspicuity on the ease of locating a road sign. These factors include the background of the road environment (Jenkins 1982), the size, definition and brightness, and type (symbols) and colour of information presented (Jenkins & Cole 1979a, 1979b). These studies suggest that the location of the curve warning signage in relation to the background environment can be critical to its relative effectiveness.

Zwahlen (1987) examined the effectiveness of advisory speed signs used in conjunction with curve warning signs in Ohio. The results indicated that drivers, on average, look about twice at a warning sign (duration of fixation 0.5 to 0.6 seconds). Based on the findings from 40 test drivers, he concluded that advisory speed signs are not more effective in causing drivers to reduce their speeds through curves than warning signs alone. It appeared that the bent black arrow in the yellow diamond of the curve warning sign represents such a strong and primary visual stimulus that an advisory speed sign adds very little additional information for the driver. Therefore, it was recommended that advisory speed sign maintenance and especially new installations be given a low priority.

In New Zealand, as well as the standard curve warning and speed signs, chevron boards with advisory speeds are also commonly used to delineate curves, in some cases without a corresponding advance warning sign. Anecdotal evidence suggests that these are more effective in highlighting posted advisory speeds by virtue of their location more directly in front of the driver's viewpoint.

2.10 Other Factors Relevant to Curve Speeds

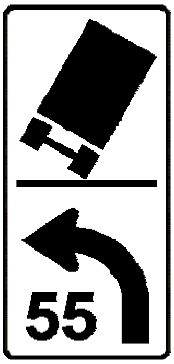
Several other issues have arisen both from the literature and from industry discussion. These are discussed below.

2.10.1 Heavy Vehicle Speeds on Curves

Currently the ball-bank method requires the test vehicle to be a medium-sized car or station-wagon. The particular dynamics of heavy vehicles have not been considered. Implicit in this is the assumption that heavy-vehicle drivers are aware of their vehicle's constraints.

Donald (1998) found that no country specifically considers heavy vehicles in the process used for setting curve advisory speeds. However, AS 1742 (Standards Australia 1994) now includes a "tilting truck" symbolic sign for use "where there is a history of trucks toppling even where all other required curve warning and delineation devices are provided". Figure 2.3 shows a typical example of the sign used.

Figure 2.3 Example of Australian curve warning sign for trucks.



Trucks exhibit different performance dynamics from cars. Cars or motorcycles will respond to excessive lateral acceleration and yaw movement by skidding, usually rolling only if they strike an object. Trucks will roll over once they exceed a critical value of lateral acceleration called the roll limit. This limit is a function of the vehicle's centre of gravity height (COG) and track width, with suspension type, trailer-combination configuration, tyre frictional characteristics and articulation angle all having an impact. Rigid trucks in particular are often more vulnerable to toppling, owing to the lack of hinges.

Navin (1992) analysed critical cornering speeds for trucks. For a typical rigid truck, the maximum lateral acceleration before rollover, a_n, can be approximated as:

$$a_n = (T + h\theta)/(h - T\theta)g \qquad (m/s^2) \tag{13}$$

where

T = half-width of truck, from middle to centre of outer tyres (m)
h = height to truck centre of gravity (COG) (m)
θ = superelevation of road (m/m).

This assumes that the truck will roll, and not slide first, i.e.

$$\text{Side friction } f \geq T/h$$

At large slip angles, f for typical truck tyres is ~0.6–0.7, so this is not likely to be an issue for the high loaded trucks of most concern. From the above, the maximum safe vehicle speed on a curve with radius R (m) can then be determined:

$$V_{max}^2 = a_n.R \tag{14}$$

These guidelines could be used to determine safe truck speeds for different curve configurations. Navin found that the average truck rollover acceleration was 0.46–0.47 g, with a standard deviation of 0.06–0.08 g.

An interesting reference by Navin suggested that drivers and carriers still contribute the largest relative influence on tractor-trailer rollover stability (about 40–45% influence). Vehicle designers of tractor/trailer units contributed 35–40%, with the balance shared between highway designers and road builders. This raises the question of how much effect improvement in curve design and signage will have if vehicle standards and fleet practices do not also change.

Harwood & Mason (1993) determined the margin of safety against skidding or rollover for a passenger car or truck on a horizontal curve and the speed at which skidding or rollover would occur. They concluded that, on lower design speed horizontal curves designed using the high-speed design criteria, the most unstable trucks can roll over when travelling as little as 5 to 10 mph (8–16 km/h) over the design speed.

Mueller et al. (1999) compared rollover crash rates for New Zealand trucks with the relative vehicle configurations involved. They found that 15% of trucks in New Zealand had a static rollover threshold (SRT, equivalent to a_n above) of less than the recommended 0.35 g minimum. Trucks with an SRT of less than 0.3 g had three times the involvement in rollover crashes. Similar findings were made when examining other dynamic truck performance measures.

In New Zealand, logging trucks are a particular concern on curves, as many of them have SRTs below 0.35 g. An LTSA study revealed that loss of control was reported in 72% of crashes of loaded logging vehicles, and most of these (82%) occurred on corners (LTSA 1999). Field surveys also found that logging trucks travelled on average up to 10 km/h above posted advisory speeds on corners. LTSA advised operators and drivers to reduce speed, especially on corners, and go at least 10% below any advisory speed sign posting on corners. They also reinforced the need for road controlling authorities to post accurate curve advisory speeds.

Together with improved enforcement and vehicle standards, such measures appear to be working. Comparison of the figures for the period July 1996 to July 1997 with those for July 1999 to July 2000 shows that, despite an increase in the number of logging trucks on the roads, the number of crashes in which they rolled over dropped by 48% (LTSA 2000).

Barnes & Thomson (1984) compared the cornering speeds of cars and trucks at six sites. The results are summarised in Table 2.5 opposite.

Although most trucks still exceeded the curve advisory speeds, the percentage of such trucks was less than the percentage of cars exceeding the advisory speeds. The survey suggested that generally trucks negotiated curves at slower speeds than cars.

2.10.2 Curve Speeds in Wet Conditions

A wet pavement produces a lower friction coefficient, leading to a lower maximum safe speed. Hence, when it is or has recently been raining, one would expect drivers to slow down somewhat to maintain a similar margin of safety.

Wallman et al. (1997) indicated that the operating speed of passenger cars on wet pavement varied from 75% to 90% of that on winter dry pavement. Speed studies in the US (Cleveland 1987) reported that speeds on wet pavements were lower than those on dry pavements by 3 to 8 km/h.

Table 2.5 Comparison of New Zealand vehicle speeds at curves.

Site	True advisory (km/h)	Posted advisory (km/h)	Vehicle type	Number surveyed	Mean speed (km/h)	% vehicles above true advisory
Desert Rd	33/34	30	Car	192	37.4	84%
			Truck	20	31.1	40%
SH58	56	50	Car	358	62.9	89%
			Truck	37	60.5	78%
Atiamuri	67	60	Car	74	73.6	74%
			Truck	38	74.6	84%
Atiamuri	67	None	Car	113	75.9	82%
			Truck	32	73.6	69%
Pokeno	67	70	Car	183	80.4	95%
			Truck	49	74.3	84%
Pokeno	69	70	Car	120	78.8	88%
			Truck	63	74.5	81%

On the other hand, one study investigated the influence of wet pavements on the operating speeds of passenger cars on 24 horizontal curves in New York State, and it was reported that light to moderate rain had no significant influence (Lamm et al. 1990). Speeds appeared to drop only when rain was heavy enough to affect visibility, suggesting that drivers place more emphasis on available sight distance than available friction. In the UK a similar study suggested that speeds at curves were not particularly affected in the wet (Shaw & Mayhew 2000). The fact that drivers do not appear to modify their behaviours at curves in wet conditions suggests a useful area for further research.

2.10.3 Day Versus Night Curve Speeds

When it is dark, drivers are more limited in their view of an approaching curve and background, particularly for those parts of the curve not in the immediate line of the headlights. To counter this, reflectorised edge marker posts and chevron arrows are usually used to assist night delineation. It is not clear whether these make up adequately for the loss of other visual cues and whether this causes drivers to go more carefully and slowly around a curve.

Bennett (1994) investigated whether or not there was a significant difference in the speeds between day and night. Since passenger cars would be most affected by light conditions, owing to their higher speeds, the analysis concentrated on these. The tests were performed on 125 survey stations at 42 sites. By far the majority of stations investigated (70%) showed no significant difference (at the 99% level) between day and night speeds.

Barnes & Thomson (1984) investigated day/night differences from six site surveys. They also found no significant difference in mean speeds in all but one case.

Standard deviations, however, were slightly greater at night, suggesting a greater dichotomy between cautious and risky drivers.

Overseas, Zwahlen (1987) also found that only some of his curve speed measures had statistically significant differences.

All of these results suggest that night driving may produce a slight reduction in speeds, but it is not particularly noticeable.

2.10.4 Variation of Speed Through Curves

Bennett (1994) suggested that generally vehicles decelerated in the first half of the curve (entry to mid-curve), and accelerated in the second half of the curve (mid-curve to exit), although usually accelerating to a lesser degree. However, his survey also showed that about 30–40% of decelerating vehicles continued to decelerate in the second half, apparently those with higher approach speeds. Also, about 20% of vehicles entered the curve below their mid-curve speed and accelerated in the first half of the curve.

Barnes & Thomson (1984) carried out a small survey at night on one unsigned curve. This showed that faster vehicles on the approach straight tended to negotiate the curve faster, although they reduced their speed more than slower vehicles.

2.10.5 Curve Speeds on Unsealed Roads

Given that over 40% of New Zealand's roading network is unsealed (albeit usually with lower traffic volumes), the applicability of advisory speeds to unsealed roads also needs to be investigated.

The previous New Zealand advisory speed criteria contained a separate nomograph for "metalled" roads (NRB 1983), but this has been removed. It assumed a friction value of approximately two-thirds that of sealed roads, with ball-bank values ranging between 6° for 80 km/h curves to 13° for 20 km/h curves.

Standards Australia (1994) appeared to discourage advisory speeds on unsealed roads, stating:

> Advisory speed signs are generally recommended for use on sealed roads only. They should not be used on unsealed roads unless it can be reasonably expected that the advisory speed will remain constant over time and will not be subject to significant variations due to changes in surface conditions caused by weather or pavement wear.

It could be argued that similar variations in skid resistance on sealed roads occur, due to wear and tear and wet weather.

The key difference with unsealed roads is the likely reduced friction available. Transit New Zealand (2000) suggests some figures from VicRoads, which specify maximum unsealed side-friction factors between 0.08 and 0.12.

Another possible factor to consider, for both sealed and unsealed surfaces, is the influence of roughness on the friction available to vehicles. Erratic changes in the road profile can affect the dynamics of the vehicle and vary the amount of friction that the tyres can generate on the road surface. Because of the complex nature of vehicle dynamics, this is a difficult problem to identify at specific sites.

2.11 Discussion

The above findings raise a number of questions about the relevance of the existing criteria for setting advisory speeds. It is not fully clear whether curve advisory speeds are providing useful additional information to that provided by stand-alone curve warning signage and the appearance of the curve itself. The fact that drivers do not appear generally to follow the posted speeds, and are often travelling markedly faster, supports the suspicion that they may not be.

Part of this inconsistency appears to stem from the choice of side-friction values used to determine safe speeds. In many cases, the values chosen are low compared with observed side-friction generated by vehicles, resulting in low calculated speeds. In selecting the side-friction values, it appears that "comfort" criteria have been used that may not be appropriate for many of today's drivers, who will travel up to a maximum "safe" (albeit more uncomfortable) speed instead. In comparison with common US and Australian standards, New Zealand's current criteria for determining curve advisory speeds are relatively higher; yet evidence suggests that drivers are still travelling notably faster than the posted speeds.

Figure 2.4 Comparison of different friction criteria.

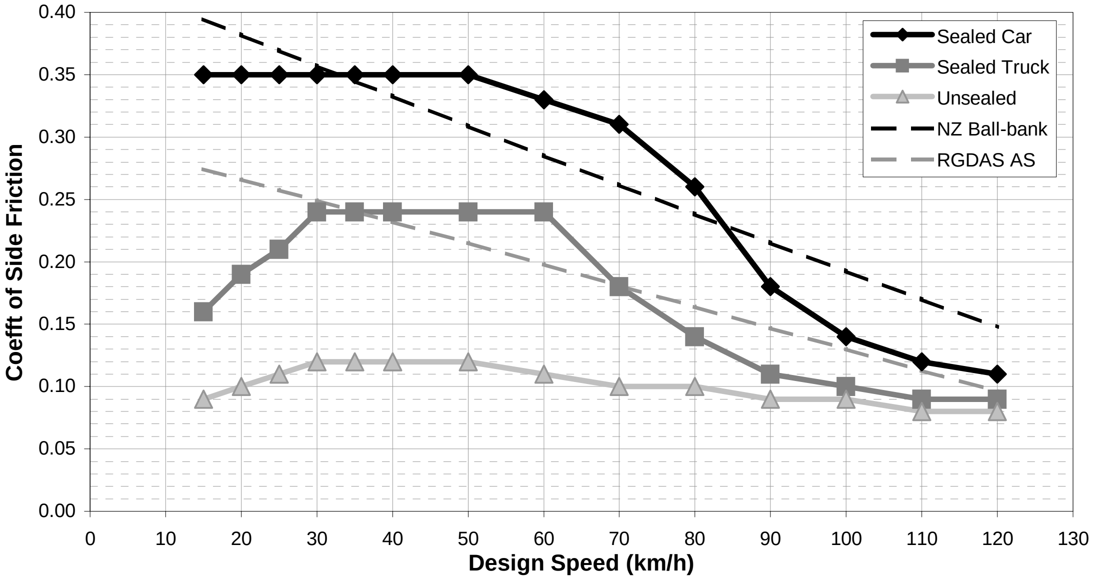


Figure 2.4 compares some of the relative friction measures identified in the literature review. General design speed friction values for cars, trucks and unsealed roads (all from Transit New Zealand 2000, based on AUSTROADS) are shown with the RGDAS (Rawlinson 1983) and New Zealand ball-bank (Equations 3 and 4) friction values

presented earlier. Note that the New Zealand ball-bank value assumes no superelevation, otherwise it would be lower.

The limitations of the linear RGDAS and ball-bank relationships are clear when compared with the curving design speed lines that have been extensively derived. Still, in the range of most advisory speeds, the New Zealand ball-bank values represent a reasonable, if slightly conservative, representation of car design speeds on sealed roads. The RGDAS relationship is an even more conservative approach, better suited to typical truck requirements, while unsealed roads clearly require their own system if they are to be posted with advisory speeds.

Overall, it appears that the key feature of advisory speeds should be consistency rather than absolute accuracy. This is a consequence of the wide range of vehicles in the national fleet: drivers are willing to accept having to apply a constant adjustment to posted speeds, as long as this applies to all curves. One potential problem with this is that drivers tend to use simple additive adjustments (e.g. + 10 km/h) rather than multiplicative ones (e.g. + 10%) that may be more appropriate.

Although not included in the tasks for this research, clearly a question still exists about the safety benefits of installing advisory speed plates. This is complicated by the fact that they are sometimes installed in conjunction with a curve warning sign and sometimes at a later date. A detailed analysis of crash data in New Zealand compared with sign installations would be valuable in justifying their use.

3. Site Surveys of Curve Speed Profiles

The main part of this research involved recording vehicle speeds at a range of curve sites. This required detailed site selection, development of specialised monitoring equipment, set-up and survey, followed by analysis of the results. These are discussed in more detail below.

3.1 Methodology

Site surveys were conducted at curves both with and without advisory speed signs. The effectiveness of advisory speeds could be checked by comparing them with actual vehicle speed profiles through the curve.

To get a good indication of speed changes through the curve, ideally a series of speeds should be recorded through the curve, as well as an approach speed far enough away from the curve. Traditional physical speed surveys using tubes or wires were likely to be problematic, owing to damage from the braking and turning of vehicles through the curve. Radar-gun observation surveys also had drawbacks: it would be difficult to record speeds accurately because of the changing vehicle paths through the curve, and the manual nature of the surveys would preclude long survey periods.

Using a series of electromagnetic wave beams across the road was therefore suggested as a practical solution for this type of survey. Investigations revealed that red-light optical beams and sensors that could provide the necessary beam link were readily available.

Figure 3.1 Layout for curve speed surveys.

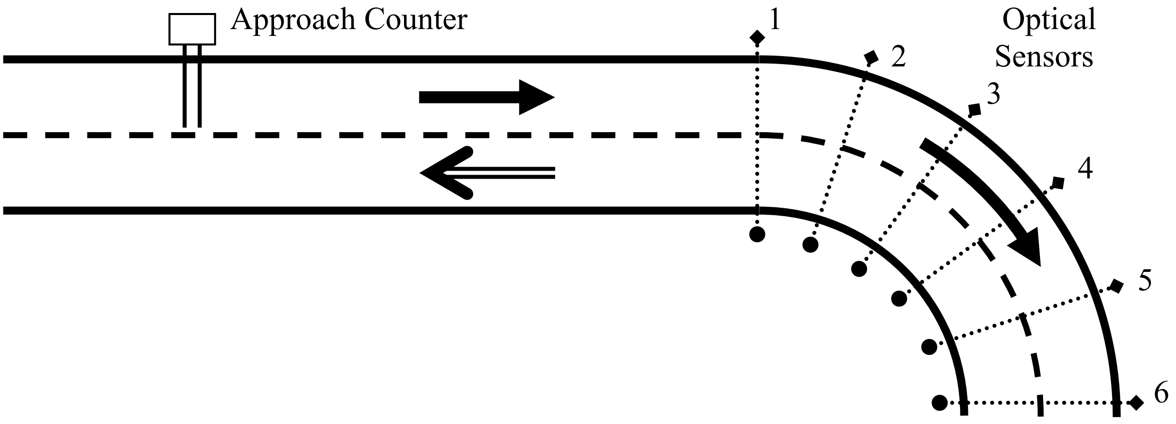


Figure 3.1 shows the planned survey layout. An ordinary tube-based counter would be used to collect approach speeds and vehicle types, with another counter on the other approach to the curve for traffic in the opposing direction. Up to six optical sensors could then be placed around the curve at pre-determined locations. Vehicles

travelling through the curve would momentarily break the light beams, and this would be recorded via an attached laptop. By comparing the time between beam breaks of adjacent sensors, the average speed between the two points could be calculated. In this way, up to five speeds through the curve could be determined for each vehicle.

Later in the survey, the original plan was modified to minimise costs and simplify data collection. Only three optical sensors were used to pick up two sets of speeds near the middle of the curve. The approach counters were also not used to collect data. Vehicle types were determined by the length of vehicles recorded breaking the optical beams (inferred from the vehicle speeds and the length of time the beam was broken). A length of 5 m was used as the cut-off between light and heavy vehicles (note that the 99th percentile length for cars and light vans using LTSA's turning vehicle templates is 4.91 m). Average approach speeds were assessed by on-site inspection. Although this reduces the data available from the subsequent sites, it still enables the key information (minimum vehicle curve speeds and vehicle types) to be determined.

Sample sizes aimed for an overall maximum error of ± 1 km/h (an estimated 300–400 samples would be needed, based on typical curve speed variance). Given the annual average daily traffic volumes (AADT) at sites and the number of "free" vehicles (i.e. not following others) likely to be recorded, it was expected that overnight surveys of approximately 20 hours would achieve this.

Several factors were identified for possible investigation, where feasible.

- The presence of a curve warning sign (with or without an advisory speed) and the presence of any chevron boards, to identify the incremental effect of each feature.
- The differences between calculated approach speeds, posted advisory speeds and calculated curve speeds.
- The effect of road and shoulder widths and roadside hazards (e.g. steep gullies) on travel speeds.
- The relative speed profiles of light vehicles (mainly cars) and heavy vehicles (trucks and buses).
- Speeds were to be checked where possible in dry/wet and day/night conditions, to identify any adjustment factors made by drivers.
- Sites selected included some identified as being incorrectly posted with too high or low an advisory speed. This would enable comparison of the speed profiles at these sites with those at more accurately signed sites. The results should indicate the relative merit that drivers place on the posted speeds.
- Information about the roughness of curves was collected to assess its impact on vehicle friction. Considerable rutting or uneven crossfall may cause vehicles to "bounce", affecting their safe curve travel speed.

Due to cost constraints, not all factors could be considered in detail at each site.

3.1.1 Site Selection

Sites were selected on state highway and local road sections. An attempt was made to find a wide range of curves within a relatively short distance, to minimise costs. All sites were in the Wellington, Wairarapa or Manawatu regions, within easy travelling distance of Opus Central Laboratories. For state highways, road geometry data was used to identify all possible curves and their attributes; Appendix A.2 contains a more detailed explanation of this. The roads were then driven to identify and confirm the sites to be used; Appendix A.3 details the general site inspection procedure. A couple of minor local routes were selected to identify potential local road sites. These were selected on-site following field measurement and assessment.

Both field data and road geometry data were used to identify the attributes of each curve. This included the horizontal radius, superelevation (crossfall), carriageway widths, roadside hazards and gradient of each curve and approach. Appendix A.4 lists the parameters of the final sites chosen.

Several factors were considered when choosing sites to investigate.

- Sites had to be signed with curve speeds or, from field ball-bank surveys, be assessed as requiring an advisory curve speed. Some sites with signed speeds differing from those measured were also favoured.
- A range of curve advisory speeds was to be chosen, as well as some sites with no posted speeds. Although advisory speeds can be specified between 15 and 95 km/h, in practice virtually all are between 25 and 85 km/h. A range of curve sign types was also preferred, including multiple curves.
- Sites should ideally have little shoulder width, particularly on the inside, to minimise the effect of vehicles “cutting corners”. In addition, sites with limited sight distance across the curve were also favoured, as this limits vehicles on the outside curve from crossing the centre line. The result is to make vehicle paths as consistent with the road geometry as possible.
- Ideally sites should have suitable locations on the shoulders for setting up the monitoring equipment in an unobtrusive manner.

Table 3.1 on page 38 lists the sites chosen for full survey. Taken in each direction (in terms of increasing or decreasing route position while driving), this provides 28 different sites to analyse.

Table 3.1 Sites used for speed surveys.

Site no.	Local road / SH RS/RP[1]	Location	PW[2] signs		Adv.[3] speeds		AADT
			Incr.	Decr.	Incr.	Decr.	
3	SH2 921/5.1	NE Rimutakas	19	19	25	25	4500
4	SH2 931/4.0	SW Rimutakas	18	17	45	35	4500
5*	SH2 931/9.1	NE of Upper Hutt	18	17	45	45	4500
6	SH2 921/2.9	NE Rimutakas	17	>>>>	55	55	4500
7	SH53 0/14.0	W of Martinborough	17	>>>>	75	-	2100
9*	SH2 858/8.1	N of Masterton	17	17	75	75	2900
11	SH3 491/5.5	W of Woodville	17	17	85	85	5900
12	SH2 931/8.3	SW Rimutakas	22	21	55	55	4500
13	SH2 931/2.6	SW Rimutakas	-	-	-	-	4500
16	SH57 26/2.8	NE Shannon	18	17	75	65	4000
17	Tiakitahuna Rd	10 km W of Palm. Nth	16	16	65	65	1900
18	Pahiatua Track Rd	5 km E of Palm. Nth	17	17	65	65	1300
19	Pahiatua Track Rd	20 km W of Pahiatua	>>>>	>>>>	25	25	1100
21	Pahiatua–Mangahao Rd	5 km W of Pahiatua	19	19	35	35	900

Notes:

1. SH = state highway; RS = reference station, RP = route position (see Appendix A.4).
2. PW = standard permanent warning sign (see Appendix A.1 for details; >>>> indicates where a chevron board has been used instead)
3. Adv. = Advisory

* Sites 5 and 9 were surveyed in detail using the full set of six detectors. These two sites were also used for the drive-over surveys described in Section 4.

3.2 Development of Equipment

A key component was the development of equipment and software suitable for collecting the data. As well as recording accurately, the equipment had to be sufficiently robust for overnight placement at remote sites. The sections below briefly describe the devices used; more detail can be found in Appendix A.5.

3.2.1 Sensors

Figure 3.2 shows a typical optical sensor (behind guardrail) and reflector post developed for this project. On one side of the road the sensor transmitted a light beam to the reflector on the opposite side, which sent the beam back to a receiver in the sensor.

The sensors used were Photoswitch Cat. No. 42GRU-9000, manufactured by Allen-Bradley Company, US. The reflectors supplied were 75 mm in diameter. To allow for the variable shape of the terrain, each sensor was installed in a plastic housing fitted to a wooden base, which could be pinned or weighted down. The construction allowed the light beam to be aligned with the reflector and then locked in place. Four core cables connected the sensors to the data acquisition system.

Figure 3.2 Typical optical sensor and reflector.

In some cases, reflectors were mounted on sight rails or fixed into slopes to suit the local terrain. In all cases, the equipment was made as inconspicuous as possible, with the devices often blending in with the surrounding marker posts. Shielding was used in many cases to prevent the reflectors from causing a distraction at night to approaching traffic.

