



Horizontal Curves



The Problem: Accidents on horizontal curves are a cause for concern in all countries, whatever the level of development of their road system. A recent study has found that in Denmark, about 20% of all personal injury accidents and 13% of all fatal accidents occur on curves in rural areas; and in France, over 20% of fatal accidents occur on dangerous curves in rural areas (Herrstedt and Greibe, 2001). Accidents on bends are undoubtedly a major problem in many developing countries, although the proportion of such accidents is dependent upon both the topography and demography of each country. Data analysed using TRL’s Microcomputer Accident Analysis Package (MAAP) shows the problem of bends is largely a rural one:

	Proportion of Casualties in Rural Areas	Casualties on Bends	
		Rural	Urban
Botswana	71.1%	19.6%	8.6%
Zimbabwe	47.3%	25.0%	5.0%
Papua New Guinea	71.5%	46.9%	16.1%

Accidents on horizontal curves tend to be of two main types: ‘Running off the road and hitting an object’ and ‘Lost control and Rolled over’. There can also be a significant number of Head On and Sideswipe accidents at higher traffic volumes. The apparent cause of these accidents is usually the driver entering the bend at too high a speed; and the reason for this can be because the driver was wilfully travelling at a high speed, was paying insufficient attention or because he misjudged the severity of the bend. Such misjudgements can be caused because of the bend’s visual configuration, poor delineation or because it was unexpectedly sharp after a series of gentle curves or after a long straight (tangent) section. Another major problem can occur when drivers sometimes ignore the ‘no-overtaking’ enforcement.

When travelling around bends, the higher forces put on the road surface by the side thrust of the tyre frequently cause the surface aggregate on bends to polish more quickly than the rest of the road, thus aggravating the problem of safety. There can also be underlying problems in the geometric design of the curve because the basic assumptions are not applicable to the design (e.g. a high proportion of drivers exceed the design speed). On gravel roads in particular, the loss of super-elevation in the cross-sectional profile through lack of maintenance may result in the effects of a horizontal curve being more severe than as designed.

Solutions

- For all bends below the desirable minimum standards, warning signs should be provided to give the driver an idea of how severe the bend is. This should ideally follow a standard whereby the most dangerous bends have the highest level of signing and road marking.
- The road alignment should be designed to provide a uniform road layout traversable with clear forward visibility.
- If head-on accidents are a problem, double white lines should be enhanced with a physical device appropriate to the road conditions, ranging from line markings that induce vibrations to heavy duty road studs or rubber posts.
- Use higher skid resistance materials on critical bends particularly in wet environments.
- Bends should be linked into the road network as simple curves without a transition or spiral curve.
- Curve widening should be applied to the inside edge of the curve.

Curve Design Considerations:

Many Developing Countries have Geometric Design Guides that provide a systematic approach to designing curve geometry. These are often abased on developing country guides, such as the UK Departmental Standard TD 9/93 'Highway Link Design' or the US AASHTO Geometric Design of Highways and Streets, but these are often not appropriate for the current traffic mix or they are ignored as roads are built to alternative standards. This can result in a non-uniform road network creating driver confusion as to the forward road conditions and drivers being surprised by difficult alignment (eg. mid-range radius curves should be avoided since the visibility may not be wholly adequate for safe overtaking, and yet not so bad as to discourage overtaking). To counteract this tendency, TRL (funded by DFID) produced guidance for engineers in Overseas Road Note 6 'A Guide to Geometric Design' published in 1988. The key observations of this report are outlined below:

Design Speed:

The design speed, V_{design} , is used as an index which links road function, traffic flow and terrain and governs the maximum safe speed that can be maintained over a section of road when conditions are so favourable that the design features of the highway govern. The design speed should ideally be measured as the 85th percentile speed of the traffic approaching the geometric element and is used to define the minimum standards for the highway. However, the design speed can be determined from the road standards, either using the above equation (V_{design} in km/h, R = curve radius in metres, e = super-elevation or crossfall in metres per metre, and f = side friction factor, typically 0.15 (120km/h) to 0.33 (30km/h)) or estimated from the table below.