3.2.2 Data Acquisition System

The data acquisition system consisted of a terminal box and a 486 laptop computer with a 1200 series LabView Data Acquisition Card fitted. A motorcar-type lead acid battery powered the computer and the lights in the sensor units. The data acquisition system was housed in a locked weatherproof steel box, which for security was pinned to the ground or chained to an object.

Customised software running on the laptop monitored when the beams were broken. When a clear series of beams in one direction was broken, the program recorded to file a sequence of ten seconds' worth of data centred on when the middle beam was broken. This provided data at 20 ms (1/50 s) intervals on the state of each sensor, i.e. when it was clear or broken. As far as possible according to the program logic, opposing traffic crossing at the same time and closely following vehicles were ignored, to provide only isolated free speed measurements.

Post-processing software later computed the relative speed between each set of adjacent sensors and also the estimated vehicle length, based on the time the sensor remained broken. This enabled light and heavy vehicles to be reasonably distinguished. Vehicle direction and the date and time of measurement were also provided in the final output.

To help identify wet and dry survey periods, a simple rainfall detector was connected to the system. Unfortunately, it was not able to perform properly in wet weather during early surveys, and so it was abandoned for later sites. As a result, the data has not been differentiated between wet and dry periods. It was noticeable, however, that a greater number of data collection errors seemed to occur during periods of observed wet weather, no doubt due to water seepage and condensation in the various components. Wet conditions can also turn various surfaces into strong specular reflectors that could produce additional unwanted light paths and subsequent false readings.

3.3 Setting Out the Apparatus

Appendix A.6 details the general procedure used for setting out the curve sensors. The original aim was to set out speed-measuring sensors around the curve in the configuration detailed in the Appendix. It was found that, using the intended equipment, too little of the source light from the unit was being reflected back to the sensor for it to be reliable in the field. Therefore, to decrease the risk of sensor unit failure, pairs of 100 mm square reflectors were used to replace the 75 mm diameter ones originally supplied.

Factors considered to affect reliable sensing included:

- the distance between the unit and the reflector (kept to a reasonable minimum),
- the total surface area of the reflective surface,
- the amount of misting or rain droplets forming on the reflectors and the sensor window (dishwashing detergent was smeared over the sensor housing window and reflectors to prevent condensation, and this reduced the diffusion of the light beam during wet or misty weather; small bags of silica gel were also placed beside the sensors to reduce misting inside the sensor housings),
- any movement in the equipment (especially the sensor unit) due to wind, public interference and the pressure wave created by large trucks on higher-speed sections.

For future surveys, more powerful sensors should be considered for widths greater than 10 m. Sensors with additional “sighting” beams would also assist with quicker initial placement of the equipment, which proved rather difficult to line up.

3.4 Speed Data Analysis

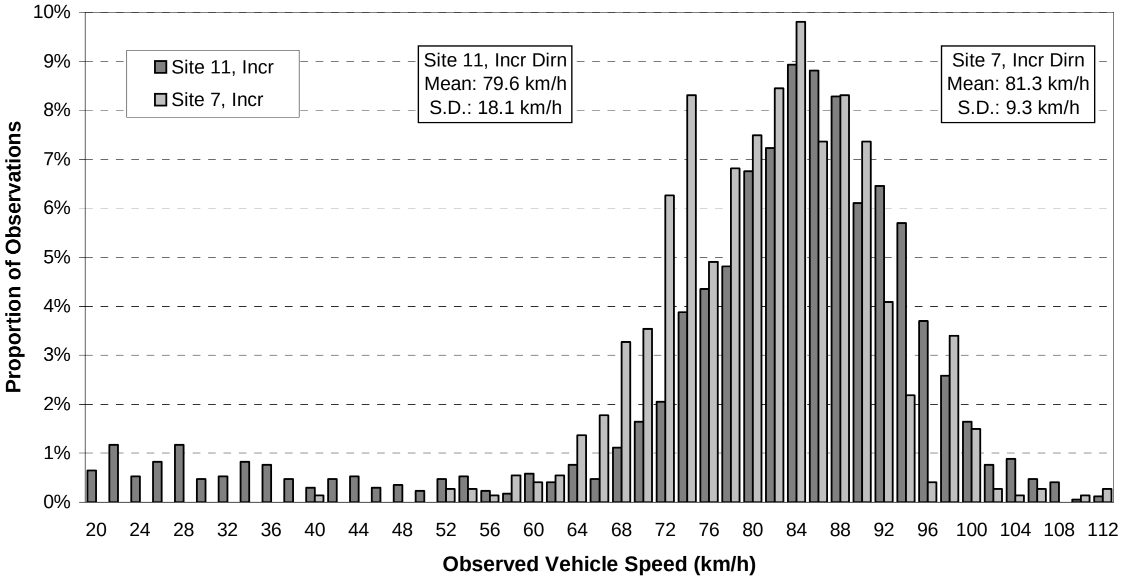
To assist in the data analysis, the site data and vehicle speed data were collected in a relational database. This enabled queries to be applied to the data sets to answer a number of different questions, as identified above. An add-on statistical package allowed more complex analysis of the data to be made. Some of the results were then exported to spreadsheets for further analysis and plotting.

The data collected varied in the number of sensors used, with two sites using six sensors (five speeds) and the rest using only three (two speeds). All the data was stored in the same table, with space for five speed measures. Blank speed values denoted those sites with fewer sensors, as well as those periods when sensors were not operating correctly. For example, if Sensor 1 was not functioning, then the first speed value would not be recorded. Where an intermediate sensor was not functioning, a speed value was calculated between the sensors on either side and stored in both of the respective speed fields.

The experimental nature of the survey equipment and analysis software meant that data collection errors were likely to creep in. To enable a sufficiently robust analysis to be made, considerable data manipulation and checking was required. This was carried out by a combination of visual checks and automated database queries.

Figure 3.3 shows the initial frequency distributions for two sites with very similar profiles (grouped into 2 km/h intervals). As is typical for speed surveys, the bell curve shape of a normal distribution is evident at both sites. However, Site 11 Incr. has a considerably higher standard deviation (SD), and inspection of the plot shows a very long lower tail. It appears that some problems with "noisy" data produced too many erroneous low speed values, suggesting that the true mean speed was actually higher than that listed, and the frequency distribution would suggest a mean value of ~82–84 km/h.

Figure 3.3 Comparison of raw speed distributions.



The data cleaning checks undertaken included:

- Records with large differences between consecutive speed measures (especially for acceleration) were removed, or at least had the anomalous value removed, e.g. >30 km/h acceleration over ~50 m.
- Very low or very high speeds were removed, depending somewhat on the curve speed. Individual sensor speed measures were compared with the overall mean sensor speed for each record, and those much greater or lower than this were targeted. Similarly, individual speed values were compared with the mean speed for the whole site. Comparison measures used included absolute speed differences (e.g. <40 km/h below mean), relative speed ratios (e.g. 50% greater than mean), and standard deviation units (e.g. >4 SD below mean).
- Records with very short (or negative) and very long (e.g. >20 m) vehicle lengths were removed, especially in conjunction with somewhat anomalous speed data. However, in some cases, where the data appeared to be picking up a platoon of vehicles and the speed values were reasonable, they were retained for speed data only.
- For most records, at least two reasonable sensor speeds were required to justify retention. However, some three-sensor records with a combination of a clear error and a reasonable value were generally retained.
- The data was sorted by various measures, and manual inspection of any unusual patterns (especially at the extreme values) identified other records for deletion.

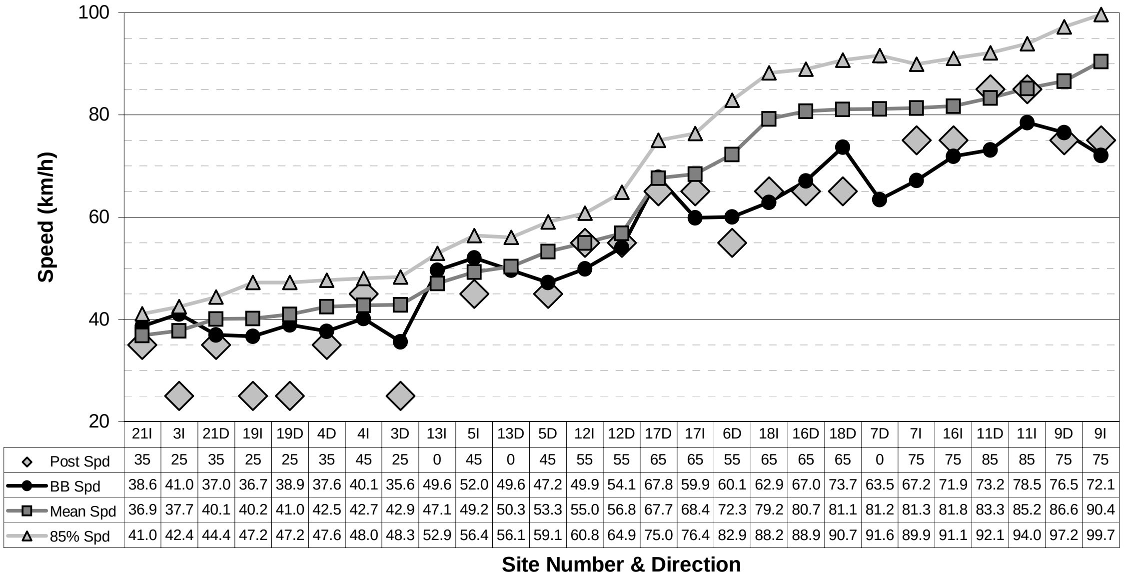
After data cleaning, over 18,700 records remained from the original 23,000, a reduction of 19%. The resulting data sets should be largely free from biases due to erroneous data. One site, the increasing direction for Site 6, was removed as having very few acceptable records left. Its counterpart site in the decreasing direction was retained, although it appears to have more variance than most other sites.

To carry out most of the data analysis, the final step was to identify the lowest speed recorded at any of the sensor sections. This was deemed to be the lowest curve speed for that vehicle for the purposes of this study. Speed profiles through the curve were also investigated and are discussed in Section 3.5.4.

3.5 Results

Figure 3.4 summarises the key measurements for each site surveyed, sorted in order of increasing (observed mean) speed. The data points have been named in terms of their site number and direction (increasing/decreasing route position), e.g. 7I, 14D. Posted advisory speeds (Post Spd) are compared with derived ball-bank speeds (BB Spd), observed mean speeds (Mean Spd) and observed 85th percentile speeds (85% Spd). Because of the good sample sizes observed at each site, the 95% confidence intervals for the observed speeds average only ± 0.7 km/h, with a maximum error of ± 1.2 km/h at site 18D.

Figure 3.4 Summary of speed measurements at survey sites.



	21I	3I	21D	19I	19D	4D	4I	3D	13I	5I	13D	5D	12I	12D	17D	17I	6D	18I	16D	18D	7D	7I	16I	11D	11I	9D	9I
◇ Post Spd	35	25	35	25	25	35	45	25	0	45	0	45	55	55	65	65	55	65	65	65	0	75	75	85	85	75	75
● BB Spd	38.6	41.0	37.0	36.7	38.9	37.6	40.1	35.6	49.6	52.0	49.6	47.2	49.9	54.1	67.8	59.9	60.1	62.9	67.0	73.7	63.5	67.2	71.9	73.2	78.5	76.5	72.1
■ Mean Spd	36.9	37.7	40.1	40.2	41.0	42.5	42.7	42.9	47.1	49.2	50.3	53.3	55.0	56.8	67.7	68.4	72.3	79.2	80.7	81.1	81.2	81.3	81.8	83.3	85.2	86.6	90.4
△ 85% Spd	41.0	42.4	44.4	47.2	47.2	47.6	48.0	48.3	52.9	56.4	56.1	59.1	60.8	64.9	75.0	76.4	82.9	88.2	88.9	90.7	91.6	89.9	91.1	92.1	94.0	97.2	99.7

Several trends are evident. First, posted speeds generally underestimate actual observed operating speeds, particularly at high and low speeds. It is only in some of the mid-range (45–65 km/h) sites that they appear to be more closely matched.

Second, the derived ball-bank speeds appear to provide a reasonable measure of observed mean speeds up to about 60 km/h. For higher speeds, however, there is a disparity of ~10–15 km/h. If it is assumed that the observed speeds are reasonable operating speeds, this suggests that the ball-bank speed calculation needs some adjustment at the upper end.

Figure 3.5 shows the comparison between the currently posted advisory speeds and those derived via ball-bank gauge during site investigation. One caveat to bear in mind with this plot is that the posted speeds are rounded and may be based on slightly different un-rounded values. Generally, the figures are in reasonable agreement, with no ball-bank reading suggesting a posted speed of more than 10 km/h different from that currently posted. However, only half of the readings would produce exactly the same (rounded) posted speed, a figure mirrored by the last New Zealand survey (LTSA 1998). In fitting a linear relationship through zero, it can be seen that the best fit suggests that posted speeds match derived ball-bank speeds very well. There is clearly, however, a pattern of underestimating at low speeds and overestimating at high speeds, which merits further investigation.

Figure 3.5 Curve advisory speeds: posted v. ball-bank derived.

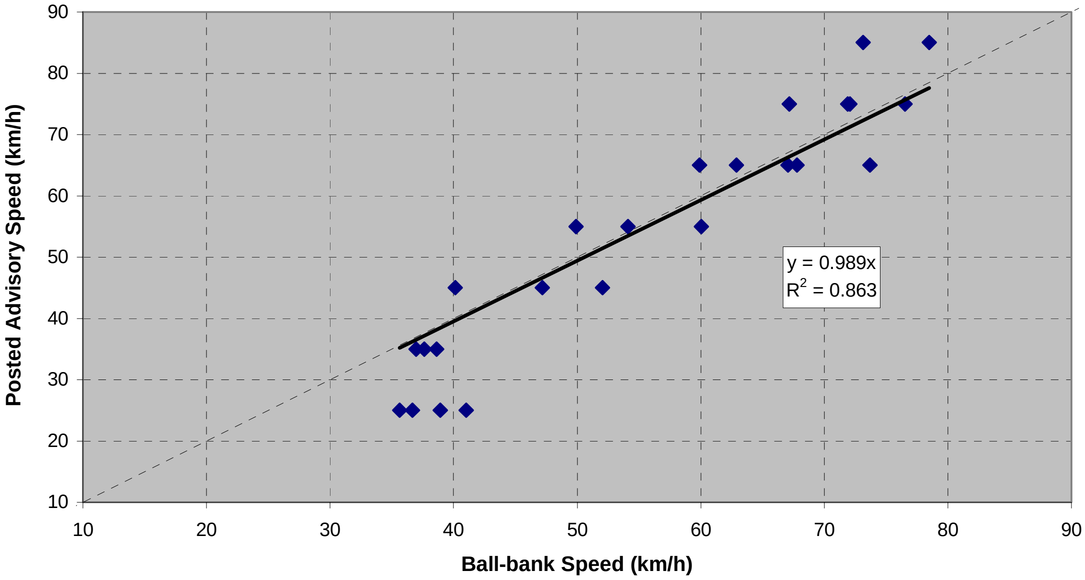


Figure 3.6 compares the posted advisory speeds with mean observed speeds. As has been found elsewhere, the results overall indicate that posted speeds underestimate actual speeds, in this case by approximately 5–10 km/h. It is interesting, however, that there is a reasonable number of sites where mean speeds follow the posted speeds quite well. This reinforces the indication from the literature review that New Zealand advisory speeds are not as conservative as some overseas. The best-fitting linear relationship runs virtually parallel to the “y=x” line, suggesting that drivers are applying a constant adjustment to their speeds in relation to the posted speed, regardless of the actual speed. Setting a zero intercept to the linear relationship results in posted advisory speeds being on average 88% of the actual mean operating speeds.

Figure 3.6 Posted advisory speeds v. mean observed speeds.

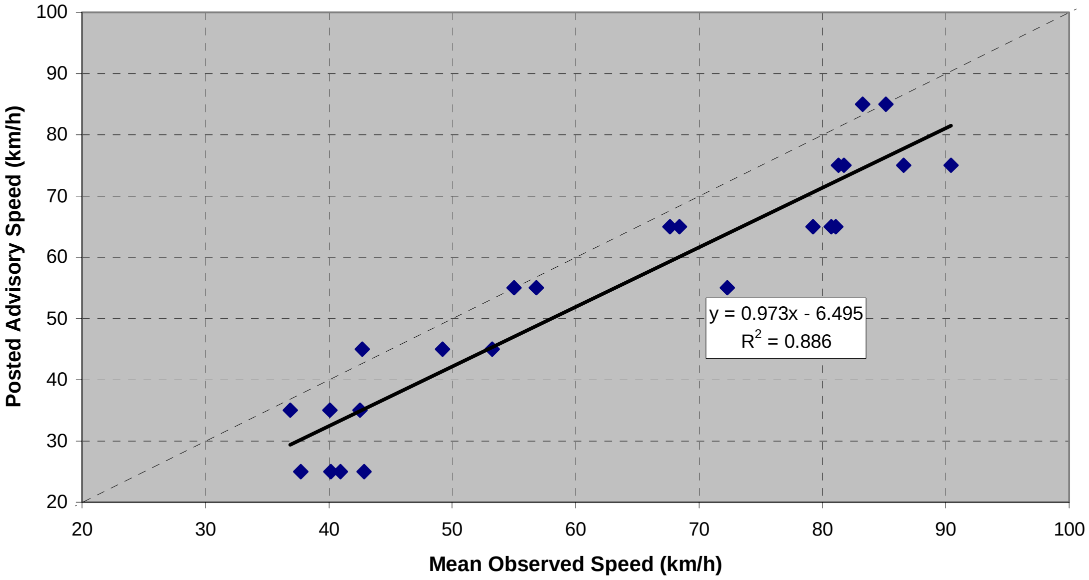


Figure 3.7 shows a similar pattern for observed 85th percentile speeds, albeit further away from parity. At this level, operating speeds typically exceed the posted speed by 10–20 km/h. Given that posted advisory speeds were originally designed to represent an 85th percentile speed, clearly this is not evident here (and it could be argued that an 85th percentile speed would not be appropriate anyway).

Figure 3.7 Posted advisory speeds v. observed 85th percentile speeds.

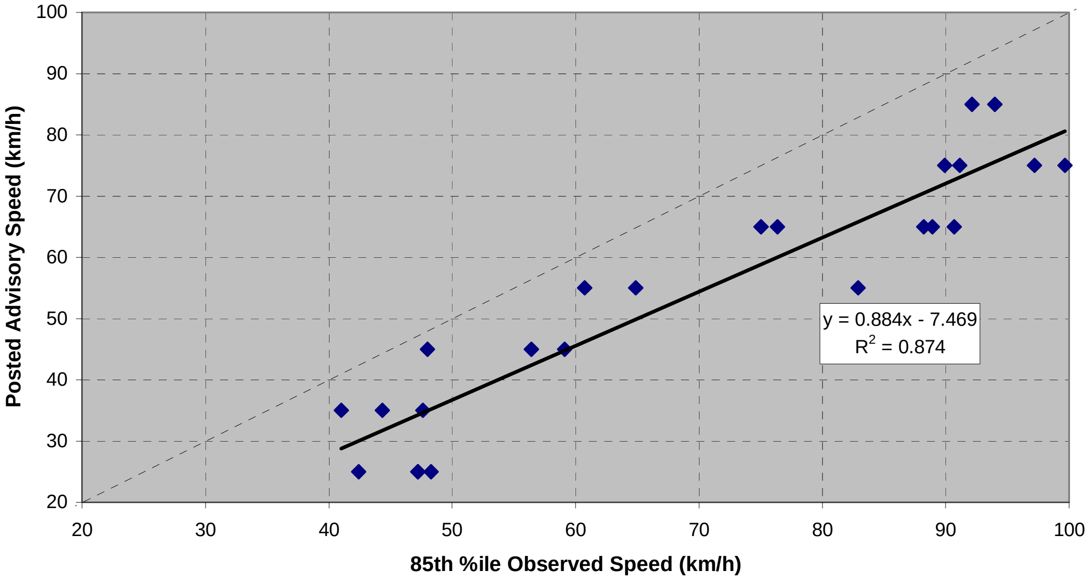
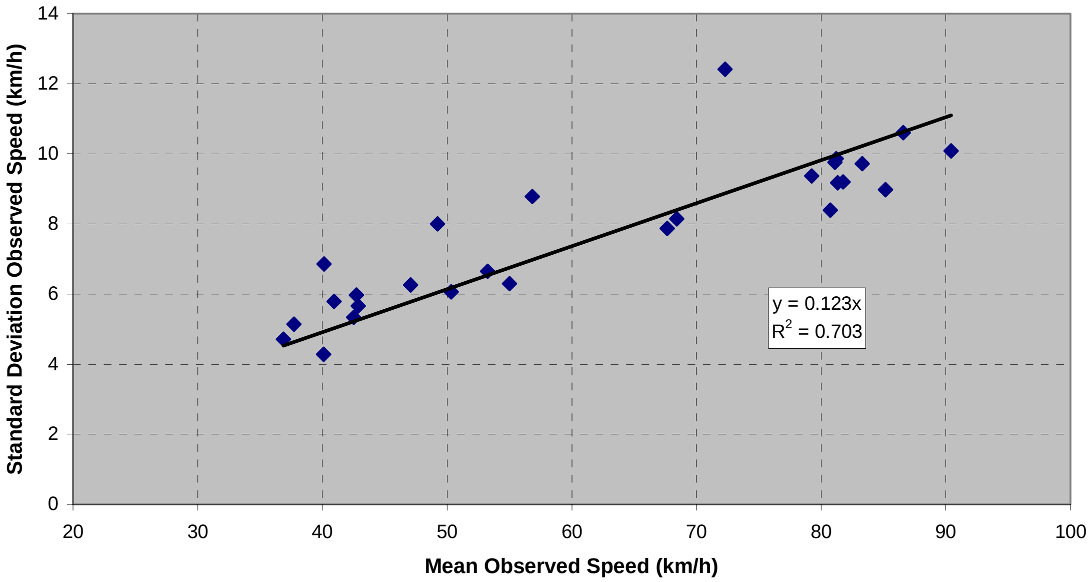


Figure 3.8 plots the standard deviation observed for each site against the mean speed. A good relationship exists here, with standard deviations being about 12% of the mean speed on average. This mirrors very well the findings from open-road free speed surveys carried out annually in New Zealand by LTSA. It is interesting that the constrained situation of a curve does not reduce the relative spread of speeds compared with a long flat straight, for example. Note that the unusually high standard deviation at ~72 km/h is related to site 6D, which as previously noted appeared to have some remaining data problems.

Figure 3.8 Observed mean speeds and standard deviations.



Several other statistical checks of the distributions were made. In particular, the relative symmetry of the distributions was looked at, especially with regard to a standard "normal" distribution. For simplicity, this distribution is often used to represent free speed distributions, so it is important to confirm its validity in curve situations. When comparing the median with the mean for each site, the average ratio of the two was 1.004, with a range of 0.986 to 1.024. Virtually identical parameters were found when comparing the 85th percentile speeds with values one standard deviation above the mean speed.

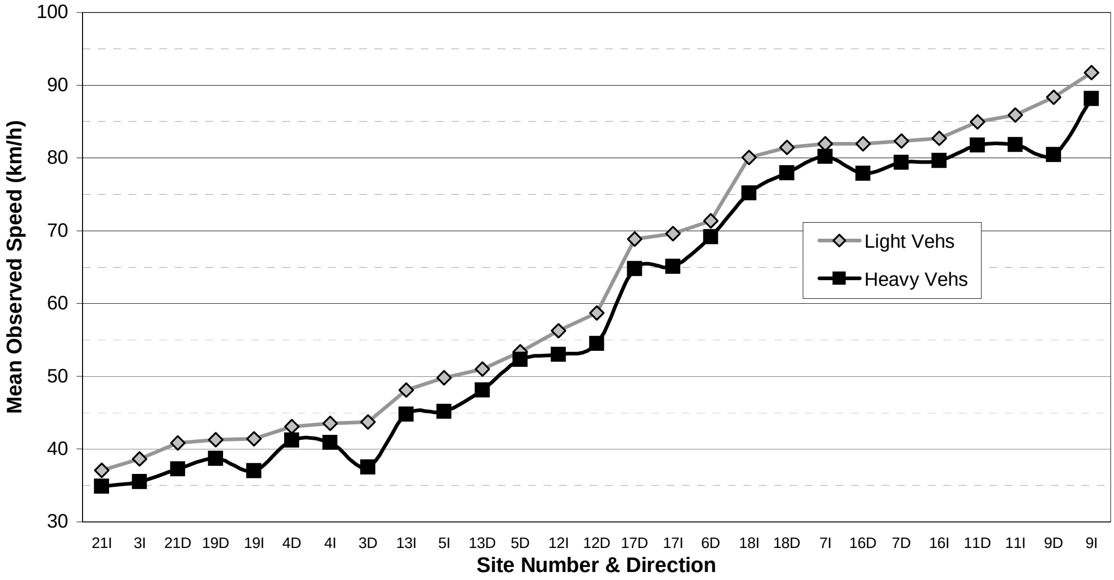
The average kurtosis was 1.33 with a range of 0.28 to 4.68. Kurtosis characterises the relative shape of a distribution compared with the normal distribution. Positive kurtosis indicates a relatively peaked distribution, while negative kurtosis indicates a relatively flat distribution. Hence the speed distributions were somewhat more peaked than a normal distribution.

The average skewness of the distribution was –0.29, with a range of –0.98 to 0.36. Skewness characterises the degree of asymmetry of a distribution around its mean. Positive skewness indicates a distribution with an asymmetric tail extending toward higher values, while negative skewness indicates a distribution with a tail extending toward lower values. Hence the speed distributions tended to have more speeds at the low end. Although this may be a consequence of the data manipulation discussed in Section 3.4, it also suggests that the distributions are slightly biased towards the posted speed limits, which were usually lower than the mean. This skewness probably also reflects the physical limits of each curve, which makes traversing them at speeds considerably greater than the mean (e.g. + 3 SD) virtually impossible to do safely.

3.5.1 Effects of Different Vehicle Types on Speeds

Figure 3.9 summarises the differences in observed mean speeds at each site for light and heavy vehicles. For the purposes of this research, any data with vehicle lengths outside the normal range of vehicles (e.g. >20 m) have been ignored as probably relating to platoons. It is likely, however, that some speeds recorded as being for heavy vehicles are in fact for light vehicles, probably travelling in close platoon. Hence the differences shown are probably understated.

Figure 3.9 Summary of light and heavy vehicle speeds at survey sites.



The summary plot shows a clear distinction between light and heavy vehicle speeds. The latter are slower on average by 4 km/h, with the difference varying between 1 and 8 km/h. Interestingly, there is no noticeable change in this difference as the mean speeds increase. The difference is small compared with LTSA open-road free speed surveys on straights, where the difference is typically ~10 km/h, although the previous comments about conservative differences must be taken into account.

T-tests have been carried out on the respective vehicle speed distributions. At the 5% significance level, all but one site have statistically significant differences between light and heavy vehicle speeds. Most of them are in fact significant at the 1% level.

Figure 3.10 plots the mean light and heavy vehicle speeds against each other. As indicated above, there is little change in the speed differences as mean speeds increase, suggesting that heavy vehicle operators apply a fairly constant rule of thumb irrespective of speed. A linear relationship with a zero intercept produces heavy vehicle speeds at 95% of light vehicle speeds, although the plotted trendline shown running virtually parallel appears more likely.

Figure 3.10 Observed light v. heavy vehicle mean speeds.

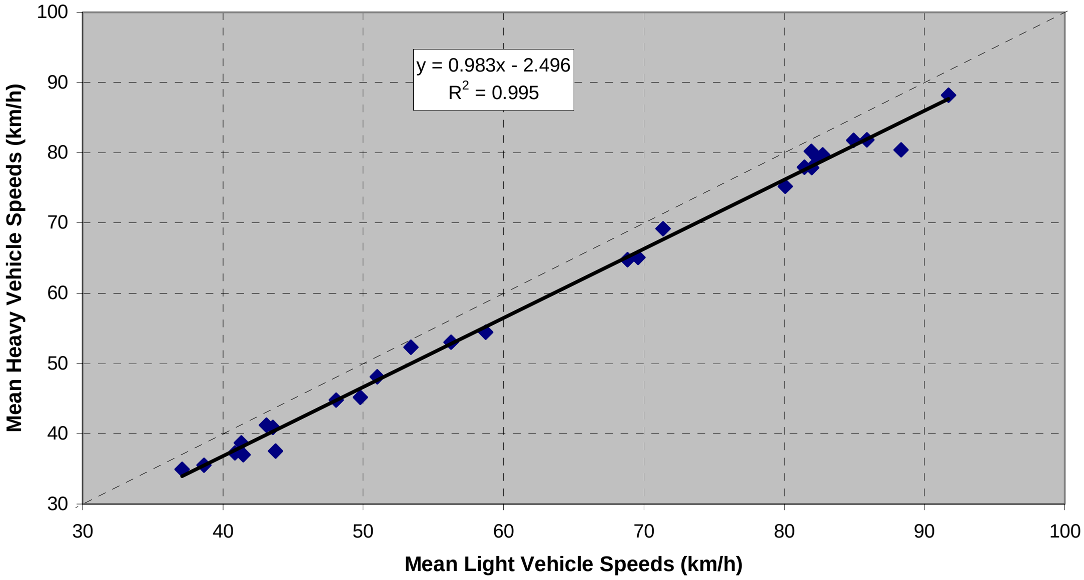
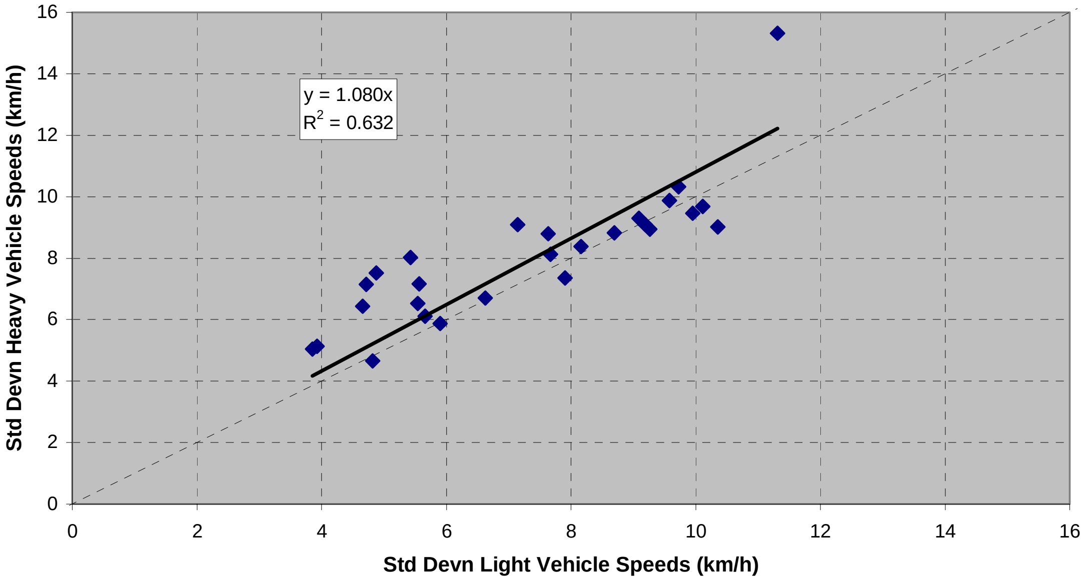


Figure 3.11 compares the standard deviations for each vehicle type. The best-fit relationship suggests little difference between the groups, although the correlation is only moderately strong. Heavy vehicles appear to have slightly greater standard deviations, possibly because of the wider range of truck performance parameters.

Figure 3.11 Observed light v. heavy vehicle standard deviations.



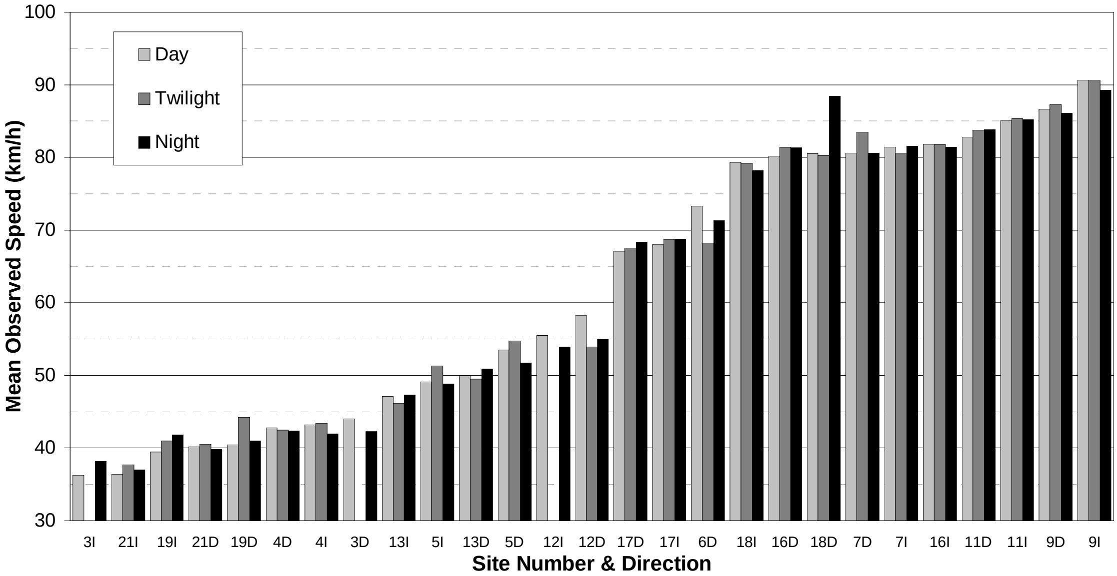
3.5.2 Effects of Time of Day on Speeds

Figure 3.12 summarises the differences in observed mean speeds at different times of the day (ordered by mean daytime speeds). Based on typical sunrise/sunset times at the time of survey, the following categorisations were made:

Daytime:	8.00 am – 4.30 pm (for Sites 5 & 9: 7.30am – 7.30pm)
Night-time:	5.30 pm – 7.00 am (for Sites 5 & 9: 8.30 pm – 6.30 am)
Twilight:	7.00 – 8.00 am, 4.30 – 5.30 pm (for Sites 5 & 9: 6.30 – 7.30 am, 7.30 – 8.30 pm).

Twilight is broadly defined as approximately half an hour either side of sunrise/ sunset. Note that, due to survey equipment problems, not every site had twilight data recorded. Also, some of the remaining data sets were quite small, averaging only 93 samples, with six having fewer than 50.

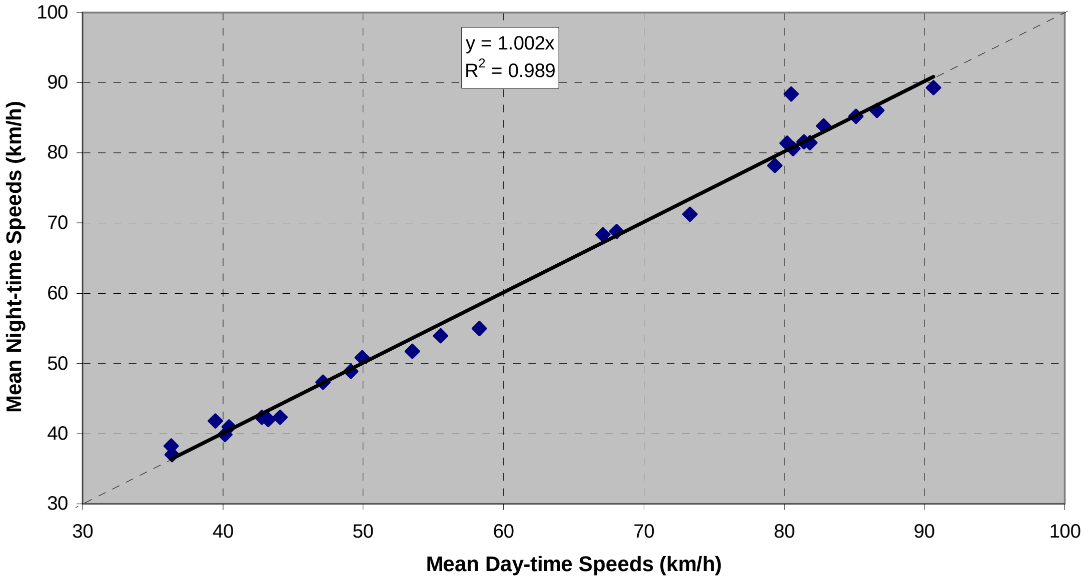
Figure 3.12 Summary of time-of-day speeds at survey sites.



No clear pattern was evident from the survey data. T-tests showed a mix of results on the respective speed distributions. At the 5% significance level, 10 out of 27 sites had statistically significant differences between daytime and night-time speeds. Only 6 out of 24 sites had statistically significant differences between daytime and twilight speeds. It would appear that, in general, there is no effect on speeds from different daylight conditions.

Figure 3.13 plots the daytime and night-time mean speeds against each other. Overall, no real difference can be seen. A similar comparison of daytime and twilight speeds shows that the latter are ~3% greater on average. Although they are not significantly different overall, it is interesting that the highest speeds appear to occur during what is often considered the riskiest time to travel. One possible explanation is that this is when commuters (i.e. regular users of the route) are often travelling to and from work.

Figure 3.13 Observed daytime v. night-time mean speeds.



3.5.3 Factors Affecting Compliance

Many other studies have summarised driver behaviour in terms of compliance with the posted limits. It is pertinent, therefore, to consider this using the current data set. Table 3.2 summarises the compliance rates for each site when compared with the posted advisory speed (% Comply Adv Spd), 10 km/h above the posted speed (% Comply AS+10) and the derived ball-bank speed (% Comply BB Spd). Various speed measures are listed for comparison, including approximate approach speed (App Spd), posted advisory speed (Adv Spd), derived ball-bank speed (BB Spd), and mean and 85th percentile observed speeds (Mean Spd, 85% Spd). For further comparison, details about any advisory speed signs and chevron boards present are also given (see Appendix A.1 for identification numbers; size in mm is given in the table in parentheses). The data is listed in increasing order of posted advisory speed, then ball-bank speed.

The results show no clear pattern in terms of compliance, and more detailed analysis failed to find many trends. The most notable was that the three sites with advisory speeds posted on a chevron board only (i.e. no curve warning sign) had lower than average compliance rates associated with the posted speed. However, it was observed that these sites also had calculated ball-bank speeds somewhat higher than the posted speed, and their compliance with the ball-bank speeds were generally no different from the norm.

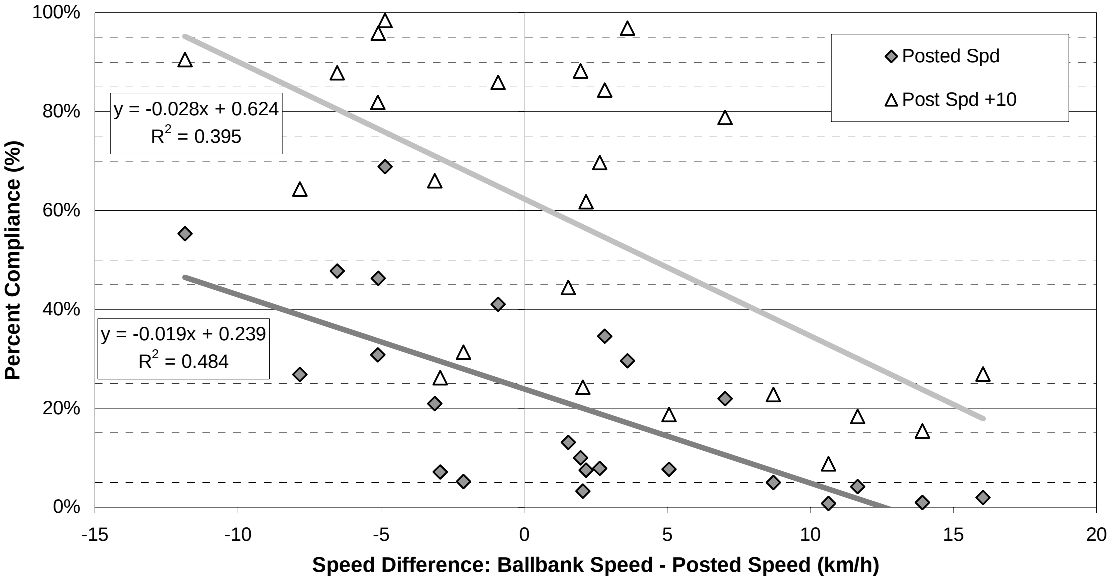
Table 3.2 Summary of compliance with curve speeds.

Site ID	Dirn	App Spd	Adv Spd	BB Spd	Mean Spd	85% Spd	% Comply Adv Spd	% Comply AS+10	% Comply BB Spd	PW Sign?	Chev-ron?
3	Decr	65	25	35.6	42.9	48.3	1%	9%	9%	19 (750)	-
19	Incr	60	25	36.7	40.2	47.2	4%	18%	27%	-	25>>>>
19	Decr	60	25	38.9	41.0	47.2	1%	15%	35%	-	25>>>>
3	Incr	60	25	41.0	37.7	42.4	2%	27%	76%	19 (750)	>,>,>
21	Decr	85	35	37.0	40.1	44.4	10%	88%	19%	19 (750)	>>>>
4	Decr	70	35	37.6	42.5	47.6	8%	70%	17%	17 (900)	-
21	Incr	75	35	38.6	36.9	41.0	30%	97%	64%	19 (750)	>>>>
4	Incr	55	45	40.1	42.7	48.0	69%	98%	28%	18 (750)	-
5	Decr	75	45	47.2	53.3	59.1	7%	62%	14%	17 (750)	45>>>>
5	Incr	80	45	52.0	49.2	56.4	22%	79%	64%	18 (750)	-
12	Incr	95	55	49.9	55.0	60.8	46%	96%	15%	22 (1200)	55>>>>
12	Decr	80	55	54.1	56.8	64.9	41%	86%	36%	21 (750)	-
6	Decr	75	55	60.1	72.3	82.9	8%	19%	11%	-	55>>>>
17	Incr	105	65	59.9	68.4	76.4	31%	82%	14%	16 (900)	65>>>>
18	Incr	95	65	62.9	79.2	88.2	5%	31%	3%	17 (750)	-
16	Decr	105	65	67.0	80.7	88.9	3%	24%	5%	17 (1200)	65>>>>
17	Decr	105	65	67.8	67.7	75.0	35%	84%	49%	16 (900)	65>>>>
18	Decr	95	65	73.7	81.1	90.7	5%	23%	22%	17 (750)	-
7	Incr	110	75	67.2	81.3	89.9	27%	64%	5%	17 (750)	75>>>>
16	Incr	105	75	71.9	81.8	91.1	21%	66%	12%	18 (900)	75>>>>
9	Incr	105	75	72.1	90.4	99.7	7%	26%	4%	17 (750)	75>>>>
9	Decr	110	75	76.5	86.6	97.2	13%	44%	17%	17 (900)	75>>>>
11	Decr	105	85	73.2	83.3	92.1	55%	91%	13%	17 (900)	-
11	Incr	105	85	78.5	85.2	94.0	48%	88%	20%	17 (900)	-
13	Incr	55	-	49.6	47.1	52.9	N/A	N/A	68%	-	-
13	Decr	65	-	49.6	50.3	56.1	N/A	N/A	44%	-	>>>>
7	Decr	105	-	63.5	81.2	91.6	N/A	N/A	3%	-	>>>>
Light vehicles							15%	50%	25%		
Heavy vehicles							25%	55%	35%		
OVERALL							**17%**	**51%**	**27%**		

It is interesting that two of the three sites without curve advisory speeds of any kind had quite high compliance rates with the calculated ball-bank speeds. The other, however, had a very low compliance rate, although the previous concerns about accurate ball-bank values on high-speed curves are relevant here. The literature review identified situations where some drivers will slow down if they are unsure about a curve, and this effect may be causing the compliance rates to remain high. The corollary of this conclusion is that, by installing a curve advisory speed sign, vehicle speeds may in fact increase owing to greater driver confidence.

The other factor likely to influence compliance with posted speeds is the relative difference between the posted advisory speed and the calculated ball-bank speed, on the assumption that drivers are more likely to be guided by similar comfort/safety criteria to those governing ball-bank speeds. This is certainly borne out, with both advisory speed compliance values showing declines as the relative difference increases, approximately – 2% compliance per 1 km/h increase, with an R^2 correlation of ~0.4 (see Figure 3.14). Unfortunately, the relationship is tainted somewhat by the built-in dependence of advisory speeds on both sides of the equation.

Figure 3.14 Compliance with posted speeds v. speed differences.



It has to be remembered that Figure 3.4 suggested that derived ball-bank speeds at high speeds (>60 km/h) were still too conservative in relation to the mean speeds. Experimentation with arbitrarily increasing these high-speed values improves the previous relationship to give R^2 values of >0.5. It also suggests that 80–100% compliance to within 10 km/h of the posted speed is likely if the ball-bank speed is actually less than that posted. Approximately half of this proportion would comply fully with the posted speed.

Some sign types appear to show greater compliance, although this must be balanced against the context in which they are used, and the relatively small samples. The PW-16 (sharp 90° curve) evidently works well, even though it was applied to two (relatively high-speed) 65 km/h curves. Both directions of Site 12 also appeared to comply well even though the related multiple curve signs were actually placed ahead of the previous curve. There was no discernible difference in compliance, however, between the three levels of curve severity presented in PW-17, -18 and -19 signs.

No trends were identified in terms of relative sign sizes, the presence of an additional chevron board, or any other more general conspicuity factors noted by the survey team (e.g. vegetation, sight-rails, approach lengths). The relative measured roughness of each site surface was also not a significant factor. These findings suggest that a more complex combination of factors is acting to produce the relative compliance rates at each site, and that the sample of sites is not large enough to identify these factors.

Another possible factor not included is the proportion of "local" travellers of the route. It is likely that regular travellers are quite familiar with the various curves of the route and set their speeds based on past experience, rather than the signs and markings. In contrast, drivers unfamiliar with the route will probably rely more on the posted speed and may attempt to apply speeds from other similar sites they have encountered before.

3.5.4 Speed Profiles

As well as examination of global parameters such as minimum curve speed, the data allows examination of how curve speeds changed throughout the length. Sites 5 and 9 in particular, which were surveyed using six sensors as well as approach-speed counters, can provide an understanding of driver behaviour through each curve.

The remaining sites had only two speed measurements, representing the two "halves" of the curve. Each section measured speeds over adjacent lengths ~20–50 m long. Table 3.3 summarises the distribution of vehicles recorded that changed their speeds between these sections, together with the minimum curve speed averaged over each group. Note that Sites 5, 9 and 6 (which had some data problems) are not included. As might be expected, most vehicles made little change to their speeds through the curve, suggesting that any speed reduction occurred largely before the curve. Still, the data suggests a wide range of speed patterns, although it must be recognised that some of the extreme speeds could be data errors that have still slipped through.

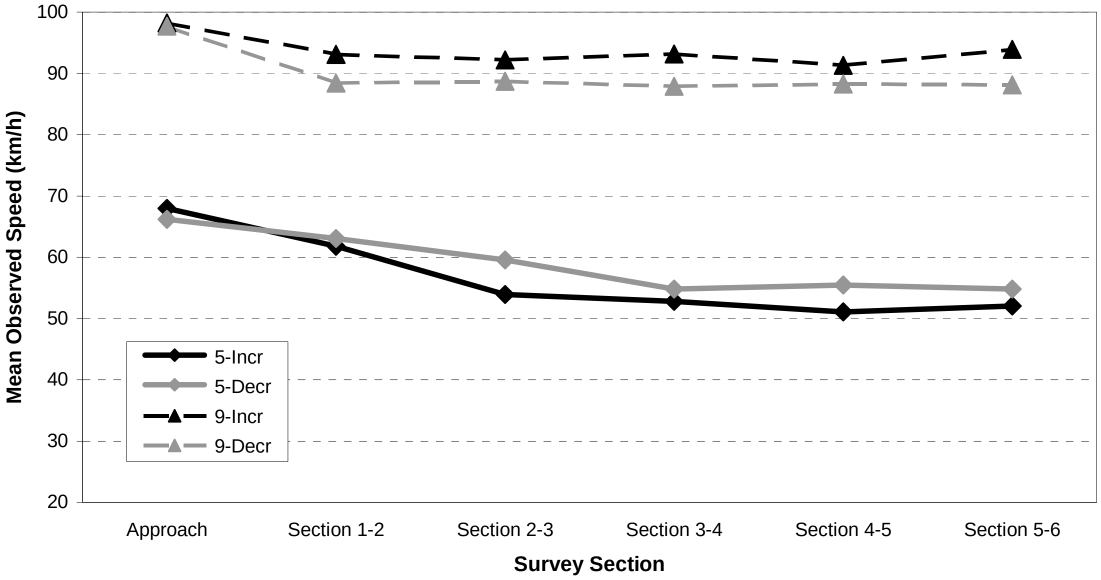
Table 3.3 Overall summary of speed changes within curves.

Speed drop (km/h)	Number of vehicles	Average min. speed (km/h)
25 to 30	35	62.9
20 to 25	44	48.1
15 to 20	66	57.6
10 to 15	97	61.5
5 to 10	**714**	**70.3**
0 to 5	**5501**	**67.2**
–5 to 0	**4344**	**60.3**
–10 to –5	**260**	**52.8**
–15 to –10	91	55.7
–20 to –15	75	53.9
–25 to –20	16	73.7
–30 to –25	4	74.5

If the only central four groupings (in bold) are considered, given that they have at least 100 records each, it appears that there is a pattern in terms of minimum curve speeds. Those vehicles that made the greatest speed drops are still likely to have the highest minimum curve speeds.

Figure 3.15 summarises the mean curve speed profiles for Sites 5 and 9. Site 9 had five sections, measuring ~20–35 m each, while the shorter Site 5 had sections ranging between 10 and 25 m in length. The approach speeds were recorded ~100–200 m before these. In the case of the higher-speed Site 9, the overall speed reduction was no more than ~5–10 km/h on average and this had been achieved largely by the first section (1–2) of the curve. For Site 5, it was not until the middle curve section (3–4) that speeds approached the minimum, a drop of ~10–15 km/h. It is also interesting to note no real increase in speed on the final curve sections, suggesting that drivers were generally waiting to leave the curve before accelerating again.

Figure 3.15 Mean curve speed profiles.



Note: Sites are named according to site number (5/9) and direction (Incr/Decr)

This figure does not explain how vehicles with differing approach speeds reacted to the curve. Figure 3.16 plots the relationship between approach speed and the drop to the minimum curve speed at Site 5. As might be expected, increasing approach speeds resulted in greater speed drops. However, the reduction was only about half the relative increase in approach speeds. So, while a high-speed vehicle may reduce its speed considerably when approaching the curve, it is still likely to travel at a higher than average speed through the curve. This is a similar finding to that identified in the literature review.

Figure 3.16 Site 5 speed reduction v. approach speed.

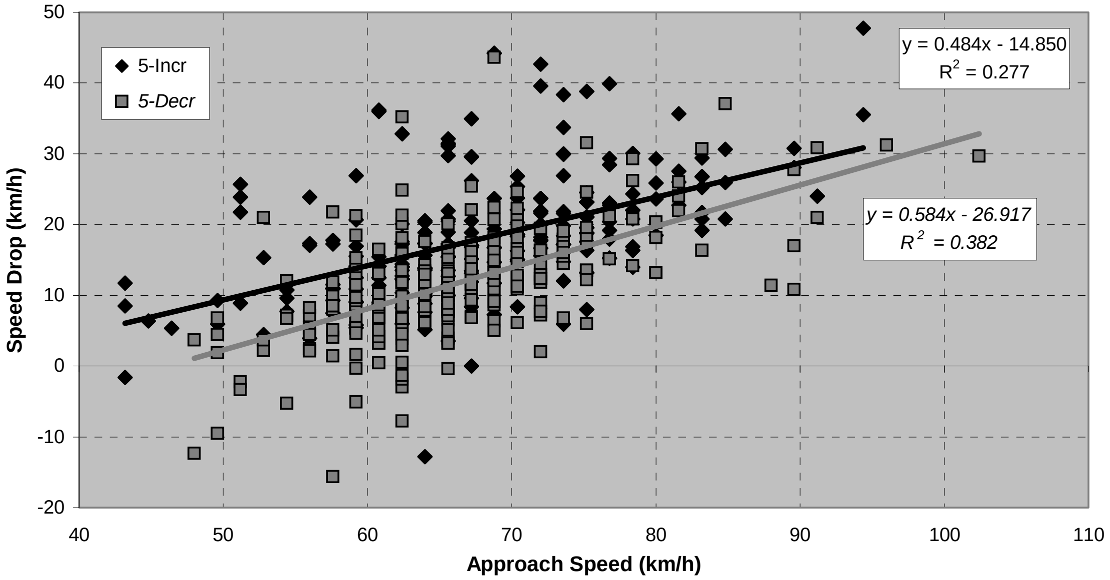
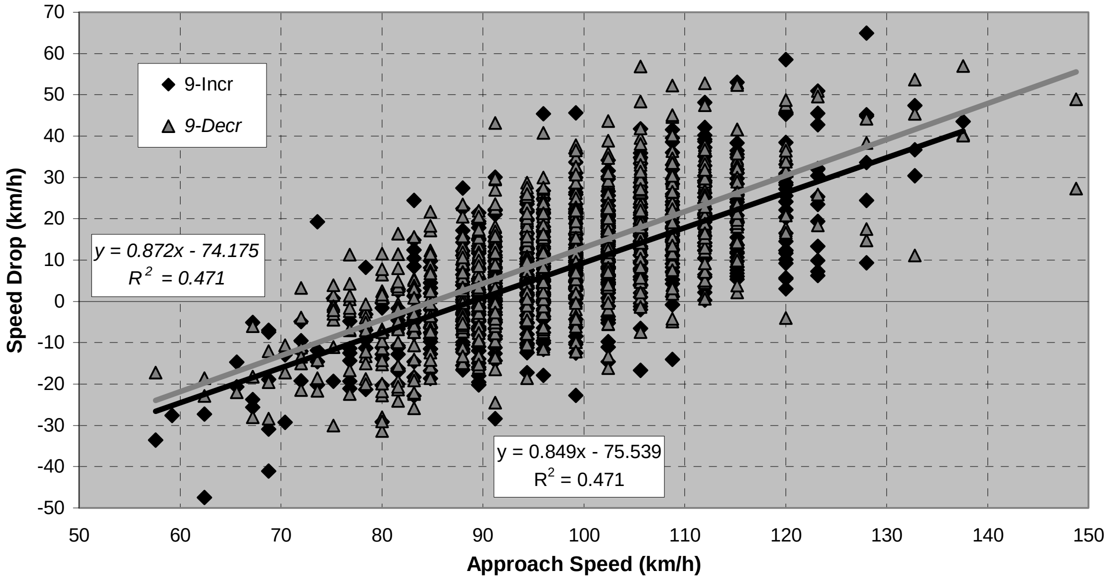


Figure 3.17 shows a similar plot for Site 9. This time the relationship is closer to one to one, with speed drops reflecting ~85% of the increased approach speed. It is also interesting to note the greater proportion of vehicles that are actually increasing their speed as they approach the curve. While this may be understandable for the increasing direction (which had another slightly easier curve 200 m beforehand), it is not clear how this should be expected in the decreasing direction, which is preceded by a two-kilometre straight.

Figure 3.17 Site 9 speed reduction v. approach speed.



4. Surveys Using Alternative Methods

The second part of the field research involved monitoring various vehicle measurements while repeatedly driving around curves. The aim of this task was to identify the relative accuracy of ball-bank and automated measurement methods for determining curve speeds. These are discussed in more detail below.

4.1 Equipment Used

In an attempt to provide a more accurate measure of curve speeds, an accelerometer-based system was developed that could be fitted to a vehicle and connected to a data logger. Opus Central Laboratories previously investigated the development of such a device for LTSA and the Police, using "off the shelf" components. This task built on the existing knowledge acquired in that work. This device could then be used to record data continuously as the vehicle traversed a corner, including lateral and longitudinal accelerations, body roll and travel speed. Analysis software on a connected laptop could then be used to present the data and ultimately derive an advisory speed for the curve.

4.1.1 Speed Profiler

For monitoring vehicle speeds throughout each curve, a speed profiler device was used. This equipment was previously developed by Opus Central Laboratories for applications such as travel–time surveys. Modification was required to enable it to be connected to a truck wheel and to interface with the other software.

Figure 4.1 Speed profiler device attached to rear wheel of truck.

Figure 4.1 shows the device attached to the rear (non-steering) wheel of a truck. The speed profiler consists of a rotary encoder built into a hub-axle that is attached securely to a rotating wheel. The hub surrounding the encoder axle is also attached

tightly to the vehicle body via a bungee cord, so that wheel revolutions can be accurately recorded. A cable carries the encoder signals to a processor box, which then passes them on to a laptop. Software in the laptop converts the signals into appropriate vehicle speeds and distances, which are recorded at regular time intervals (e.g. every second). For different vehicles, calibration runs must be carried out first to produce accurate measurements.

4.1.2 Gyro/Accelerometer

To record vehicle movements, an off-the-shelf system was obtained: the DMU-FOG vertical gyro from Crossbow Technology Inc. The DMU (Dynamic Measurement Unit) gyro is a six-axis inertial measurement system designed to measure:

- linear acceleration along three orthogonal axes,
- rotation rates around three orthogonal axes,
- stabilised pitch and roll in dynamic environments (these were not used for the measurements done on this project).

It utilises solid-state micro-electro-mechanical systems (MEMS) gyros and accelerometers to provide a complete determination of measures. Analogue voltage outputs are taken directly from the sensors and converted using customised software into common measurement units. Figure 4.2 shows the gyro (black box) in a test vehicle, held in place by an adjustable mounting pole. Appendix A.5.2 provides further technical details about the gyro.

Figure 4.2 **Gyro/accelerometer mounted inside test vehicle.**

4.1.3 Test Vehicles

Three different vehicles were used for the surveys. Table 4.1 summarises the key parameters of each vehicle. It can be seen that switching from car to van to truck resulted in increases in the height of the driver seat, the dashboard (where the ball-bank gauge was placed), and where the gyro was placed.

Table 4.1 Parameters of test vehicles used.

Type	Make/model	Wheel-base length (m)	Vehicle track width (m)	Seat-to-road height (m)	Dash-to-road height (m)	Gyro-to-road height (m)
Car	Nissan Pulsar 3-dr hatchback	2.41	1.39	0.46	0.86	0.71
Van	Mitsubishi L300 SWB	2.23	1.41	0.80	1.15	1.05
Truck	Nissan Diesel CM180, 400 Series	5.15	2.07	1.20	1.55	1.45

Both the car and the truck were driven without additional load, but the van was surveyed carrying a full load of equipment, adding about 1000 kg to its normal 1280 kg unladen weight. Figure 4.3 shows the test truck used for the surveys. The high-sided rigid truck is typical of those commonly involved in rollover crashes, although it is a little shorter than average.

Figure 4.3 Test truck used for drive-over surveys.

4.2 Survey Methodology

Two curves selected from the previous surveys (Sites 5 and 9) were run using the accelerometer/gyro device described above. Each curve was also tested using the ball-bank indicator for accuracy and repeatability, particularly at different survey speeds. Several different surveyors were used to identify any operator biases or inconsistencies inherent in the process. The three different vehicles – hatchback, van and small rigid truck – were also compared. At each site, approximately 36 different combinations of travel speeds (4), vehicles (3) and drivers (3) were used. Repeat runs using the same configurations were considered, but in the end were done only when something was wrong, e.g. the speed driven had been too inconsistent.

A laptop with running software enabled both speed-profiler and gyro data to be automatically recorded throughout each run. At the same time, an observer noted the maximum ball-bank readings during each run. Appendix A.6.3 details the procedures used for conducting the ball-bank and gyro/profiler surveys.

The speed-profiler was calibrated before the runs, using two reference-position marker posts on the side of the road one kilometre apart near Kaitoke. The calculated calibration constants were then used for all runs with the same vehicle. For the purposes of this relatively short-distance exercise, the readings for the speed-profiler are therefore sufficiently accurate.

For the car, the speedometer reading was approximately 5% less than the speed-profiler reading. This is likely to be due to an error in the car speedometer rather than the speed-profiler.

Where ball-bank readings went off the scale (i.e. >18°), an arbitrary value of 18.9° was assumed. Generally, this was a problem only at the highest test speeds.

4.3 Gyro Advisory Speed Derivations

The gyro continuously monitors changes in roll and acceleration about its three main axes. For curve speed prediction, the key measurement is the horizontal (lateral) acceleration out from the side of the vehicle. This mirrors the forces measured by the ball-bank gauge. A derivation formula is needed to convert the gyro readings into an equivalent ball-bank value.

Figure 4.4 Forces acting on a vehicle while cornering.

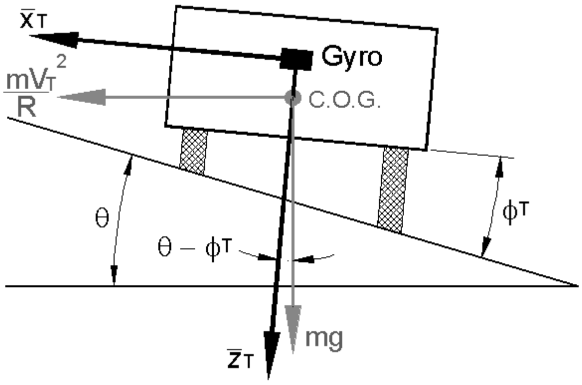


Figure 4.4 represents a vehicle of mass *m* negotiating a corner of radius *R*, at a test speed V_T. The vehicle is on a surface with superelevation of θ. The vehicle also experiences body roll of ϕ_T, resulting in it being at an angle of $(\theta - \phi_T)$ relative to level ground. As the vehicle corners, gravitational (*mg*) and centrifugal (mV_T^2/R) forces act on the vehicle through its centre of gravity. A gyro placed in the vehicle

will record accelerations (in m/s^2), both laterally (x_T) and vertically (z_T), relative to the vehicle angle. The figure does not display the reactive forces acting against these: the surface friction and normal ground forces.

By removing mass from the equations, the lateral acceleration can be related to the known forces acting on the vehicle:

$$\bar{x}_T = \frac{V_T^2}{R}\cos(\theta - \phi_T) - g\sin(\theta - \phi_T) \tag{15}$$

If the lateral acceleration is represented in units of g by a_T, then the above equation changes to:

$$a_T = \frac{V_T^2}{Rg}\cos(\theta - \phi_T) - \sin(\theta - \phi_T) \tag{16}$$

Preisler et al. (1992) noted that there was a relationship between the ball-bank reading b_T at a given test speed:

$$\tan(b_T + \theta - \phi_T) = \frac{V_T^2}{Rg} \tag{17}$$

By a series of rearrangements and simplifications, derived in detail in Appendix A.7, the above equations can produce the following:

$$\tan(b_T) = \frac{a_T\cos(\theta - \phi_T)}{a_T\sin(\theta - \phi_T) + 1} \tag{18}$$

As shown in Section 2.3.1, a reasonably constant value can be applied to $(\theta - \phi_T)$, such as 3°. This enables the ball-bank value b_T to be determined from a given lateral acceleration force a_T. The equation for curve advisory speed can then be applied to the calculated ball-bank value and measured test speed.

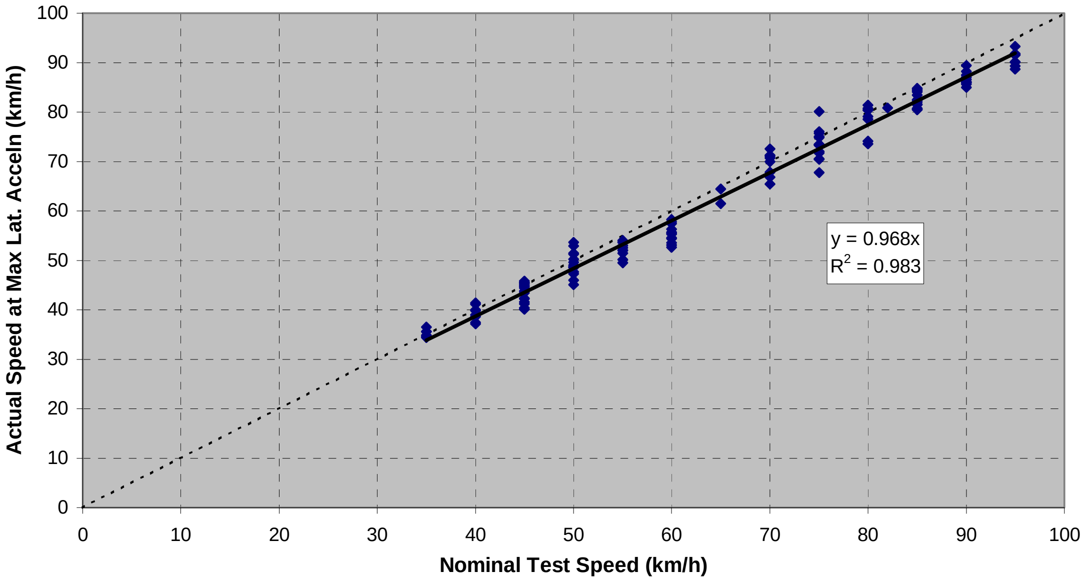
4.4 Results

The gyro data was processed as described above and the results compared with those recorded from the ball-bank surveys. Appendix A.8 contains curve advisory speeds calculated from the lateral accelerations measured by the gyro, assuming a value for $(\theta - \phi_T)$ of 3°.

4.4.1 Comparison of Manual and Automated Measurements

Figure 4.5 shows the comparison between the “nominal” test speed (i.e. the speed the driver attempted to travel at) and the actual recorded speed at the point of maximum lateral acceleration. Generally, the two measurements are in very good agreement (although this would be expected anyway), with the profiler speeds being only slightly less than the nominal speeds. Although runs with inconsistent speeds (on the basis of manual speedometer observation) were generally re-run, it is of some concern that recorded speeds of ± 6 km/h about the nominal speed were still obtained.

Figure 4.5 Nominal test speeds v. actual recorded speeds.



Inspection of the speed profiles through the test runs indicates fairly constant driving speeds throughout. This suggests that driver observation of the speedometer is sufficient to ensure consistent vehicle speeds. It is clear that the speeds may still vary somewhat from the targeted nominal speed, and this has to be taken into account when considering the variance of ball-bank results. For the moment, the correlation will suffice to enable comparison of ball-bank and advisory speed measurements.

Figure 4.6 Ball-bank values: observed v. calculated gyro.

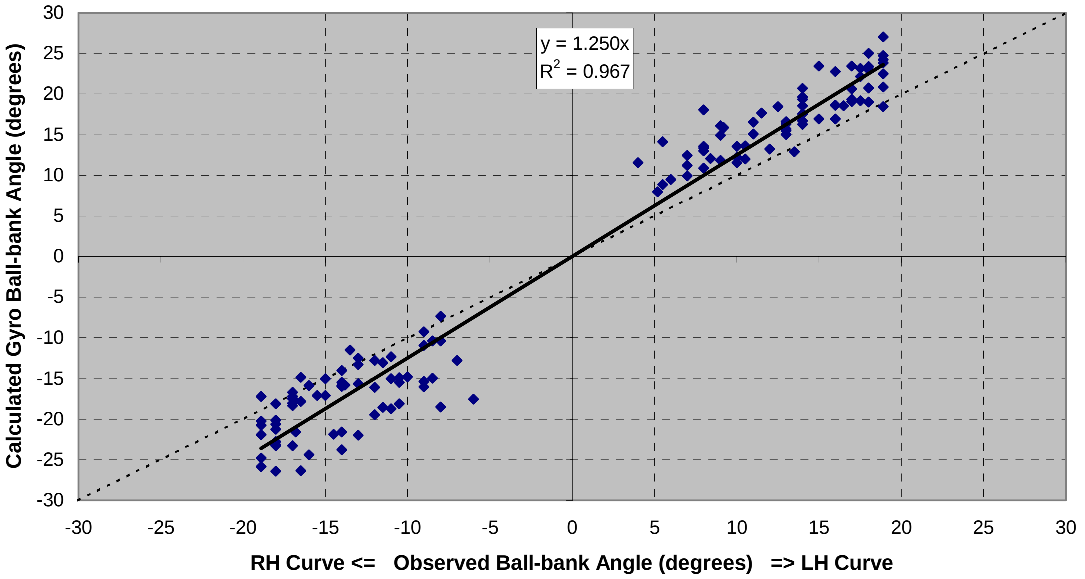
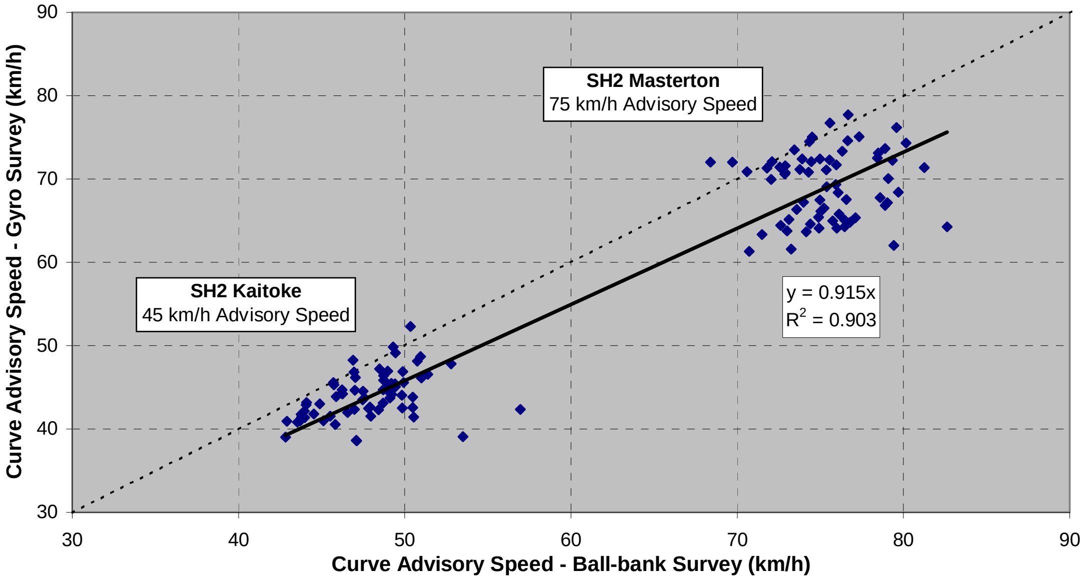


Figure 4.6 compares the observed ball-bank gauge readings with those calculated from the maximum lateral acceleration of the gyro. Note that the observed ball-bank values are constrained by the maximum angle (18°) that can be measured, with other values given an arbitrary 18.9° value. It is clear, however, that all observed ball-bank

values underestimate those identified by the gyro, by an average factor of 20%. This may reflect the fact that the ball-bank response is damped (i.e. the tube is filled with water). It may also reflect observers' ignoring any isolated "jumps" in the readings. The other possibility is that a systematic bias is inherent in the calculated gyro readings, although every attempt was made to eliminate this. The split of results for left-hand and right-hand curves shows that no "lateral shift" bias was evident (e.g. due to incorrect zeroing of the gyro).

Figure 4.7 compares the traditionally derived curve advisory speeds (via the ball-bank readings) with those calculated from the gyro measurements. As might be expected from the previous ball-bank comparison, the gyro speed measurements were generally less than the equivalent ball-bank speeds, by ~9% on average. Certainly, for the Masterton site at least, this would translate into many readings recommending a 65 km/h advisory speed instead of 75 km/h. Since it is suspected that, at higher speeds, ball-bank speeds are already somewhat low compared with operating speeds, this makes the gyro speeds seem even more conservative.

Figure 4.7 Curve advisory speeds: ball-bank derived v. gyro calculated.



The results suggest that, when operated accurately, both manual ball-bank and automated accelerometer devices can produce reasonably matching advisory speed measurements. But a means of "smoothing" the automatically recorded gyro readings may reduce the lateral acceleration peaks and produce less conservative values. Alternatively, some calibration by comparison with ball-bank surveys at a few test sites would enable the calculated gyro speeds to be appropriately adjusted.

The predicted curve advisory speeds are largely insensitive to relative body angle $(\theta - \phi_T)$. Tests were made comparing the values using the assumed 3° angle with values using 0°. Overall, the computed speeds were only 1.3% lower on average, with a range of ± 6%. The most extreme changes generally matched the ball-bank extremes, especially for small ball-bank angles, where $(\theta - \phi_T)$ is quite significant in comparison. Because the gyro, as installed, was unable to isolate superelevation from body roll, it would be useful to conduct some future tests on flat and constantly sloped surfaces to identify the amount of body roll in typical New Zealand vehicles.

4.4.2 Comparison of Different Test Runs

The large number of ball-bank tests using various configurations allows examination of the relative consistency of ball-bank derived advisory speed values. To do this, one-way Anova tests were performed, comparing differences between target speeds, vehicles used and drivers used. Appendix A.9 summarises the results.

They were something of a mixed bag, with some significant differences showing up, but generally no major patterns. Comparing individual derived advisory speeds, a range of ~12 km/h was found at each site, an interestingly consistent figure. Rounding the figures in accordance with *MOTSAM* would have meant that the results straddled two posted speeds in each case, with one test even making it into a third speed grouping. However, at least some of this variation is to be expected from individual tests with known measurement errors, hence the usual instruction to aggregate results from a number of tests. Comparing the absolute differences between adjacent runs, the average difference was only 2.7 km/h, with a standard deviation of 2.4 km/h and only ~10% of differences above 6 km/h. This is slightly higher than the LTSA findings discussed in Section 2.3 but, given the greater variation of people and vehicles in this research, is perhaps to be expected.

When looking at the variation between drivers, two of the four sites had significant differences between the means for each driver (at the 5% level). The mean speeds for each driver differed from the overall site mean by less than ± 3 km/h at most. The drivers themselves were fairly consistent in terms of being usually faster or slower than the group mean.

Vehicles also showed significant differences in speeds at two of the sites. Again, mean speeds for each vehicle were no greater than ± 3 km/h of the site mean. Car speeds generally proved to give the highest advisory speeds, with little between the van and truck.

Two of the four sites were also significantly different when comparing test speeds. There is a concern, though, that the highest test speeds were affected by too many cases of ball-bank values going off the scale. Overall, no distinct pattern was identified to link test speeds with ball-bank speeds.

Only one site (5 Decr) had significant differences in all three categories. This was also the only site to indicate a consistent trend of increasing ball-bank speeds with increasing test speeds, with the mean derived speed increasing by ~8 km/h as the test speed increased by 25 km/h. It is not clear whether there was a site-specific effect that may explain the greater sensitivity found at this location.

4.5 Derivation of Speeds Using Road Geometry Data

Measured road geometry data for state highway and local road sections can also theoretically be used to derive curve advisory speed measurements, as described in Section 2.4. To confirm the validity of this approach, advisory speeds calculated using road geometry and using ball-bank gauges were compared. Fifty curves at 25 sites were investigated, including all of the sites surveyed in the previous tasks.

Road geometry data is available in RAMM for all state highways, at 10 m intervals. However, some minor inaccuracy clearly exists in the numbers being recorded. This is evident when comparing radii in opposing directions, as often the difference is much more than a lane’s width. For comparison, aerial photographs of all the sites were obtained so that curve radii could also be measured manually.

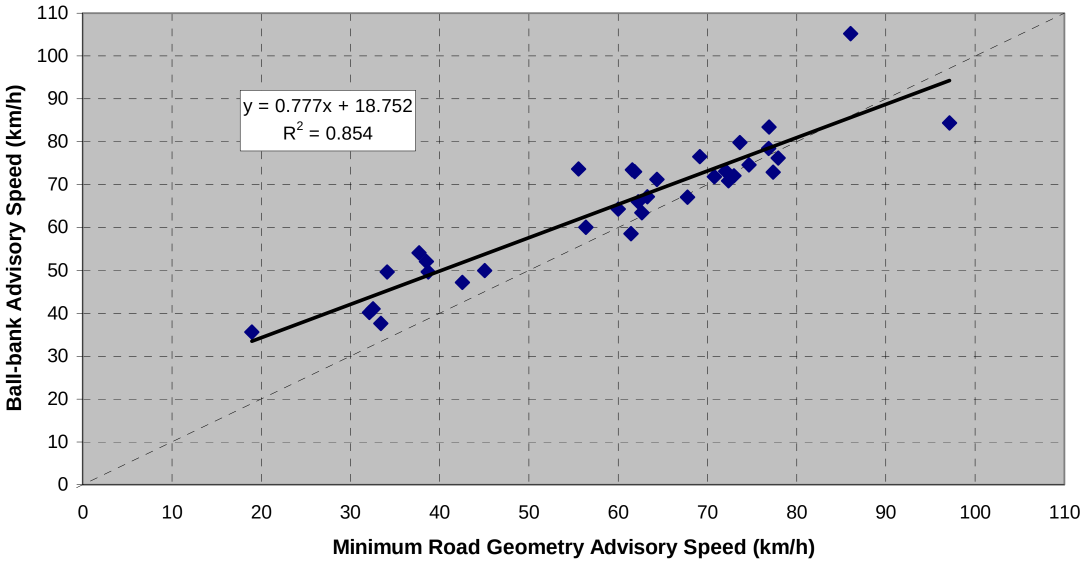
Radii measured from aerial photos were generally found to be 15–20% greater than the minimum radii listed in the road geometry data. This probably reflects the fact that the road geometry data would pick up any minor “kinks” in the road and record them as slightly tighter radii, whereas the measured radii are based on the curve as a whole. The former is probably more appropriate, however, as it will better identify any inconsistencies that may cause problems when negotiating the curve.

Identifying curve radii for the local road sites was more difficult, because of the absence of collected geometry data. Instead, an attempt was made to estimate curve radii from either aerial photos, GIS plots or land boundary plans. Problems with inaccurate scales or insufficiently precise curve segments, however, meant that many estimated speeds from the resulting radii were clearly not accurate. Therefore, only state highway sites were analysed further. Another possible way to determine curve radius on local roads is to relate lateral acceleration from a gyro system to vehicle speed; this is not explored further here.

The various road geometry speed measurements were calculated during the initial site selection phase (see Appendix A.2), and are listed in the summary of sites in Appendix A.4. The measurements are based on the RGDAS advisory speed calculation (with average gradient also allowed for), described in Section 2.4 and used in Australia as an alternative advisory speed measurement to the ball-bank gauge. These were then matched with the ball-bank speeds derived during site investigation.

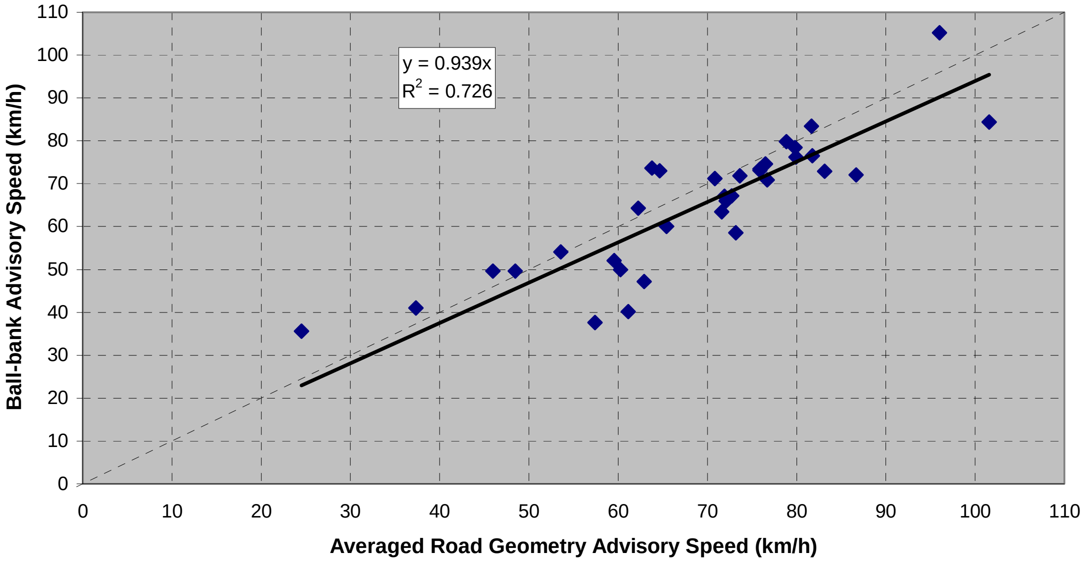
Figure 4.8 compares the measured ball-bank advisory speeds with the minimum speed value calculated using road geometry data (“Min Adv Spd” in Appendix A.4). This measurement should in theory represent the “worst” part of the curve where the slowest speeds are required. In terms of the “y=x” line, the relationship is generally very good, with road geometry tending just to underestimate advisory speeds. However, without a zero-intercept, the best-fitting line suggests a speed-dependent relationship, with road geometry data being more conservative at low speeds. This may be a consequence of the different assumptions made in deriving the two speed measurements. It may also be a reflection of the variability found when recording high-speed road geometry data, giving rise to “jumps” in the data and more conservative values.

Figure 4.8 Advisory speeds: ball-bank v. minimum road geometry.



To try to correct for any extreme values resulting from “noisy” road geometry data, an adjusted measure was used providing a rolling average over 100 m (i.e. ten 10 m records). This was designed to smooth out any “kinks” associated with unusually low advisory speeds. Figure 4.9 plots the relationship of this averaged measure (“Ave Spd Env” in Appendix A.4) against ball-bank advisory speeds.

Figure 4.9 Advisory speeds: ball-bank v. 100 m averaged road geometry.



This time the correction was probably too great, causing a slight overestimation of advisory speeds using road geometry. However, given the previously identified problems with low ball-bank speeds at higher speeds, the road geometry speeds may be more representative of driver behaviour. Still, a shorter rolling average, e.g. over 50 m, may provide a more accurate measure. It would allow a compromise between eliminating unusually extreme road geometry values and still identifying the relative severity of a curve. Interestingly, this is similar to the approach used by the original RGDAS surveys, which used rolling averages over 56 m of readings.

Clearly, there are still a few data points that would result in posted speeds of 10 km/h higher or lower than expected. Given the relatively poor “hit rate” observed from ball-bank surveys in the past, however, road geometry data would appear to provide no less accurate a method for assessing curves. Where a network or route is being rechecked for sign inconsistencies, a combined approach may be best, whereby road geometry is used first, to identify the anomalies, and ball-bank surveys are then used to confirm them, thus cutting down the number of sites to check in the field.

One aspect not examined further is whether the formula used to determine curve advisory speeds should be adjusted. The key to its make-up is an assumption of friction related to speed (described in Section 2.4), but the current relationship may not be the most appropriate. For example, as seen in Figure 2.4, the AUSTROADS design-speed friction assumes higher f values, which would lead to higher calculated speeds. These may be more representative of actual observed speeds.

5. Review of Existing Advisory Speed Criteria

In light of the findings in previous sections, it is pertinent now to consider the methods currently used for determining appropriate advisory speeds in New Zealand.

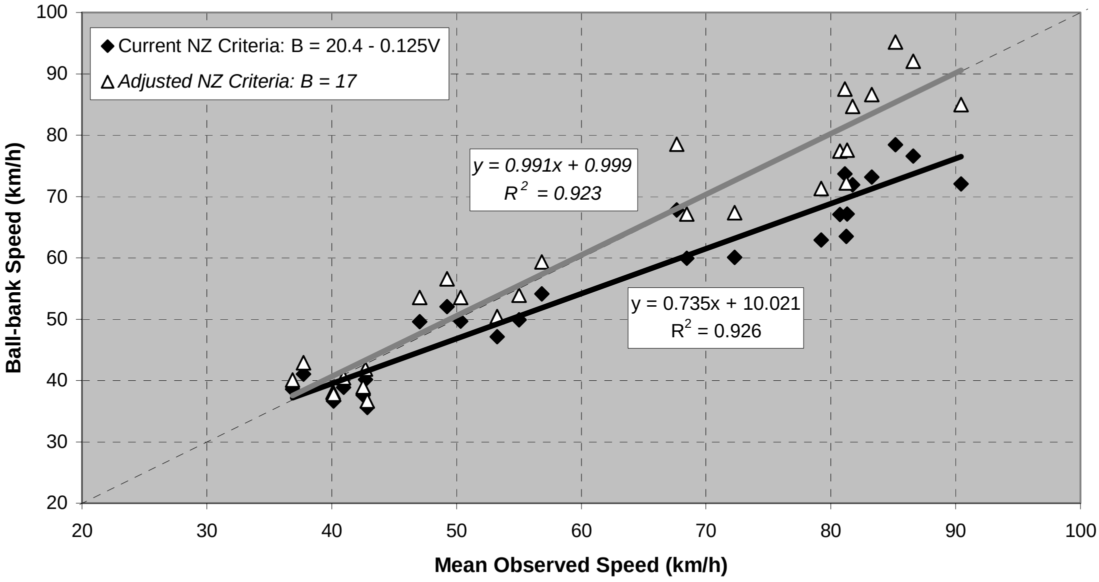
At this point, it is important to differentiate between the tools used (e.g. ball-bank, gyro, road geometry data) and the subsequent procedures and criteria used to derive an advisory speed. Most attention should focus on the latter area, to develop credible measures for each of the tools.

5.1 Ball-bank Surveys

Roading practitioners both here and overseas clearly have a “comfortable familiarity” with ball-bank surveys, and few want to venture away from them. This is despite evidence that the speeds derived using them often do not represent what drivers themselves perceive as a safe speed. The reluctance to change is probably due in part to the lack of information about suitable alternatives, and this is discussed below.

The field studies suggested that ball-bank surveys do not derive sufficiently high advisory speeds for higher-speed (>60 km/h) curves. In fact, if the ball-bank derived advisory speeds (V_A) from Section 3.5 are plotted against the observed mean speeds (as shown in Figure 5.1, dark points), a fairly flat relationship is produced. The equivalent advisory ball-bank reading, b_A (degrees), was back-calculated for each point (using the current New Zealand equation, $b_A = 20.4 - 0.125V_A$) and then various other ball-bank/advisory-speed relationships were tested. It was found that the equation $b_A = 17$ (i.e. with no V_A term) appeared to fit a one-to-one relationship very well (as shown in Figure 5.1, light points).

Figure 5.1 Comparison of ball-bank criteria v. observed mean speeds.



The implication of this is that drivers do not change their level of comfort (as represented by lateral acceleration) for different curves. This is contrary to past suggestions that drivers are willing to accept more discomfort at lower curve speeds.

Deriving a general equation (using this adjusted relationship) for varying test speeds, as was done in Section 2.3.1, produces the following relatively simple formula:

$$V_A = \frac{4.47\, V_T}{\sqrt{(b_T + 3)}} \tag{19}$$

where

V_A = curve advisory speed (km/h)
V_T = test speed (km/h)
b_T = ball-bank angle (deg) at test speed.

This relationship is based on the mean observed speeds. A similar exercise was not carried out using the 85th percentile speeds, although it may be a more appropriate measure to aspire to. Clearly, however, a move to 85th percentile speeds would result in ball-bank speeds even higher again for the same ball-bank reading. Given that the adjusted relationship presented above already represents a radical departure from the *status quo*, it does not seem worth exploring this further at this stage.

Irrespective of the relationship used, the other clear problem is in the correct use of the ball-bank method. Without a standard documented method for carrying out ball-bank surveys, it is inevitable that different areas will have inconsistent posted speeds, either through random error (due to insufficient survey runs) or systematic error (due to incorrect technique). Even simple things, such as uncalibrated speedometer readings, may be enough to move the recommended posted speed up by 10 km/h. Although a test-speed dependence effect is not greatly in evidence, the use of varying test speeds can also help to reduce any error here due to bias at varying speeds.

5.2 Alternative Advisory Speed Methods

Alternative methods for deriving curve advisory speeds have not been well documented, and this has limited their acceptance by road controlling authorities and practitioners alike. On reviewing the evidence, it appears to be time to expand the range of allowable tools.

While road geometry has been enshrined in curve design for a long time, the link between the design speeds used for geometric design and curve advisory speeds has not been clearly spelt out. The former allows road improvements to provide for a smooth transition between successive geometric elements. Advisory speeds, however, are invariably placed in locations where this principle cannot be followed. Hence drivers' expectations of what they can do when traversing a lone sub-standard curve are different from encountering the same curve as part of a well-designed (probably lower-speed) alignment.

This makes it all the more important that geometry-derived speeds for curves take into account the immediately preceding travel speeds. For example, by using a rolling average over 100 m of speeds determined for each 10 m segment, the effects of acceleration and deceleration can be better incorporated.

For state highways at least, the ready availability of regularly surveyed road geometry data is hard to overlook as a useful tool. Given the time and cost involved in field surveys using ball-bank gauges, any method that allows efficiencies in this process with similar levels of accuracy has to be considered. One caveat has to be mentioned, based on the experiences of the researchers. As well as road geometry data, analysts also need to have an accurate inventory of existing signs to enable comparisons to be made. Some aspects of the RAMM database do not provide easy matching, particularly with regard to sign direction and multiple signs.

Local authorities do not as a rule have such road geometry data, but there is no reason they cannot collect it for this kind of work, via site survey and aerial plans. Given the wide range of potential applications for road geometry data, as highlighted by Koorey et al. (1998), high-speed collection of such data at least along major arterials is highly recommended. The most important requirement is for sufficiently accurate data, e.g. curve radii to ± 5–10%. This was a major sticking-point in attempting to check road geometry methods on local roads during this project.

Automated advisory speed systems such as electronic inclinometers do not appear to have been studied widely in comparison with the more traditional measures, with only McLean (1974) being cited as having considered the relative accuracies of each method. The manufacturers of these devices do themselves no favours in not widely providing sound technical documentation of how their systems compare. This is partly because they tend to promote such devices for a wide range of uses (e.g. car-racing analysis), of which curve speed determination is just one.

Because a variety of devices is available, it is difficult to recommend any or all of them for the task at hand. However, the exercise described in Section 4 showed that, properly calibrated, they can provide a reasonable speed determination. The important requirement for validity would be a series of test runs for each device that compared their results to the equivalent ball-bank standard. This includes consideration of the level of damping present or lacking in these devices; as seen with the gyro, this can have a considerable effect on results. Provided that the device could replicate a wide range of speeds consistently, its use should be allowed here. Although some manufacturers have promoted the ability of automated devices to determine speeds using just one run, it is recommended that the same method be adopted for these as used in ball-bank surveys.

5.3 Changes to New Zealand Advisory Speed Determination

The above findings suggest that changes to the existing advisory speed system would be necessary to obtain a more accurate method of posting speeds that were appropriate to observed speeds. In the case of derived ball-bank speeds above

60 km/h, for example, Figure 5.1 shows that mean drivers' speeds often exceed this by 10–15 km/h.

The biggest problem in suggesting a change in the speed criteria adopted, however, is the potential safety impact. Drivers used to travelling more than 10 km/h above posted advisory speeds would be in for a nasty shock if they found a more realistic approach had been applied to posted speeds. Although a public education campaign could be carried out (as was done when the new international symbolic signs were introduced), invariably the message would not get to everyone, with potentially tragic results.

When the last revision to the system was made, in 1992, a slight increase in the speed criteria was introduced. However, this was masked by the simultaneous introduction of the new symbolic signs. Where, in the past, drivers were familiar with advisory speeds of 30, 40, 50, etc. (km/h), they now faced 35, 45, 55, etc. Probably, in most cases, curves could be signed with the new speed 5 km/h above the old value without inducing additional confidence in drivers.

Without changing the signing system every time our speed standards are reviewed, such an opportunity is not available this time. A possible approach instead would be to change the standard subtly by very small increments, causing only a few "borderline" posted speeds to be increased to the next level. Over time this would have the effect of subconsciously lowering the general expectation of drivers that the advisory speed can be exceeded. However, to effect a fairly large change in driver expectation (e.g. of 10 km/h) would require a number of such changes over a long period of time (e.g. + 2 km/h every five years).

5.4 Other Changes in Curve Signing Practice

Several other issues have been touched on, either in the literature review or in the field surveys, that warrant resolution. These are discussed below.

5.4.1 Signing on Unsealed Roads

Because of the differing friction available, the existing criteria for determining advisory speeds cannot be applied to unsealed roads. One key difference is that driver discomfort is not likely to be reached before insufficient friction causes loss of control. Therefore, the use of design friction values is more likely to produce accurate curve speeds than for sealed roads.

The use of advisory speeds on unsealed roads has been questioned. However, such roads are even more likely to suffer from sub-standard curves, and not every driver recognises the additional dangers they pose. Evidence of poor or variable surfacing on some unsealed roads also suggests that work to bring them up to standard is required, rather than automatically disqualifying them from measures such as curve advisory speeds. Further research may be required to observe traffic behaviour at a number of unsealed sites and confirm the feasibility of applying such speeds.

The only other valid concern is cost-efficiency, considering the amount of traffic often involved. However, this is an issue for road controlling authorities to consider and should not prevent the development of guidelines for unsealed roads if feasible.

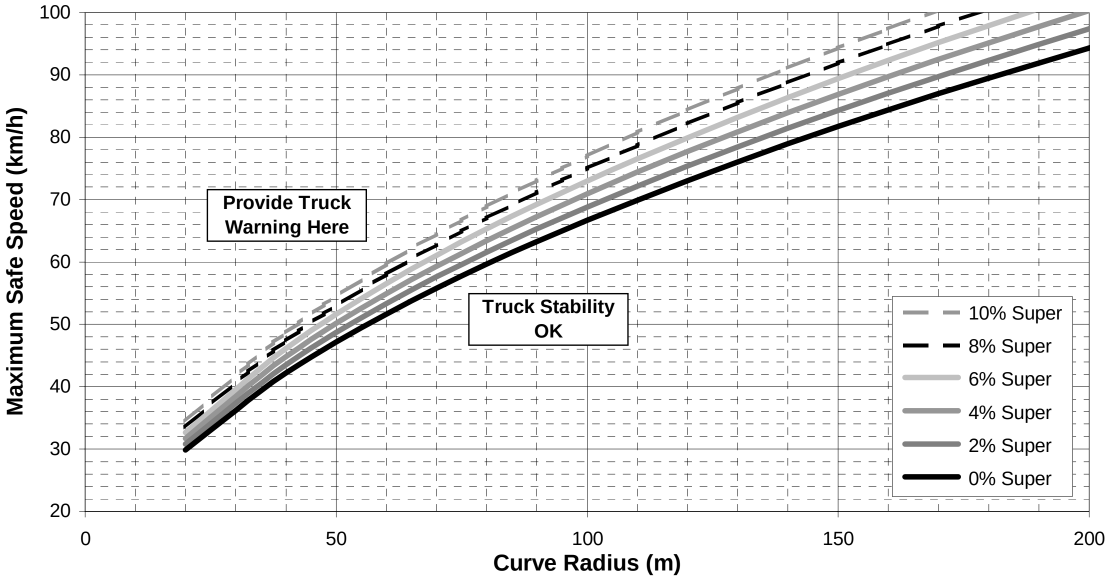
5.4.2 Curve Warning for Trucks

Many of the problems that have affected trucks at curves are being dealt with through improvements in the relative stability of truck design. Continuing truck-driver education to explain the effects of different speeds on their vehicles is also recommended.

At the sites where trucks experience problems, superelevation (or lack of it) generally plays a greater part than the curve radius itself. These sites may not meet the normal conditions for posting advisory speeds because of the surrounding environment. However, it may be worth placing specific truck-warning signs (like that in Figure 2.3) at sites where the combination of typical speed, radius and superelevation exceed the rollover threshold for a typical high truck.

Figure 5.2 shows a possible example for trucks with rollover thresholds of <0.35 g, based on the calculations in Section 2.10.1. Where it is observed that trucks will attempt greater speeds than that shown (perhaps on the basis of the 85th percentile speed), and no other curve warning is present, then a truck-specific warning sign could be warranted.

Figure 5.2 Truck stability requirements (rollover threshold < 0.35 g).



5.4.3 Advisory Speed Intervals

Some road practitioners and users alike have questioned the practice of using advisory speed values ending in five. Certainly, some road controlling authorities already have advisory speed signs that depart from the current standard practice. One theory behind the system is that it clearly differentiates advisory speeds from regulatory speed limits (which end in zero). Whether there is in fact any real confusion among drivers, given the quite different appearance of these speed signs, is a valid point. There is also the possibility that using numbers ending in five suggests a precision in the values to the nearest 5 km/h, rather than the actual precision to the nearest 10 km/h. It is not clear, however, whether this presents any real problem.

The ball-bank surveys described in Section 4.4.2 showed that a range of up to 12 km/h can be expected from any given test on a curve, although the average difference between any two tests is likely to be less than 3 km/h. When grouped by various categories, the differences were still ± 3 km/h, indicating the variability even when multiple tests are averaged. It may not be reasonable, therefore, to expect accuracy to the nearest 5 km/h (although countries that use 5 mph increments could reasonably do so). Another issue would be whether road users would find such accuracy credible, given the inaccuracies in the past. The question therefore becomes one of which "base ten" system to use. One potential advantage of reverting back to values ending in zero is the possibility of shifting the relative driver perception to more realistic values, as discussed in Section 5.3.

5.4.4 Sign Sizes and Types

The field results indicated few significant effects related to the level of signage at sites. For example, contrary to anecdotal opinion, the presence of an additional chevron board did not seem significantly to influence observed speeds. This confirms the view that drivers are still taking more notice of the surrounding road environment than the signs when assessing curve speeds. It may be, however, that additional signs have more effect at night, when the other visual cues are not visible; this has not been explored further.

The variety of curve signs does not appear to have a great effect on driver behaviour. Evidently, the significance of the relative shape of the curve on the sign is lost on the average driver. The one exception (albeit from only two sites) is the PW-16 (sharp 90° curve) sign, which appears to be taken more seriously. This begs the question of what constitutes a "sharp" curve – e.g. can an 85-km/h curve be signed using one of these? Concern has also been raised about the diminishing effect of a "multiple curve" sign on speeds through the second curve. It appears, however, that the slowing effect of the first curve usually provides a sufficient "safety net". If the second curve is too far away, the curves should be signed separately.

5.5 Other Means of Speed Reduction

Although curve advisory speed signs provide a relatively inexpensive and simple way to reduce vehicle speeds, it is apparent that at some locations additional guidance may be appropriate. Several techniques have been tried overseas that are worth trialling here.

Dynamic speed warning signs detect the approach speed of an oncoming vehicle and flash a warning before it reaches the curve. Shaw & Mayhew (2000) report on the use of such devices in the UK. They are set to trigger at a certain level (e.g. the 85th percentile speed) and then display a light-emitting diode picture and text warning the driver to slow down. One site studied in the UK found a 6 mph reduction in mean speeds after the installation of such a curve speed warning system.

By using automated classifiers, such warning systems can also be targeted to a particular group of vehicles, such as trucks. Freedman et al. (1992) studied special truck rollover-warning signs for effectiveness in slowing tractor-trailer trucks to a speed below that associated with rollover on highway exit ramps. Advisory speeds were verified for trucks at three highway exit ramps with high truck-rollover crash frequencies, and rollover-warning signs specific to trucks were posted to supplement the standard speed advisory signs already in place. The rollover-warning sign was equipped with a yellow light triggered to flash for every alternate tractor-trailer truck travelling above a predetermined ramp approach speed. Mean speeds at mid-ramp associated with the flashing sign were lower than for the non-flashing sign. Although the flashing signs did not significantly increase the number of trucks complying strictly with maximum safe speeds, they did significantly reduce the number of trucks that were travelling more than 5 and 10 mph faster than the calculated maximum safe speed. These findings suggest that speed-actuated rollover advisory signs specific to trucks may reduce truck rollover crashes at highway ramps.

Another approach being investigated in Australia is the use of “perceptual countermeasures” (Gunatillake et al. 2000). These are road or roadside treatments designed, through their visual effect, to induce motorists to reduce their speed by altering their perceptions of speed, risk or comfort. Generally, they are low-cost treatments such as changes to road markings or edge delineation – e.g., lane narrowings, transverse lines across the lane, “kinked” edge marker posts. Simulator testing has identified significant speed reductions of up to ~10 km/h for some treatments. Field testing of selected treatments is under way at the moment, with results likely in June 2002. Assuming some favourable findings, it would be worth considering trial implementation of similar devices in New Zealand.

6. Conclusions

This research provided some up-to-date local field data on a difficult topic. By combining these findings with the background information found, the merits or otherwise of the existing system in New Zealand could be ascertained.

6.1 Literature Review

A review of local and international literature on relevant topics revealed:

1. Curve speeds adopted in New Zealand are generally less conservative than measurements used elsewhere, such as most parts of Australia and the US. The relationship used between advisory speed (V_A) and ball-bank gauge value (b_A) is $b_A = 20.4 – 0.125V_A$.
2. There is little guidance or documentation available locally to inform road practitioners of the "correct" ball-bank survey procedure.
3. Driver compliance with curve advisory speed signs is historically poor throughout the world. This brings into question the friction criteria that have been used to determine the speeds.
4. Posted advisory speeds may have modest effects on speeds, compared with equivalent curves that are unsigned or have only curve warning signs.
5. The safety effect of advisory speed signs is unclear, especially in comparison with curve warning signs on their own.
6. There are many concerns about the accuracy of posted speeds in relation to the standard test procedures. Only about half of the signs locally have been found to have posted speeds matching those determined by ball-bank surveys, with some sites not warranting a sign at all.
7. Multiple ball-bank test runs are required to reduce random errors, with ideally at least one run very close to the true advisory speed.
8. Although truck speeds through curves are lower than for light vehicles, curves that pose dangers for trucks with low rollover thresholds may warrant specific signing.
9. No appreciable difference between curve speeds in dry and wet weather was observed in most studies. Similarly, no significant differences between day and night speeds were evident either.

6.2 Site Surveys of Curve Speed Profiles

Field surveys at 28 rural curves showed:

1. Posted speeds generally underestimate mean observed speeds by approximately 5–10 km/h, and 85th percentile speeds by ~10–20 km/h. However, at about a quarter of the sites mean speeds seem to follow the posted speeds quite well.

2. Ball-bank derived speeds appear to provide a reasonable measure of observed mean speeds up to about 60 km/h. For higher speeds, however, there is a disparity between the two measurements of ~10–15 km/h.
3. Posted speeds matched ball-bank derived speeds to within 10 km/h in the majority of cases. However, only half of the ball-bank readings produced exactly the same (rounded) posted speed.
4. Curve speeds collected produced reasonably normal distributions, usually with slightly longer tails at the low end. Standard deviations were generally about 12% of the mean speed, indicating no reduction in the coefficient of variance from speeds on straights.
5. Heavy vehicles were slower than light vehicles by 4 km/h on average, with the difference varying between 1 and 8 km/h. There appeared to be no noticeable change in this difference as the mean speeds increased.
6. Driver compliance with the posted advisory speed, 10 km/h above the posted speed and the ball-bank speed averaged 17%, 51% and 27% respectively. However, between sites there was a wide variation from almost no compliance to almost total compliance.
7. It is estimated that 40–50% compliance of vehicle speeds with the posted speed is likely if the ball-bank speed is actually less than that posted. Approximately double that proportion would comply within 10 km/h of the posted speed.
8. Sharp 90° curve (PW-16) signs and the second curve for multiple curve signs appeared to have good levels of compliance, albeit from few observed sites.
9. Vehicles making the greatest speed drops when approaching a curve were still likely to travel faster through the curve.

6.3 Surveys Using Alternative Methods

Analysis of measurements taken during repeated drive-over surveys at four sites found:

1. Comparison between the “nominal” test speed (i.e. the speed the driver attempted to travel at) and the actual recorded speed at the point of maximum lateral acceleration suggested that driver observation of the speedometer is a sufficient way to ensure consistent vehicle speeds.
2. Observed ball-bank values underestimated those identified by an electronic gyro, by an average factor of 20%. This may be due to the water damping of the ball-bank gauge or to observers ignoring any isolated “jumps” in the ball-bank readings.
3. Advisory speeds calculated from the gyro were generally less than the equivalent ball-bank speeds, by ~9% on average. A means of “smoothing” the automatically recorded gyro readings may reduce the lateral acceleration peaks and produce less conservative values.

4. Predicted curve advisory speeds were largely insensitive to the relative body angle chosen. Tests made comparing the assumed 3° angle with 0° found that the computed speeds were only 1.3% lower on average, with a range of ± 6%.
5. Ball-bank surveys provide a fairly consistent measure, irrespective of driver, vehicle or test speed. One-way Anova tests, comparing differences between these factors, found significant differences half of the time, but generally no major patterns.
6. The ball-bank surveys carried out showed a range of up to 12 km/h between individual tests. When grouped by driver, vehicle used or test speed, the differences between groups were still ± 3 km/h.
7. Comparing measured ball-bank advisory speeds with the minimum speed value calculated using road geometry data produced a fairly good relationship, with road geometry tending just to underestimate advisory speeds. Using a rolling average of 50–100 m produced a more accurate fit.

6.4 Review of Existing Advisory Speed Criteria

Consideration of the above findings in the context of existing procedures concluded:

1. Ball-bank surveys do not derive sufficiently high advisory speeds at higher-speed values when compared with the observed mean speeds. It was found that assuming a constant advisory ball-bank reading of 17° (irrespective of advisory speed) appeared to fit a one-to-one relationship very well. This suggests that drivers do not change their level of comfort for different curves.
2. Road geometry data can provide a reasonable alternative to field survey measures and appears to present no less accurate a method for assessing curve speeds. In particular, as a desktop task to minimise the amount of field surveying done, it is very cost-effective.
3. Automated devices for determining curve speeds should be allowed in New Zealand, provided they can replicate a wide range of speeds consistently. This should be confirmed by a series of test runs for each device that compared their results to the equivalent ball-bank standard.
4. A move significantly to change the existing curve speed criteria to produce more realistic posted speeds would have a potential impact on safety for drivers unaware of the change. A possible approach instead would be to change the standard subtly by very small increments, causing only a few “borderline” posted speeds to be increased to the next level. However, this may require a number of such changes over a long period of time.
5. The existing criteria for determining advisory speeds cannot be applied to unsealed roads, as driver discomfort is not likely to be reached before insufficient friction causes loss of control.

6. Many of the problems that have affected trucks at curves are being dealt with through improvements in the relative stability of truck design and truck-driver education. However, sites at which less stable trucks experience problems but do not meet the normal conditions for advisory speed signing should be considered for truck-specific warning signs.
7. Ball-bank surveys are not accurate enough to warrant allowing a curve advisory speed system with intervals of 5 km/h.
8. Several alternative curve warning devices have the potential to provide more effective guidance where required. These include various road delineation countermeasures, and dynamic vehicles warning systems.

7. Recommendations

The following items are recommended for further investigation or action.

1. A standard methodology for carrying out ball-bank survey procedures correctly should be made available for local road practitioners, e.g. in *MOTSAM*.
2. The relative safety benefits of curve advisory speed signs should be identified separately from those of curve warning signs, using local crash data.
3. Driver education on the dangers of travelling at the same curve speeds in the wet should be promoted.
4. The effect on driver behaviour of changing curve signing should be studied. In this research some sites were identified where the currently signed speed (if any) differed from that measured from field and geometry data. Before and after surveys would be useful where a speed plate was changed, added or removed. This would eliminate site differences found in the current survey that can mask the underlying effect of the advisory speed.
5. A documented road geometry method should be allowed as an alternative for deriving curve advisory speeds in New Zealand. Allowance should also be made for using automated inclinometer devices instead of ball-bank gauges, provided it could be demonstrated that the device had been properly calibrated.
6. The merits of non-mechanistic linear curve speed formulae should be investigated further, e.g. using approach speed and curve radius only.
7. Further tests using the in-vehicle gyro on flat and constantly sloped surfaces could help to identify the amount of body roll in typical New Zealand vehicles.
8. Guidelines for curve advisory speeds on unsealed roads should be developed, making use of available design friction values. However, further research to observe traffic behaviour at a number of unsealed sites is suggested to confirm the feasibility of applying these.
9. Guidelines should be developed for truck-specific warning signs at sites where the combination of typical speed, radius and superelevation exceed the rollover threshold for a typical high truck.
10. Changing the curve advisory speed system to round to posted speeds ending in zero should be considered. This could be done in conjunction with making a slight change in speed criteria.
11. Alternative curve warning devices, such as the road marking counter-measures investigated in Australia and dynamic warning systems, should be trialled in New Zealand.
12. Further development of the optical speed-detection equipment should be investigated, to produce a more robust system with fewer data collection errors.

13. One of the prime outputs of the study was a database of speeds, by vehicle type, for a series of curves with measured geometric properties. This data has the potential to shed more light on the whole dynamics of speed choice in curves – a greater objective than simply curve advisory speeds. Further investigation of this database should be considered.

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Schedule of Appendices

Appendix A.1 Standard New Zealand Curve Signs

For more information, refer to the *Manual of Traffic Signs and Markings* (TNZ/LTSA 1999).

PW-16
Sharp 90° curve

PW-17
Curve of less than 90° deflection

PW-18
Curve of between 90° and 120° deflection

PW-19
Curve of greater than 120° deflection

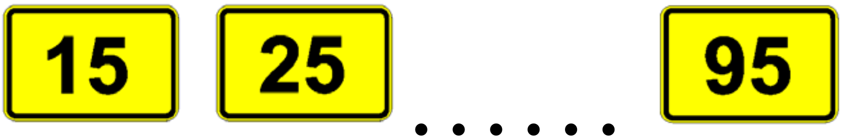
PW-20
Reverse curve of less than 60° deflection

PW-21
Reverse curve of greater than 60° deflection

PW-22
Reverse curve with decreasing radii

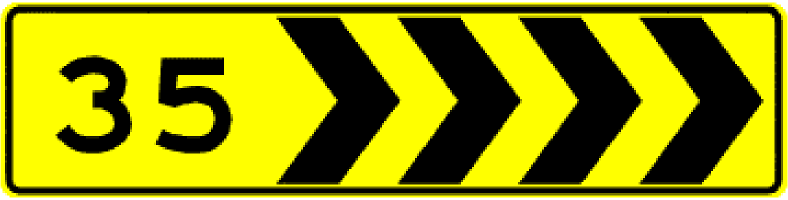
PW-23
Multiple reverse curves

PW-25
Curve advisory speed plate



In some cases, advisory speeds are also present on chevron boards, e.g.

PW-66



PW-67

(Note: this is the new Transit specification; many boards are still white on black.)

Appendix A.2 Curve Database Derivation Details

Using RAMM road geometry and sign inventory data, and existing (Microsoft Access) database programming scripts, a curve database was developed for this project to enable selection of appropriate survey sites.

Data from the Wellington, Wairarapa and Manawatu regions was used. All urban situations, motorways and their corresponding on/off ramps were ignored. Roads with AADTs of greater than 10,000 vehicles per day were also ignored because of the traffic hazard when investigating sites.

First, highway curves were identified. For each direction, adjacent geometry sections with radii less than 1500 m were found and grouped as "curves". Within these curve sections, basic parameters about the curve were derived, including location, length, deflection angle, and minimum and average radius. Minimum, maximum and average values of crossfall and National Association of Australian State Road Authorities (NAASRA) roughness values were also determined. Calculated advisory speeds and speed environments were found using geometric calculations, as detailed in Section 2.4.

This was reasonably straightforward, as a similar method has been used for previous projects. The more difficult task was to match up the curve data with the existing signs. As we were dealing only with curve advisory speeds, we filtered out most of the signs in the database, so that only advisory speed signs, curve signs and chevrons were left, i.e. sign codes PW-16–PW-25, PW-66 and PW-67 (see descriptions in Appendix A.1).

The signs needed to be further subdivided according to position. Curve and speed signs are generally before the start of the curve, to warn the driver there is a curve coming, whereas the chevrons are generally on the curve itself, indicating where the danger is. Therefore the chevron signs were treated as a separate case.

As there is no clear-cut positioning of signs for a curve, a series of matching queries was used to assign the signs to the curves, with an increasing range at each step and a self-check to ensure signs were not assigned to more than one curve. The range extended from 100 m to 300 m before the curve (depending on direction of travel) to 50 m before the end of the curve.

With the chevrons, it was assumed that they must lie within the curve itself, but they posed a slightly different problem owing to the cases of multiple chevrons (up to five in a row). A "multiple_chevron?" field was introduced to accommodate this.

Distinctions were made between signs in the increasing and decreasing route position directions, using the "side of road" and "facing direction" information. From this data, cases of multiple signs were also addressed, although inconsistencies in the database proved problematic. From this, speed, curve and chevron signs could be assigned to each curve. Table A.2.1 below shows the number of signs remaining at the last stage of the database site selection.

Table A.2.1 Number of signs remaining at final stage of database site selection.

	Advisory speed sign	Curve sign only	Chevron sign
Increasing direction	79	46	28
Decreasing direction	73	41	32

It should be noted that this does not indicate the actual number of signs in the region, as we were interested only in the sharper curves in the non-urban environment. It should also be noted that the matching queries still resulted in quite a few signs not being matched up automatically. Moreover, the nature of the curve-finding scripts meant that quite a few curved areas that needed signs for multiple curves but had no single sharp curves were also missed out. Owing to the reasonably small sample of survey sites needed, this was considered acceptable rather than spending a lot more time matching up every sign.

The final result was 299 signs over 1059 curves.

Appendix A.3 Site Selection Process

This process was used when initially selecting potential sites for survey.

1. Stop on increasing side of curve, turn on hazard lights, put on vests, put sign on back of vehicle, and place "road works" and "works end" signs on the side of the road in the appropriate location (as stated in traffic management plan).
2. Observe the following:

Increasing direction

- suitability of curve and shoulder for further surveying,
- suitability of shoulder and surroundings for setting up logging gear,
- STOP AT THIS POINT IF CURVE IS THOUGHT UNSUITABLE, RECORD REASONS WHY AND TAKE A LOOK AT THE CURVE FROM THE DECREASING DIRECTION TO CONFIRM,
- zero point, record marker for zero point on table,
- start of the curve,
- apex if possible,
- signs present compared with signs mentioned in database, record,
- side roads and other possible obstacles, record,
- visibility of approach, record approximate length of straight before curve starts,
- visibility through inside of curve,
- vegetation, record,
- guardrail or sight rail present.

3. While one person drives through the curve, the other walks the curve making general observations; determine apex of curve and mark with dazzle and a cone.
4. Place cone at start of curve (station 1), mark with dazzle and start to make a sketch.
5. The driver drives to the other side of the curve and turns around.
6. Park in a safe position, before the curve begins on the decreasing side.
7. Together, observe the following and make notes.

Decreasing direction

- suitability of curve and shoulder for further surveying,
- suitability of shoulder and surroundings for setting up logging gear,
- STOP AT THIS POINT IF CURVE IS THOUGHT UNSUITABLE, RECORD REASONS WHY,
- zero point, record marker for zero points on sketch and table,
- start of the curve,
- apex if possible,

- signs present compared with signs mentioned in database, record,
- side roads and other possible obstacles, record
- visibility of approach, record approximate length of straight before curve starts,
- visibility through inside of curve,
- vegetation, record,
- guardrail or sight rail present.

8. Leave the van, taking a cone, distance-measuring wheels, dazzle, calculator and clipboard.
9. Determine zero location, mark with dazzle and record (if not already recorded).
10. Measure distance from zero location to sign, and record.
11. Determine start of curve, place a cone, mark with dazzle, record on table and sketch (station 6).
12. Measure distance from sign to start of curve, and record distance.
13. Measure distance from station 6 (start of curve) to apex and note distance.
14. Locate stations 3 and 4, 10 m either side of the apex, record and mark with dazzle.
15. Calculate the location of station 5, i.e. half-way between stations 4 and 6.
16. Measure back to station 5, mark with dazzle.
17. Measure distance between stations 6 and 5, and between stations 5 and 4.
18. Continue measuring towards station 1, record distance between each station.
19. Calculate the location of station 2, i.e. half-way between stations 3 and 1.
20. Using distance-measuring wheel, measure back to station 2, mark with dazzle.
21. Continue measuring towards station 1, the speed advisory sign and the zero location, record separate distances between all, add these up on table and calculate cumulative distances.

Increasing direction

22. Observe, discuss and record:
    - approximate length of straight before curve starts,
    - general comments about curve.
23. One person walks across the road and locates station 1 on this side (i.e. perpendicular to the station 1 already marked).
24. Mark the second station 1 with dazzle.
25. With one distance-measuring wheel, measure width of shoulders and lanes, and record.
26. With other distance-measuring wheel, measure cumulative distance between stations.
27. Move to station 2 and repeat locating station, marking with dazzle and measuring shoulder and lane widths.
28. Repeat for stations 3 to 6.
29. Measure and record distances from station 6 to speed sign to zero location.

Decreasing direction

30. Collect level, tape measure and camera from van, drop off distance-measuring wheels and dazzle.
31. Measure and record size of speed advisory sign, record ID code of signs (e.g. PW-17).
32. Measure and record crossfall and gradient in one lane at each station
33. Walk back to van, while
    - measuring and recording crossfall and gradients at each station in the other lane,
    - taking photos of the curve in both directions; at start and end of curve and at apex (take fewer photos if this shows the way around the curve),
    - assessing roughness only if extreme.
34. Carry out ball-bank measurements travelling at the curve advisory speed and at ± **5k m/h**, in each direction, and record.
35. Collect cones.
36. Pick up “road works” and “works end” signs.
37. Take sign off the back of the vehicle.

Appendix A.4 Original Survey Sites

Only data for state highway sites is recorded here. Eight suitable local road sites were also identified.

Explanation of columns in Table A.4.1 on page 94.

- Site Num: unique ID number for each site.
- Curve Dirn: whether vehicles approach in an increasing (Incr) or decreasing (Decr) direction in terms of route position.
- Start Location: State Highway (SH), Reference Station (RS) and Route Position (RP, km) to start of site.
- 1999 AADT: annual average daily traffic volumes (vehicles/day, two-way) in 1999.
- Orientn: whether the site curves to the left (LH) or right (RH) on approach
- Length: approximate length of curve (m), defined as the section with <1500 m radius.
- Defln Angle: approximate deflection angle (in degrees) over the above curve length.
- Radius: the minimum and average horizontal radii (m) recorded over the curve length.
- Ave Grad: the average gradient (%) over the curve length; positive = uphill.
- Min Adv Spd: the minimum advisory speed (km/h) calculated through the curve. Used to represent the estimated safe curve speed.
- Ave Spd Env: the average speed environment (km/h) calculated through the curve. Used to represent the estimated approach speed.
- Spd Diff: the difference between the previous two measures (km/h). Used to determine whether a curve should be signed or not (ignoring multiple curves).
- Calc'd Spd: the rounded minimum advisory speed (km/h) to represent the recommended posted speed. Values in parentheses do not warrant signing.
- Existing PW Sign: the *MOTSAM* code and orientation for any existing sign. Refer to Appendix A.1 for more details.
- Posted Speed: the current PW-25 speed displayed (if any)
- Xfall: the average and maximum crossfall (superelevation) throughout the curve (%). Positive = slopes upwards to the right as you approach it
- Roughness: the average and maximum surface roughness throughout the curve (NAASRA counts). New roads typically have figures <70.
- Chevron: the presence of any additional chevron warning boards [>>>>] or individual chevron arrows [>].

Table A.4.1 Original survey sites (state highways only).

Site	Curve	Start Location			1999	Orientn	Length	Defln	Radius		Ave	Min	Ave	Spd	Calc'd	Existing	Posted	Xfall (%)		Roughness		Chevron
Num	Dirn	SH	RS	RP	AADT	(LH/RH)	(m)	Angle	Min	Ave	Grad	Adv Spd	Spd Env	Diff	Spd	PW Sign	Speed	Ave	Max	Ave	Max	
3	Incr	002	921	4.92	4480	RH	190	210	30	130	9.2	37.3	60.3	23.0	35	PW19-RH	25	3.8	9.2	107	138	
3	Decr	002	921	5.02	4480	LH	180	205	27	163	-11.0	24.5	67.2	42.7	25			8.0	-3.9	117	180	
4	Incr	002	931	3.96	4480	LH	100	87	29	210	-10.1	61.1	73.8	12.7	(65)	PW18-LH	45	-3.1	-3.7	113	151	
4	Decr	002	931	3.96	4480	RH	110	86	29	280	8.2	57.4	68.0	10.6	(55)	PW19-RH	35	4.1	9.8	83	110	
5	Incr	002	931	9.03	4480	LH	100	63	50	211	4.4	59.5	78.8	19.2	55	PW18-LH	45	-1.1	-5.0	113	162	
5	Decr	002	931	9.06	4480	RH	130	66	49	352	-7.4	62.9	76.2	13.2	(65)	PW18-RH	45	5.6	7.3	80	116	
6	Incr	002	921	2.85	4480	LH	260	82	102	227	1.5	63.8	89.3	25.5	65	PW17-LH	55	-3.1	-4.2	57	82	
6	Decr	002	921	3.05	4480	RH	260	80	107	215	0.1	65.4	80.2	14.8	(65)			3.1	4.9	60	102	
7	Incr	053	0	14.73	2100	RH	130	38	117	334	1.6	72.7	109.3	36.6	75	PW22-RH	65	5.1	8.1	62	90	[>>>>]
7	Decr	053	0	14.80	2100	LH	140	38	116	313	-1.9	71.6	107.4	35.9	75	PW17-LH	65	-4.1	-7.3	87	109	
8	Incr	002	873	4.30	7900	RH	150	26	226	381	-3.0	83.1	104.2	21.1	85		75	3.6	4.7	79	167	
8	Decr	002	873	4.46	7900	LH	160	28	226	412	4.5	81.6	109.9	28.2	85	PW21-LH	75	-2.9	-4.8	80	132	
9	Incr	002	858	8.06	2900	RH	120	25	151	488	-0.5	86.6	106.7	20.0	85		75	5.4	10.2	55	59	[>>>>]
9	Decr	002	858	8.16	2900	LH	120	27	151	423	2.0	81.7	109.7	27.9	85	PW17-LH	75	-4.6	-6.8	42	63	
10	Incr	002	788	9.09	4570	LH	330	81	153	342	-0.3	76.5	102.9	26.4	75	PW17-LH	85	-9.3	-12.3	80	113	
10	Decr	002	788	9.36	4570	RH	290	66	181	298	-0.4	79.9	98.1	18.2	75	PW17-RH	75	7.7	10.3	85	129	
11	Incr	003	491	5.37	5900	LH	200	38	215	371	-0.4	79.8	101.7	21.9	75	PW17-LH	85	-3.3	-5.4	70	98	
11	Decr	003	491	5.51	5900	RH	210	47	187	295	1.5	75.9	107.4	31.5	75	PW17-RH	85	3.7	5.8	50	66	
12	Incr	002	931	8.29	4480	RH	90	54	63	117	-3.7	60.3	101.1	40.8	55			1.3	3.7	100	128	[>>>>]
12	Decr	002	931	8.30	4480	LH	90	50	66	240	4.4	53.6	78.4	24.8	55			2.2	-4.3	57	77	
13	Incr	002	931	2.57	4480	RH	120	89	44	141	-5.0	48.5	64.6	16.1	45			2.7	4.8	96	107	[>>>>]
13	Decr	002	931	2.67	4480	RH	110	92	44	105	4.6	46.0	71.9	25.9	45			-0.3	-8.3	102	137	
14	Incr	057	36	11.65	1650	RH	190	27	280	477	2.6	96.0	98.7	2.7	(95)		65	5.7	10.4	77	100	
14	Decr	057	36	11.77	1650	LH	210	29	312	499	-2.6	101.6	112.3	10.7	(105)	PW17-LH	65	-8.8	-12.3	77	129	
15	Incr	057	26	4.24	2950	LH	410	87	156	411	-0.9	78.9	99.7	20.9	75	PW17-LH	75	-9.9	-14.5	63	136	
15	Decr	057	26	4.59	2950	RH	400	86	163	392	0.7	76.7	99.6	22.9	75	PW17-RH	75	7.3	11.4	73	156	[>>>>]
16	Incr	057	26	2.71	4100	LH	250	67	143	281	-0.6	73.7	105.3	31.7	75	PW26-LH		-9.1	-11.4	93	139	
16	Decr	057	26	2.90	2950	RH	250	66	137	290	0.1	71.9	102.6	30.7	75	PW18-RH	65	7.8	10.4	88	143	[>>>>]
25	Incr	056	0	3.85	3100	RH	230	78	109	298	0.1	62.2	104.7	42.5	65	PW18-RH	55	3.4	7.8	61	129	[>>>>]
25	Decr	056	0	4.03	3100	LH	230	78	108	331	-0.2	64.7	106.3	41.6	65	PW18-LH	55	-6.7	-11.1	61	77	
26	Incr	057	36	10.79	5670	LH	110	33	110	296	3.8	75.9	89.5	13.6	(75)		65	-7.1	-9.5	69	76	
26	Decr	057	36	10.84	3660	RH	110	32	119	342	-3.5	73.2	106.5	33.3	75	PW17-RH	65	2.7	5.4	71	83	[>]
27	Incr	057	36	10.58	5670	RH	190	53	109	307	6.7	72.1	89.3	17.2	75			6.4	10.8	65	113	[>]
27	Decr	057	36	10.71	5670	LH	200	55	110	359	-7.4	70.8	98.9	28.1	65	PW18-LH	45	-7.6	-10.6	90	151	

Appendix A.5 Equipment/Software Used for Curve Advisory Speed Monitoring

A.5.1 Sensor

PHOTOSWITCH 42GRU-9000 10-40v DC Sensor made by Allen-Bradley, Rockwell Automation.

Attributes:

- retro-reflective on/off and timing photoelectric sensors,
- maximum 9 m sensing distance with 76 mm reflectors, in ideal conditions (i.e. clean air, no dust or water in the air).
- indicator lights: yellow – power, green – output, red – marginal (when all three lights are on the sensor is getting maximum return signal from reflector; if only two lights are on you are getting close),
- visible red transmitting LED,
- field of view = 1.5°,
- sensitivity adjustment = single turn potentiometer,
- power consumption = 1.2 watts maximum,
- response time: 2 ms.

A.5.2 Vertical gyro

Crossbow Technology Inc., DMU-FOG vertical gyro.

The DMU-FOG is a six-axis measurement system designed to measure:

- linear acceleration along three orthogonal axes,
- rotation rates around three orthogonal axes,
- stabilised pitch and roll in dynamic environments (not used for the measurements undertaken on this project).

The DMU-FOG uses 3 MEMS accelerometers, which are surface micro-machined silicon devices that use differential capacitance to sense acceleration, making them responsive and reliable. The device uses fibre-optic gyros to provide angular rate measurement, which are more accurate and subject to less drift than the silicon-based rate sensors.

“Voltage Mode” was used, whereby:

1. Analogue voltage outputs for x, y, and z were taken directly from the sensors through a buffer. The linear accelerations in ‘g’ were then determined by converting the DMU voltage output using the factory-supplied sensitivity values (g/V).

2. Analogue voltage outputs for roll, pitch and yaw were created by the 12-bit D/A converter internal to the DMU. Angular rates (degrees) were then determined by converting the DMU voltage output using the factory-supplied conversion factors.

The DMU-FOG comes with X-view software that allows immediate viewing of the outputs of the DMU on a PC running Windows 95 or Windows NT.

The device has a sticker on one face illustrating the DMU co-ordinate system. Facing the connector, and with the mounting plate down, the axes are defined as:

- x axis – from face with connector through the DMU,
- y axis – along the face with connector from left to right,
- z axis – along the face with the connector from top to bottom.

The axes are for an orthogonal right-hand co-ordinate system. Acceleration is positive when it is oriented towards the positive side of the co-ordinate axis.

A.5.3 LabView Data Manipulation Programs

A.5.3.1 Cornering Program

For optical sensors:

- Measures the time difference between the 1st and 2nd, 2nd and 3rd (3rd–4th, 4th–5th, 5th–6th) sensors as the signal is interrupted by a vehicle.
- The distance between the sensors is entered into the program, hence the velocity between sensors can be calculated.
- The first and last sensors are trigger sensors; once they have been triggered then the previous 5–10 seconds of data are saved.
- Post-processing takes out speeds <5 km/h and >120 km/h, plus any vehicles with speed differences between sensors of >25 km/h (approx 20% of readings).
- Post-processing takes out platoons.
- Measures the length of time that the signal is interrupted to determine the length of the vehicle (used to classify light/heavy vehicles).
- Collected between 284 and 2900 vehicles at 28 curves, with equipment left out between about 15 and 60 hours.
- Day = 8.30am–5pm.
- Night = 6pm–7.30am.
- Twilight = 7.30–8.30am and 5–6pm.

Data collected includes:

- ID,
- site ID,

- date,
- time,
- weather,
- light,
- direction,
- speed between 1st and 2nd, 2nd and 3rd sensors, etc.,
- lowest speed,
- length 1,
- length 2 (if a platoon of 2 vehicles is passing).

A.5.3.2 Data Collection Program

For collecting continuous speeds around curves while collecting gyro data in x, y and z directions, plus roll, pitch and yaw:

- modified from the speed profiling data collection program,
- 200 MHz sampling rate,
- six channels added for recording the DMU gyro data.

Survey table contains the following information relating to the drive-over surveys:

- run ID,
- run number,
- direction,
- vehicle,
- driver,
- speed,
- ball-bank reading,
- comments,
- survey date,
- average speed,
- site,
- DataFile,
- EventFile,
- StatsFile.

A.5.3.3 Filtering Program

To filter out vibrations from the vehicle (engine, body, etc.):

- Vibrations over 5 Hz are filtered out.
- The vehicle is calibrated by measuring the voltage corresponding to the zero acceleration when the vehicle is parked in one direction and again with the vehicle rotated through 90° and parked.

- These calibration voltages are entered into the program and deducted from the voltages recorded during a test run.
- The gradual swaying movements of the vehicle are recorded and are usually greater than ½ Hz.

A.5.3.4 Statistics Program

StatsData gives the following data columns:

- data ID,
- run ID,
- force (x, y, z, roll, pitch, or yaw),
- peak values for each force,
- peak location for each acceleration and angular rate (position around curve),
- minimum acceleration/angular value,
- location of minimum value (position around curve, in metres),
- mean value for each acceleration/angular value,
- standard deviation,
- calibration constants for x, y and z accelerations (i.e. offsets).

Two points should be noted. The first is that the data generated by this program and saved in the StatsData table was not properly zeroed, i.e. each signal had an offset – even when the acceleration (or angular rate) was zero. This meant that:

1. ‘peak’ values in the StatsData table are actually ‘peak’ + ‘zero-offset’,
2. ‘min’ values in the StatsData table are actually ‘min’ + ‘zero-offset’,
3. ‘mean’ values in the StatsData table are actually ‘mean’ + ‘zero-offset’.

To find the zero-offset for each signal, the six outputs from the gyro were plotted as a function of time. The mean value of each signal for a straight part of the road was then determined and used as the zero-offset. This procedure was repeated for each of the tests (the software package used was Matlab). The zero-offsets were then subtracted from the original statistics recorded

The second point is that the x, y, z and pitch signals for some tests were approximately 1/6–1/8 of the values expected (roll and yaw were OK). To try to make this erroneous data usable, a correction factor was applied. It was chosen by comparing the signals from tests where the gyro was working properly with the signals from tests where the gyro was not. The comparisons were made for the same vehicle at the same speed but with a different driver. This approach is not ideal (the tests should really have been repeated), but attempts to make the data “usable”.

Appendix A.6 Survey Operation Details

A.6.1 Placing Optical Sensors Around Curve (Initial Procedure)

1. Locate curve for logging.
2. Put out traffic control.
3. Park vehicle off the road and turn on amber flashing light.
4. Locate station marks made during site selection process.
5. Decide which side of the road the sensors are best located and which side the logging equipment is best located.
6. Set up logging equipment.
7. Set up sensors.
8. Decide on the distribution of sensors around the corner, depending on:
    - how many sensors are being used,
    - length of cables available,
    - slowest part of the curve.
9. Secure sensors,
    - using steel pins through the base plate,
    - placing rocks on base plate if ground is too hard to hammer in pins.
10. Secure reflectors, using
    - guard or site rails for support,
    - wooden batten for support,
    - steel pins or wooden peg hammered into bank.
11. Run cables from sensors to logger unit.
12. Align reflectors and sensors.
13. Measure distance between sensors, and record.
14. Measure distance between reflectors, and record.
15. Enter measurements into computer logging program.
16. Put out rain sensor.
17. Start computer logging.
18. Record all necessary information on site data sheet.
19. Make a number of runs through the curve in vehicle at a pre-selected speed, so Alex can check whether the logging function is operating correctly.
20. Close and secure metal box housing the logging equipment, camouflage if necessary.
21. Pick up road signs.

A.6.2 Placing Optical Sensors Around Curve (Revised Procedure)

1. On arrival, “road works” and “works end” signs were set out.
2. Determined which side of the road to set out the sensors, and where to position the box housing the computer and other hardware.
3. Most suitable positions for (normally three) sensors were determined, taking into account:
   - aim of setting sensors up on the stations as originally marked and measured,
   - driveways,
   - wide shoulders,
   - openness to interference from the public,
   - exposure to the elements,
   - ease and safety when setting up,
   - length of cables.

In most cases the sensors were set up on the original stations 3 and 4 and either station 2 or 5 depending on which was judged to be more useful, e.g. where the traffic approach speed was higher. Where the original stations were not visible, or if the sensors were not installed on the marked stations, the distance between them was re-measured and recorded.

4. Sensors were fixed in position by:
   - pinning down the housing base with steel pegs if the surface would allow,
   - loading the base of the housing with rocks, gravel or other available material,
   - a combination of the above, plus when needed an attachment to the steel barrier as a steady.
5. Reflectors were fixed in position, either:
   - screwed directly to the wooden guard-rail,
   - screwed to wooden pegs driven into the shoulder,
   - fitted to boards that were taped to steel pegs driven into the bank.
6. When satisfied that the system was operational, data logging began and was observed to ensure sensible data was being collected.
7. On returning (normally the next day), the system was checked to ensure it was still logging satisfactorily and, if not, at what time logging ceased.
8. Data was then copied to the Jazz Drive and the computer prepared for the next site.
9. All equipment was then removed from the site and installed at the next.

A.6.3 Drive-over (Gyro/Ball-bank) Surveys

1. Decide on location.
2. Mount gyro in vehicle.
   - Gyro orientation:
     Y = longitudinal
     Z = vertical
     X = lateral
     roll = rotation about longitudinal axis (Y)
     pitch = rotation about lateral axis (X)
     yaw = rotation about vertical axis (Z).
   - Gyro position: behind driver's seat at approximate height of passenger centre of mass.
3. Attach speed-profiling equipment to rear wheel on driver's side.
4. Set up ball-bank device on dashboard (passenger's side).
5. Measure height of dashboard above road (stored in VehicleData table in database).
6. Locate curve for drive-over survey.
7. See site selection data for zero locations.
8. Locate zero locations at the start and end of curves.
9. Determine average speed for the three drivers.
10. Each driver makes runs through the curve at average speed, average speed ± 5 km/h and at the curve advisory speed while recording:
    - speed profile,
    - accelerations in x, y, z directions, and angular rate of roll, pitch and yaw,
    - ball-bank maximum reading.
11. Repeat each run in the opposite direction.
12. Do the same in each of the three vehicles, i.e. car, van and truck.

Appendix A.7 Derivation of Equivalent Ball-bank Values from Gyro Readings

If the lateral acceleration is represented in units of g by a_T, then:

$$a_T = \frac{V_T^2}{Rg}\cos(\theta - \phi_T) - \sin(\theta - \phi_T) \tag{20}$$

Preisler et al. (1992) noted that there was a relationship between the ball-bank reading b_T at a given test speed:

$$\tan(b_T + \theta - \phi_T) = \frac{V_T^2}{Rg} \tag{21}$$

which can be substituted back into the previous equation to produce:

$$a_T = \tan(b_T + \theta - \phi_T)\cos(\theta - \phi_T) - \sin(\theta - \phi_T) \tag{22}$$

By applying the trigonometric rule:

$$\tan(x + y) = \frac{\tan(x) + \tan(y)}{1 - \tan(x)\tan(y)} \tag{23}$$

the equation can be expanded to:

$$a_T = \frac{[\tan(b_T) + \tan(\theta - \phi_T)]\cos(\theta - \phi_T)}{1 - \tan(b_T)\tan(\theta - \phi_T)} - \sin(\theta - \phi_T) \tag{24}$$

Rearranging the elements produces:

$$[a_T + \sin(\theta - \phi_T)][1 - \tan(b_T)\tan(\theta - \phi_T)] \quad = \quad [\tan(b_T) + \tan(\theta - \phi_T)]\cos(\theta - \phi_T) \tag{25}$$

$$\begin{aligned} &\Rightarrow \tan(b_T)[\cos(\theta - \phi_T) + a_T \tan(\theta - \phi_T) + \sin(\theta - \phi_T)\tan(\theta - \phi_T)] \\ &= a_T - \tan(\theta - \phi_T)\cos(\theta - \phi_T) + \sin(\theta - \phi_T) \end{aligned} \tag{26}$$

But, using the fact that $\tan(x) = \sin(x)/\cos(x)$, the equation can be simplified to:

$$\tan(b_T)\left[\cos(\theta - \phi_T) + a_T\frac{\sin(\theta - \phi_T)}{\cos(\theta - \phi_T)} + \frac{\sin^2(\theta - \phi_T)}{\cos(\theta - \phi_T)}\right] = a_T \tag{27}$$

Multiplying the whole equation by $\cos(\theta - \phi_T)$ produces:

$$\tan(b_T)[\cos^2(\theta - \phi_T) + a_T \sin(\theta - \phi_T) + \sin^2(\theta - \phi_T)] = a_T \cos(\theta - \phi_T) \tag{28}$$

Given that $\sin^2(x)+\cos^2(x)=1$, the equation can be reduced to:

$$\tan(b_T) = \frac{a_T \cos(\theta - \phi_T)}{a_T \sin(\theta - \phi_T) + 1} \tag{29}$$

Appendix A.8 Gyro and Ball-bank Speed Calculations

Explanation of columns in Table A.8.1, on pages 106–10:

- Run ID: unique ID number for each test run.
- Dirn: whether vehicles approach in an increasing (Incr) or decreasing (Decr) direction in terms of route position.
- Veh Type: the vehicle used for the test run, either Car, Van or Truck.
- Driver: name of the driver carrying out the test run.
- Site Num: unique ID number for each site.
- Test Spd: nominal test speed (km/h) that the driver attempted to maintain throughout the curve.
- Spd at Max Lat Accn: the speed recorded by the speed profiler (km/h) at the time of the peak lateral acceleration.
- Zeroed Max X: the adjusted maximum lateral acceleration recorded in units of g. A zero offset is applied to the raw values to remove initial bias.
- Zeroed Min/Mean X: similar minimum and mean measures of lateral acceleration (g) recorded throughout the curve and adjusted for zero offset afterwards.
- Lateral Accn: the peak lateral acceleration (g), being either the minimum or maximum recorded value depending on curve direction.
- Gain Factor: an adjustment made to some of the runs to correct their erroneous readings.
- Adj Lat Accn: final adjusted lateral acceleration, a_T (g).
- Equiv BB Ang: calculated ball-bank angle (degrees) from a_T.
- Actual BB Ang: maximum ball-bank angle (degrees) observed in vehicle during test runs.
- BB CA Spd: derived curve advisory speed (km/h), based on observed ball-bank angle.
- Rnd BB CA Spd: the previous advisory speed (BB CA Spd), rounded to the nearest posted speed.
- Gyro CA Spd: derived curve advisory speed (km/h), based on gyro-calculated ball-bank angle.
- Rnd Gyro CA Spd: the previous advisory speed (Gyro CA Spd), rounded to the nearest posted speed.
- Ratio BB/Gyro: the ratio of the two calculated curve advisory speeds, (BB CA Spd)/(Gyro CA Spd).

Note: an additional 20 records had ball-bank readings only.

Run ID	Dirn	Veh. Type	Driver	Site No.	Test Spd (km/h)	Spd at Max Lat Accn (km/h)	Zeroed Max X (g)	Zeroed Min X (g)	Zeroed Mean X (g)	Lateral Accn (g)	Gain Factor	Adj Lat Accn (g)	Equiv BB Ang (deg)	Actual BB Ang (deg)	BB CA Spd (km/h)	Rnd BB CA Spd (km/h)	Gyro CA Spd (km/h)	Rnd Gyro CA Spd (km/h)	Ratio BB/Gyro
1	Incr	Car	Peter	5	45	40.1	0.216	-0.066	0.029	0.216	1	0.216	12.0	10.5	45.9	45	43.9	45	1.046
2	Decr	Car	Peter	5	45	41.2	0.046	-0.276	-0.066	-0.276	1	-0.276	-15.6	-13.0	43.7	45	41.0	35	1.067
3	Decr	Car	Peter	5	55	52.0	0.183	-0.412	-0.060	-0.412	1	-0.412	-22.8	-18.0	47.5	45	43.5	45	1.091
4	Incr	Car	Peter	5	55	49.5	0.435	-0.240	0.031	0.435	1	0.435	23.0	18.0	45.5	45	41.5	45	1.096
5	Incr	Car	Peter	5	50	45.1	0.310	-0.122	0.026	0.310	1	0.310	16.9	15.0	44.9	45	43.0	45	1.044
6	Decr	Car	Peter	5	50	47.3	0.138	-0.303	-0.040	-0.303	1	-0.303	-17.1	-15.5	46.2	45	44.7	45	1.034
7	Incr	Car	Peter	5	60	54.3	0.525	-0.210	0.040	0.525	1	0.525	27.0	18.9	48.4	45	42.3	45	1.144
8	Decr	Car	Peter	5	60	55.3	0.230	-0.473	-0.065	-0.473	1	-0.473	-25.8	-18.9	49.1	45	43.7	45	1.124
9	Incr	Car	Alex	5	45	44.5	0.206	-0.210	0.009	0.206	1	0.206	11.5	10.0	51.0	45	48.7	45	1.047
10	Decr	Car	Alex	5	45	44.8	0.120	-0.230	-0.007	-0.230	1	-0.230	-13.1	-11.5	49.0	45	46.9	45	1.043
11	Incr	Car	Alex	5	55	53.0	0.343	-0.249	0.037	0.343	1	0.343	18.6	14.0	52.8	55	47.8	45	1.104
12	Decr	Car	Alex	5	55	53.7	0.205	-0.262	0.010	-0.262	1	-0.262	-14.9	-16.5	50.3	45	52.3	55	0.963
13	Incr	Car	Alex	5	50	48.8	0.322	-0.096	0.045	0.322	1	0.322	17.5	14.0	49.2	45	45.4	45	1.083
14	Decr	Car	Alex	5	50	47.6	0.104	-0.234	-0.016	-0.234	1	-0.234	-13.3	-13.0	49.4	45	49.2	45	1.006
15	Incr	Car	Alex	5	60	55.5	0.340	-0.248	-0.004	0.340	1	0.340	18.4	18.9	49.3	45	49.8	45	0.989
16	Decr	Car	Alex	5	60	52.6	0.170	-0.485	-0.074	-0.485	1	-0.485	-26.4	-18.0	48.0	45	41.5	45	1.155
17	Incr	Car	Alex	5	60	53.1	0.424	-0.197	0.053	0.424	1	0.424	22.5	18.9	47.5	45	44.5	45	1.066
18	Incr	Van	Peter	5	45	45.0	0.344	-0.114	0.037	0.344	1	0.344	18.6	16.0	43.8	45	41.4	45	1.057
22	Decr	Van	Peter	5	45	45.4	0.126	-0.283	-0.037	-0.283	1	-0.283	-16.0	-14.0	46.3	45	44.2	45	1.047
23	Incr	Van	Peter	5	55	54.0	0.444	-0.293	0.015	0.444	1	0.444	23.4	18.0	49.0	45	44.5	45	1.102
24	Decr	Van	Peter	5	50	53.6	0.202	-0.382	-0.048	-0.382	1	-0.382	-21.3	-18.0	48.7	45	45.9	45	1.062
25	Decr	Van	Peter	5	50	48.6	0.193	-0.311	-0.020	-0.311	1	-0.311	-17.5	-17.0	45.7	45	45.3	45	1.010
26	Incr	Van	Peter	5	60	58.3	0.472	-0.396	-0.045	0.472	1	0.472	24.7	18.9	51.4	55	46.6	45	1.104
27	Decr	Van	Peter	5	60	57.8	0.294	-0.452	-0.002	-0.452	1	-0.452	-24.8	-18.9	51.0	45	46.1	45	1.105
28	Incr	Van	Alex	5	45	45.5	0.303	-0.153	0.052	0.303	1	0.303	16.6	13.0	47.6	45	43.7	45	1.089
29	Decr	Van	Alex	5	45	45.3	0.110	-0.280	-0.025	-0.280	1	-0.280	-15.9	-14.0	46.2	45	44.2	45	1.044
30	Incr	Van	Alex	5	55	52.5	0.385	-0.253	0.008	0.385	1	0.385	20.6	17.0	48.9	45	45.6	45	1.072

Appendix A.8 Table A.8.1

Run ID	Dirn	Veh. Type	Driver	Site No.	Test Spd (km/h)	Spd at Max Lat Accn (km/h)	Zeroed Max X (g)	Zeroed Min X (g)	Zeroed Mean X (g)	Lateral Accn (g)	Gain Factor	Adj Lat Accn (g)	Equiv BB Ang (deg)	Actual BB Ang (deg)	BB CA Spd (km/h)	Rnd BB CA Spd (km/h)	Gyro CA Spd (km/h)	Rnd Gyro CA Spd (km/h)	Ratio BB/Gyro
31	Decr	Van	Alex	5	55	52.0	0.263	-0.327	-0.024	-0.327	1	-0.327	-18.4	-17.0	48.5	45	47.2	45	1.027
32	Incr	Van	Alex	5	50	51.4	0.387	-0.150	0.049	0.387	1	0.387	20.7	18.0	47.0	45	44.7	45	1.053
33	Decr	Van	Alex	5	50	48.5	0.224	-0.305	-0.029	-0.305	1	-0.305	-17.2	-17.0	45.7	45	45.6	45	1.003
34	Incr	Van	Alex	5	60	55.7	0.452	-0.272	0.016	0.452	1	0.452	23.8	18.9	49.4	45	45.4	45	1.089
35	Decr	Van	Alex	5	60	57.5	0.322	-0.394	-0.009	-0.394	1	-0.394	-21.9	-18.9	50.8	45	48.1	45	1.054
36	Incr	Van	Alex	5	60	56.4	0.462	-0.317	0.007	0.462	1	0.462	24.2	18.9	49.9	45	45.6	45	1.096
37	Decr	Van	Alex	5	55	53.6	0.214	-0.370	-0.036	-0.370	1	-0.370	-20.6	-18.0	48.7	45	46.4	45	1.050
38	Incr	Car	Robert	9	75	70.5	0.106	-0.181	-0.024	-0.181	1	-0.181	-10.4	-8.0	78.5	75	73.1	75	1.074
39	Decr	Car	Robert	9	75	70.5	0.201	-0.061	0.022	0.201	1	0.201	11.2	7.0	81.2	85	71.4	75	1.139
40	Incr	Car	Robert	9	80	74.1	0.132	-0.216	-0.024	-0.216	1	-0.216	-12.3	-11.0	74.4	75	72.1	75	1.033
41	Decr	Car	Robert	9	80	73.6	0.212	-0.121	0.030	0.212	1	0.212	11.8	9.0	78.4	75	72.5	75	1.081
42	Incr	Car	Robert	9	85	82.4	0.155	-0.219	-0.031	-0.219	1	-0.219	-12.5	-13.0	76.7	75	77.7	75	0.987
43	Decr	Car	Robert	9	82	80.8	0.273	-0.114	0.014	0.273	1	0.273	15.0	13.0	75.6	75	72.3	75	1.045
44	Decr	Car	Robert	9	85	80.5	0.286	-0.118	0.045	0.286	1	0.286	15.7	13.0	75.4	75	71.1	75	1.060
45	Incr	Car	Robert	9	70	65.4	0.086	-0.162	-0.024	-0.162	1	-0.162	-9.3	-9.0	71.8	75	71.3	75	1.007
46	Decr	Car	Robert	9	70	66.8	0.195	-0.073	0.027	0.195	1	0.195	10.9	8.0	75.4	75	69.1	65	1.092
47	Incr	Car	Robert	9	90	85.9	0.206	-0.273	-0.045	-0.273	1	-0.273	-15.5	-14.0	77.3	75	75.1	75	1.030
48	Decr	Car	Robert	9	90	86.6	0.445	-0.040	0.124	0.445	1	0.445	23.5	15.0	76.1	75	65.8	65	1.157
49	Incr	Car	Robert	5	45	41.6	0.282	-0.156	0.014	0.282	1	0.282	15.5	13.0	44.0	45	41.4	45	1.064
51	Decr	Car	Robert	5	45	40.3	0.084	-0.225	-0.025	-0.225	1	-0.225	-12.8	-12.0	44.1	45	43.2	45	1.021
52	Incr	Car	Robert	5	55	51.4	0.352	-0.215	-0.028	0.352	1	0.352	19.0	18.0	47.0	45	46.2	45	1.019
53	Decr	Car	Robert	5	55	50.1	0.203	-0.305	-0.020	-0.305	1	-0.305	-17.2	-17.0	47.0	45	46.8	45	1.003
54	Incr	Car	Robert	5	40	37.4	0.177	-0.072	0.028	0.177	1	0.177	9.9	7.0	49.2	45	44.2	45	1.115
55	Decr	Car	Robert	5	40	37.1	0.084	-0.128	-0.004	-0.128	1	-0.128	-7.3	-8.0	46.9	45	48.2	45	0.972
57	Incr	Car	Robert	5	60	53.6	0.479	-0.206	0.050	0.479	1	0.479	25.0	18.0	48.7	45	43.1	45	1.130
58	Decr	Car	Robert	5	60	54.5	0.345	-0.418	0.004	-0.418	1	-0.418	-23.1	-18.0	49.4	45	45.1	45	1.096
59	Incr	Van	Peter	9	75	70.4	0.022	-0.039	-0.005	-0.039	7	-0.273	-15.5	-10.5	72.6	75	64.4	65	1.127

Run ID	**Dirn**	**Veh. Type**	**Driver**	**Site No.**	**Test Spd** (km/h)	**Spd at Max Lat Accn** (km/h)	**Zeroed Max X** (g)	**Zeroed Min X** (g)	**Zeroed Mean X** (g)	**Lateral Accn** (g)	**Gain Factor**	**Adj Lat Accn** (g)	**Equiv BB Ang** (deg)	**Actual BB Ang** (deg)	**BB CA Spd** (km/h)	**Rnd BB CA Spd** (km/h)	**Gyro CA Spd** (km/h)	**Rnd Gyro CA Spd** (km/h)	**Ratio BB/Gyro**
60	Decr	Van	Peter	9	75	73.4	0.034	-0.017	0.003	0.034	7	0.239	13.2	12.0	72.0	75	70.0	65	1.029
61	Incr	Van	Peter	9	90	87.0	0.028	-0.046	-0.008	-0.046	7	-0.322	-18.1	-18.0	72.1	75	72.1	75	1.000
62	Decr	Van	Peter	9	90	89.4	0.064	-0.021	0.003	0.064	7	0.445	23.5	17.0	75.0	75	67.5	65	1.111
63	Incr	Van	Peter	9	85	81.5	0.024	-0.035	-0.006	-0.035	7	-0.246	-14.0	-14.0	74.3	75	74.5	75	0.998
64	Decr	Van	Peter	9	85	83.4	0.044	-0.016	0.004	0.044	7	0.309	16.9	16.0	72.6	75	71.4	75	1.016
65	Incr	Van	Peter	9	95	91.8	0.030	-0.052	-0.007	-0.052	7	-0.362	-20.2	-18.9	73.9	75	72.4	75	1.021
66	Decr	Van	Peter	9	95	93.2	0.051	-0.015	0.008	0.051	7	0.354	19.2	17.5	76.7	75	74.6	75	1.028
68	Incr	Van	Alex	9	75	73.5	0.021	-0.038	-0.005	-0.038	7	-0.265	-15.0	-11.0	74.0	75	67.2	65	1.100
69	Decr	Van	Alex	9	75	73.4	0.031	-0.017	0.003	0.031	7	0.219	12.2	10.0	76.0	75	71.7	75	1.059
70	Incr	Van	Alex	9	90	88.2	0.037	-0.069	-0.007	-0.069	7	-0.483	-26.3	-16.5	74.9	75	64.1	65	1.169
71	Decr	Van	Alex	9	90	87.5	0.050	-0.036	0.004	0.050	7	0.353	19.1	17.0	73.8	75	71.1	75	1.037
72	Incr	Van	Alex	9	85	81.6	0.043	-0.056	-0.005	-0.056	7	-0.389	-21.6	-14.0	74.4	75	64.6	65	1.152
73	Decr	Van	Alex	9	85	84.3	0.061	-0.056	0.000	0.061	7	0.429	22.7	16.0	73.1	75	65.1	65	1.123
74	Incr	Van	Alex	9	95	91.6	0.035	-0.051	-0.006	-0.051	7	-0.360	-20.1	-18.0	75.0	75	72.4	75	1.035
75	Decr	Van	Alex	9	95	90.1	0.056	-0.038	0.001	0.056	7	0.390	20.9	18.9	72.8	75	70.6	65	1.032
76	Incr	Car	Peter	9	75	72.0	0.023	-0.029	-0.007	-0.029	7	-0.202	-11.5	-13.5	68.4	65	72.0	75	0.950
77	Decr	Car	Peter	9	75	71.7	0.047	-0.035	0.003	0.047	7	0.332	18.0	8.0	79.4	75	62.0	65	1.281
78	Incr	Car	Peter	9	90	86.1	0.026	-0.046	-0.008	-0.046	7	-0.321	-18.0	-17.0	72.9	75	71.6	75	1.018
79	Decr	Car	Peter	9	90	86.1	0.049	-0.024	0.005	0.049	7	0.343	18.6	16.0	74.3	75	70.8	65	1.049
80	Incr	Car	Peter	9	85	80.5	0.022	-0.040	-0.008	-0.040	7	-0.281	-15.9	-16.0	70.6	65	70.9	65	0.996
81	Decr	Car	Peter	9	85	82.1	0.033	-0.015	0.004	0.033	7	0.232	12.9	13.5	75.6	75	76.7	75	0.985
82	Incr	Car	Peter	9	95	90.1	0.028	-0.053	-0.007	-0.053	7	-0.372	-20.7	-18.9	72.9	75	70.8	65	1.029
83	Decr	Car	Peter	9	95	91.5	0.051	-0.026	0.006	0.051	7	0.358	19.3	17.0	76.3	75	73.3	75	1.040
84	Incr	Car	Alex	9	75	67.7	0.015	-0.037	-0.006	-0.037	7	-0.261	-14.8	-10.0	71.5	75	63.3	65	1.129
85	Decr	Car	Alex	9	75	72.0	0.035	-0.025	0.000	0.035	7	0.244	13.5	8.0	79.7	75	68.4	65	1.164
87	Incr	Car	Alex	9	90	85.0	0.009	-0.044	-0.009	-0.044	7	-0.305	-17.2	-18.9	69.7	65	72.0	75	0.968
88	Decr	Car	Alex	9	90	85.7	0.043	-0.023	0.001	0.043	7	0.298	16.3	13.0	78.9	75	73.7	75	1.071

Appendix A.8   Table A.8.1

Run ID	Dirn	Veh. Type	Driver	Site No.	Test Spd (km/h)	Spd at Max Lat Accn (km/h)	Zeroed Max X (g)	Zeroed Min X (g)	Zeroed Mean X (g)	Lateral Accn (g)	Gain Factor	Adj Lat Accn (g)	Equiv BB Ang (deg)	Actual BB Ang (deg)	BB CA Spd (km/h)	Rnd BB CA Spd (km/h)	Gyro CA Spd (km/h)	Rnd Gyro CA Spd (km/h)	Ratio BB/Gyro
89	Incr	Car	Alex	9	85	82.5	0.012	-0.038	-0.008	-0.038	7	-0.265	-15.0	-15.0	73.4	75	73.5	75	0.999
90	Decr	Car	Alex	9	85	80.7	0.039	-0.026	0.002	0.039	7	0.273	15.1	11.0	79.3	75	72.3	75	1.098
91	Incr	Car	Alex	9	95	88.7	0.011	-0.042	-0.007	-0.042	7	-0.296	-16.7	-17.0	74.5	75	75.0	75	0.993
92	Decr	Car	Alex	9	95	89.3	0.042	-0.024	-0.001	0.042	7	0.296	16.2	14.0	79.6	75	76.2	75	1.045
93	Decr	Truck	Neil	5	45	43.8	0.265	-0.303	-0.003	-0.303	1	-0.303	-17.1	-15.0	43.8	45	41.8	45	1.048
94	Incr	Truck	Neil	5	45	42.3	0.270	-0.250	0.030	0.270	1	0.270	14.9	9.0	50.5	45	42.6	45	1.186
95	Incr	Truck	Neil	5	50	52.9	0.416	-0.300	0.026	0.416	1	0.416	22.1	17.5	48.7	45	44.7	45	1.090
96	Decr	Truck	Neil	5	50	46.0	0.351	-0.317	0.042	-0.317	1	-0.317	-17.8	-16.5	44.1	45	42.9	45	1.028
97	Incr	Truck	Neil	5	40	39.9	0.234	-0.178	0.055	0.234	1	0.234	13.0	8.0	49.9	45	42.5	45	1.173
98	Decr	Truck	Neil	5	40	40.0	0.228	-0.263	-0.014	-0.263	1	-0.263	-14.9	-10.5	45.8	45	40.6	35	1.130
99	Incr	Truck	Neil	5	35	35.6	0.157	-0.311	-0.005	0.157	1	0.157	8.9	5.5	50.5	45	43.8	45	1.151
100	Decr	Truck	Neil	5	35	34.8	0.240	-0.182	0.021	-0.182	1	-0.182	-10.4	-8.5	43.6	45	40.8	35	1.067
101	Incr	Truck	Peter	5	45	45.8	0.342	-0.303	-0.001	0.342	1	0.342	18.6	16.5	44.0	45	42.2	45	1.043
102	Decr	Truck	Peter	5	45	44.8	0.134	-0.389	-0.047	-0.389	1	-0.389	-21.6	-16.8	42.8	45	39.0	35	1.098
103	Incr	Truck	Peter	5	50	50.2	0.438	-0.370	0.003	0.438	1	0.438	23.2	17.5	46.6	45	42.0	45	1.110
104	Decr	Truck	Peter	5	50	51.3	0.383	-0.421	0.014	-0.421	1	-0.421	-23.3	-17.0	47.9	45	42.6	45	1.123
105	Incr	Truck	Peter	5	40	38.6	0.217	-0.187	0.017	0.217	1	0.217	12.1	8.4	47.8	45	42.4	45	1.127
106	Decr	Truck	Peter	5	40	41.4	0.256	-0.279	-0.012	-0.279	1	-0.279	-15.8	-13.8	42.9	45	40.9	35	1.049
107	Incr	Truck	Peter	5	35	34.4	0.141	-0.208	-0.008	0.141	1	0.141	8.0	5.2	49.8	45	44.0	45	1.131
108	Decr	Truck	Peter	5	35	36.5	0.143	-0.191	-0.013	-0.191	1	-0.191	-10.9	-9.0	44.5	45	41.8	45	1.065
109	Incr	Truck	Neil	9	75	75.7	0.131	-0.329	-0.113	-0.329	1	-0.329	-18.5	-8.0	82.6	85	64.2	65	1.286
110	Decr	Truck	Neil	9	75	74.9	0.302	-0.132	0.029	0.302	1	0.302	16.6	11.0	75.0	75	66.1	65	1.135
111	Incr	Truck	Neil	9	80	81.4	0.112	-0.395	-0.127	-0.395	1	-0.395	-22.0	-13.0	76.0	75	64.1	65	1.185
112	Decr	Truck	Neil	9	80	79.1	0.340	-0.174	0.025	0.340	1	0.340	18.5	12.5	75.2	75	66.5	65	1.131
113	Incr	Truck	Neil	9	85	84.6	0.128	-0.432	-0.121	-0.432	1	-0.432	-23.8	-14.0	76.4	75	64.3	65	1.190
114	Decr	Truck	Neil	9	85	84.1	0.364	-0.140	0.036	0.364	1	0.364	19.6	14.0	76.1	75	68.3	65	1.113
115	Incr	Truck	Neil	9	70	71.1	0.067	-0.271	-0.111	-0.271	1	-0.271	-15.3	-9.0	76.5	75	65.1	65	1.175

Run ID	Dirn	Veh. Type	Driver	Site No.	Test Spd (km/h)	Spd at Max Lat Accn (km/h)	Zeroed Max X (g)	Zeroed Min X (g)	Zeroed Mean X (g)	Lateral Accn (g)	Gain Factor	Adj Lat Accn (g)	Equiv BB Ang (deg)	Actual BB Ang (deg)	BB CA Spd (km/h)	Rnd BB CA Spd (km/h)	Gyro CA Spd (km/h)	Rnd Gyro CA Spd (km/h)	Ratio BB/Gyro
116	Decr	Truck	Neil	9	70	70.7	0.240	-0.112	0.024	0.240	1	0.240	13.3	8.0	78.6	75	67.8	65	1.160
117	Incr	Truck	Peter	9	70	71.2	0.068	-0.322	-0.102	-0.322	1	-0.322	-18.1	-10.5	73.2	75	61.6	65	1.189
118	Decr	Truck	Peter	9	70	72.5	0.289	-0.132	0.018	0.289	1	0.289	15.9	9.2	77.1	75	65.3	65	1.180
119	Incr	Truck	Peter	9	75	75.0	0.078	-0.331	-0.104	-0.331	1	-0.331	-18.6	-11.5	74.1	75	63.7	65	1.165
120	Decr	Truck	Peter	9	75	76.0	0.325	-0.134	0.022	0.325	1	0.325	17.7	11.5	74.9	75	65.4	65	1.145
121	Incr	Truck	Peter	9	80	80.7	0.110	-0.394	-0.123	-0.394	1	-0.394	-21.9	-14.5	73.0	75	63.8	65	1.145
122	Decr	Truck	Peter	9	80	80.4	0.358	-0.134	0.025	0.358	1	0.358	19.3	14.0	73.6	75	66.4	65	1.109
123	Incr	Truck	Peter	9	85	80.7	0.131	-0.444	-0.115	-0.444	1	-0.444	-24.4	-16.0	70.7	65	61.3	65	1.153
124	Decr	Truck	Peter	9	85	84.8	0.386	-0.154	0.038	0.386	1	0.386	20.7	14.0	76.6	75	67.6	65	1.133
125	Incr	Truck	Bob	5	35	34.6	0.026	-0.021	0.003	0.026	8	0.207	11.6	4.0	53.5	55	39.1	35	1.369
126	Decr	Truck	Bob	5	35	35.6	0.024	-0.028	0.002	-0.028	8	-0.225	-12.8	-7.0	47.1	45	38.6	35	1.219
127	Incr	Truck	Bob	5	40	41.1	0.032	-0.027	0.002	0.032	8	0.256	14.2	5.5	57.0	55	42.4	45	1.345
128	Decr	Truck	Bob	5	40	39.0	0.028	-0.036	-0.001	-0.036	8	-0.284	-16.1	-9.0	47.1	45	38.6	35	1.222
129	Incr	Truck	Bob	5	45	42.3	0.037	-0.029	0.003	0.037	8	0.294	16.1	9.0	50.5	45	41.4	45	1.220
130	Decr	Truck	Bob	5	45	43.4	0.029	-0.036	0.000	-0.036	8	-0.285	-16.1	-12.0	47.0	45	42.4	45	1.109
131	Incr	Truck	Bob	5	50	49.6	0.038	-0.028	0.004	0.038	8	0.306	16.7	14.0	49.9	45	46.9	45	1.064
132	Decr	Truck	Bob	5	50	49.0	0.044	-0.053	-0.001	-0.053	8	-0.421	-23.3	-18.0	45.1	45	41.0	35	1.100
133	Incr	Truck	Bob	9	65	61.5	-0.022	-0.312	-0.135	-0.312	1	-0.312	-17.6	-6.0	76.4	75	55.3	55	1.383
134	Decr	Truck	Bob	9	65	64.4	0.168	-0.102	0.012	0.168	1	0.168	9.5	6.0	79.1	75	70.1	65	1.128
135	Incr	Truck	Bob	9	70	70.0	0.042	-0.264	-0.109	-0.264	1	-0.264	-15.0	-8.5	76.8	75	64.8	65	1.185
136	Decr	Truck	Bob	9	70	67.9	0.223	-0.141	0.021	0.223	1	0.223	12.4	7.0	79.0	75	67.2	65	1.177
137	Incr	Truck	Bob	9	75	80.1	0.069	-0.334	-0.130	-0.334	1	-0.334	-18.8	-11.0	78.9	75	66.8	65	1.180
138	Decr	Truck	Bob	9	75	73.3	0.245	-0.112	0.022	0.245	1	0.245	13.6	10.0	75.9	75	69.3	65	1.095
139	Incr	Truck	Bob	9	80	78.5	0.014	-0.347	-0.109	-0.347	1	-0.347	-19.5	-12.0	75.8	75	65.0	65	1.166
140	Decr	Truck	Bob	9	80	80.4	0.246	-0.137	0.036	0.246	1	0.246	13.6	10.5	80.1	75	74.3	75	1.078

Appendix A.9 Ball-bank Surveys: Analysis of Variance

Carried out over four sites, comparing drivers, vehicles and test speeds.

Table A.9.1 Summary of analyses.

Site	Dirn	Source of variation	Sum of squares	Degrees of freedom	Mean square	F-value	Probability (sig. Diff.)	Critical F	Sig. diff.?
		Drivers							
5	Incr	Main: [Driver]	64.1	4	16.02	1.905	0.133	2.659	NO
		Residual	277.4	33	8.40				
		Total	341.4	37	9.23				
5	Decr	Main: [Driver]	95.5	4	23.89	2.724	0.047	2.668	YES
		Residual	280.6	32	8.77				
		Total	376.1	36	10.45				
9	Incr	Main: [Driver]	161.6	4	40.40	10.444	0.000	2.659	YES
		Residual	127.7	33	3.87				
		Total	289.3	37	7.82				
9	Decr	Main: [Driver]	56.4	4	14.11	1.387	0.258	2.641	NO
		Residual	356.1	35	10.17				
		Total	412.5	39	10.58				
		Vehicles							
5	Incr	Main: [Vehicle]	15.6	2	7.82	0.841	0.440	3.267	NO
		Residual	325.8	35	9.31				
		Total	341.4	37	9.23				
5	Decr	Main: [Vehicle]	159.1	2	79.57	12.469	0.000	3.276	YES
		Residual	217.0	34	6.38				
		Total	376.1	36	10.45				
9	Incr	Main: [Vehicle]	19.0	2	9.52	1.232	0.304	3.267	NO
		Residual	270.2	35	7.72				
		Total	289.3	37	7.82				
9	Decr	Main: [Vehicle]	226.5	2	113.25	22.529	0.000	3.252	YES
		Residual	186.0	37	5.03				
		Total	412.5	39	10.58				
		Test Speeds							
5	Incr	Main: [TestSpd]	130.9	5	26.18	3.979	0.006	2.512	YES
		Residual	210.5	32	6.58				
		Total	341.4	37	9.23				
5	Decr	Main: [TestSpd]	269.6	5	53.92	15.697	0.000	2.523	YES
		Residual	106.5	31	3.44				
		Total	376.1	36	10.45				
9	Incr	Main: [TestSpd]	11.8	6	1.97	0.221	0.967	2.409	NO
		Residual	277.4	31	8.95				
		Total	289.3	37	7.82				
9	Decr	Main: [TestSpd]	19.9	6	3.32	0.279	0.943	2.389	NO
		Residual	392.6	33	11.90				
		Total	412.5	39	10.58				

Table A.9.2 Details of analyses.

Site	Dirn	Variable	Count	Mean	Min	Max	Range	Variance	Coeff. var.	Std. dev.	Std. error
		Drivers									
5	Incr	Alex	10	51.1	45.9	54.4	8.5	7.1	0.05231	2.67062	0.84452
		Bob	4	53.3	50.2	55.7	5.5	5.2	0.04288	2.28523	1.14262
		Neil	4	49.9	46.4	53.2	6.8	7.8	0.05605	2.79405	1.39703
		Peter	11	48.9	43.3	52.6	9.4	10.0	0.06470	3.16314	0.95372
		Robert	9	50.4	46.5	53.6	7.1	9.3	0.06036	3.04204	1.01401
5	Decr	Alex	8	50.2	45.9	53.6	7.7	7.3	0.05394	2.70994	0.95811
		Bob	4	47.3	45.9	48.4	2.5	1.6	0.02654	1.25409	0.62705
		Neil	4	45.4	43.8	47.4	3.6	2.4	0.03409	1.54885	0.77442
		Peter	13	47.2	41.7	52.6	11.0	12.0	0.07347	3.46770	0.96177
		Robert	8	49.6	45.1	53.6	8.5	10.4	0.06510	3.22778	1.14119
9	Incr	Alex	8	76.1	72.8	78.4	5.6	3.0	0.02261	1.71989	0.60807
		Bob	4	77.1	75.1	79.6	4.5	3.4	0.02394	1.84526	0.92263
		Neil	4	77.3	75.0	82.1	7.1	10.5	0.04188	3.23946	1.61973
		Peter	12	74.2	70.6	76.7	6.1	3.4	0.02479	1.83964	0.53106
		Robert	10	79.6	75.6	82.1	6.5	3.1	0.02218	1.76497	0.55813
9	Decr	Alex	8	78.9	73.6	83.2	9.6	14.6	0.04834	3.81554	1.34900
		Bob	4	79.4	77.2	80.8	3.6	2.3	0.01925	1.52834	0.76417
		Neil	4	76.4	75.1	78.1	2.9	1.6	0.01643	1.25586	0.62793
		Peter	12	76.2	73.2	82.1	8.9	6.8	0.03424	2.60805	0.75288
		Robert	12	77.2	72.9	84.9	12.1	15.2	0.05054	3.90317	1.12675
		Vehicles									
5	Incr	Car	13	51.2	47.1	54.4	7.3	4.1	0.03961	2.02935	0.56284
		Van	13	49.7	43.8	53.6	9.8	11.2	0.06742	3.35213	0.92971
		Truck	12	50.2	43.3	55.7	12.4	12.9	0.07149	3.58681	1.03542
5	Decr	Car	12	50.5	47.1	53.6	6.4	4.3	0.04122	2.08320	0.60137
		Van	13	48.6	45.1	53.6	8.5	9.6	0.06394	3.10451	0.86104
		Truck	12	45.4	41.7	48.4	6.8	4.9	0.04857	2.20679	0.63705
9	Incr	Car	13	76.5	70.6	82.1	11.5	9.9	0.04111	3.14327	0.87179
		Van	13	77.6	74.0	81.0	7.0	5.3	0.02957	2.29338	0.63607
		Truck	12	75.9	72.3	82.1	9.8	8.1	0.03741	2.83759	0.81914
9	Decr	Car	14	80.4	76.8	84.9	8.1	7.0	0.03278	2.63647	0.70463
		Van	14	74.8	72.9	77.7	4.9	2.7	0.02189	1.63677	0.43745
		Truck	12	76.9	73.3	80.8	7.5	5.5	0.03058	2.35112	0.67871
		Test									
5	Incr	35	3	51.5	49.8	54.0	4.2	5.1	0.04379	2.25357	1.30110
		40	5	50.7	46.6	55.7	9.1	11.6	0.06718	3.40659	1.52347
		45	9	48.5	43.3	53.2	10.0	14.4	0.07840	3.80105	1.26702
		50	6	48.0	45.9	50.2	4.3	4.1	0.04233	2.03294	0.82994
		55	6	50.9	49.8	54.4	4.6	3.2	0.03512	1.78798	0.72994
		60	9	53.0	52.6	53.6	0.9	0.2	0.00879	0.46521	0.15507
5	Decr	35	3	44.4	42.9	46.5	3.5	3.4	0.04159	1.84626	1.06594
		40	5	46.2	41.7	50.0	8.3	10.1	0.06875	3.17322	1.41911
		45	9	46.5	43.0	49.1	6.2	4.0	0.04319	2.00630	0.66877
		50	8	47.5	45.9	51.5	5.6	3.4	0.03857	1.83104	0.64737
		55	6	50.4	49.8	51.4	1.6	0.5	0.01382	0.69657	0.28437
		60	6	53.1	52.6	53.6	0.9	0.3	0.00960	0.50962	0.20805
9	Incr	65	1	79.6	79.6	79.6	0.0	0.0	0.00000	0.00000	0.00000
		70	5	76.2	72.3	80.8	8.5	9.4	0.04033	3.07352	1.37452
		75	9	76.9	70.6	82.1	11.5	14.4	0.04935	3.79469	1.26490
		80	5	76.8	72.5	81.0	8.5	10.8	0.04273	3.28243	1.46795
		85	8	76.3	73.6	79.4	5.8	4.4	0.02750	2.09744	0.74156
		90	6	76.4	72.8	80.0	7.2	9.2	0.03971	3.03297	1.23820
		95	4	76.8	75.8	78.4	2.6	1.5	0.01607	1.23363	0.61682
9	Decr	65	1	79.6	79.6	79.6	0.0	0.0	0.00000	0.00000	0.00000
		70	5	77.1	73.3	80.8	7.5	8.5	0.03774	2.90879	1.30085
		75	9	77.7	73.2	84.9	11.7	18.9	0.05591	4.34389	1.44796
		80	5	77.5	73.3	83.3	10.0	16.5	0.05244	4.06287	1.81697
		85	9	76.7	72.9	82.4	9.5	9.1	0.03939	3.02147	1.00716
		90	7	76.9	74.0	81.8	7.8	6.6	0.03330	2.56133	0.96809
		95	4	78.8	75.8	83.2	7.4	9.8	0.03971	3.12916	1.56458