$$V_{design} = \sqrt{127.R.(e + f)}$$

Road function	Design class	Traffic flow (ADT)	Surface type	Width		Maximum Gdt (%)	Terrain / Design speed (km/h)		
				Carriageway	Shoulder		Mountainous	Rolling	Level
Arterial	A	5,000-15,000	Paved	6.5	2.5	8	85	100	120
	B	1,000-5,000	Paved	6.5	1.0	8	70	85	100
Collector	C	400-1,000	Paved	5.5	1.0	10	60	70	85
	D	100-400	Paved / Unpaved	5.0	1.0+	10	50	60	70
Access	E	20-100	Paved / Unpaved	3.0	1.5+	15	40	50	60
	F	<20	Paved / Unpaved	2.5/3.0	Passing Places	15/20	N/A	N/A	N/A

Where the traffic mix leads to large speed differentials, then it is safer to lower both the design speed and the legal speed limit to reflect the needs of the slowest road users.

Curve radius:

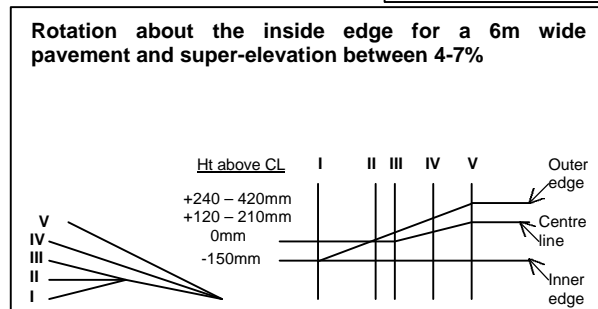
Whenever possible, the curve radius should be designed at or above the desirable minimum standards. When lower standards are used warning signs and devices must be provided. If the curve radius <400m (for 2 lane roads), it may be necessary to widen the outside edge of the curve to provide an adequate travel path for two-axle heavy goods vehicles.

Design Speed / Curvature relationship			
Single Lane Design Standards		Minimum horizontal curvature values (m)	
Design Speed (km/h)	Stopping Sight Distance (m)	Paved <10% super-elevation	Unpaved <0% super-elevation
60	130	85	125
50	100	60	80
40	70	30	40
30	50	15	20

Camber and super-elevation:

When vehicles negotiate a curve, a sideways frictional force, f , is developed between the tyres and road surface. Removal of an adverse crossfall or the possible introduction of super-elevation enables a component of the vehicle's weight to counteract the effects of the frictional force. The direction of the camber, e , should be into the curve and provide sufficient super-elevation so that a vehicle at design speed has to steer into the curve. If non-motorised transport or slow moving traffic are present, the super-elevation should be limited to a maximum of 5% and/or the shoulder constructed with a reverse camber.

$$e = \frac{V^2}{127R} - f$$



Skid Resistance:

To prevent a vehicle slipping off the road, the road surface must have adequate skid resistance to create a large enough inwards friction force to overcome the outwards friction force produced by traversing the bend at high speed. The portable skid resistance pendulum has been shown to provide useful quick measurements of skid resistance and correlates well with the findings of polished stone value testing. Good skid resistance requires both micro and macro texture of the aggregate. Typically the pendulum skid resistance reading should be > 60. Ideally, if the road surface is less than this, then 'slippery road' warning signs and advisory speed limits should be provided to warn approaching drivers.



Sight Distance:

Sight distance is maintained at a safe level for stopping by designing the curve at or above the desirable minimum standard and ensuring a clear zone adjacent to the highway. Typically roadside objects should be at least 1.5m from the carriageway. Where this is not possible, this may be reduced to 1m. Overtaking manoeuvres will not be safe on bends at or below the desirable minimum standards, therefore solid lines and/or physical deterrents should be provided to inform drivers of the danger.

Measure visibility, VISI, separately in both directions at 50m intervals over a minimum distance of 2km

$$VISI = \frac{n}{\sum_{i=1}^n \frac{1}{X_i}}$$

where n = number of observations, and Xi = sight distance at point i.

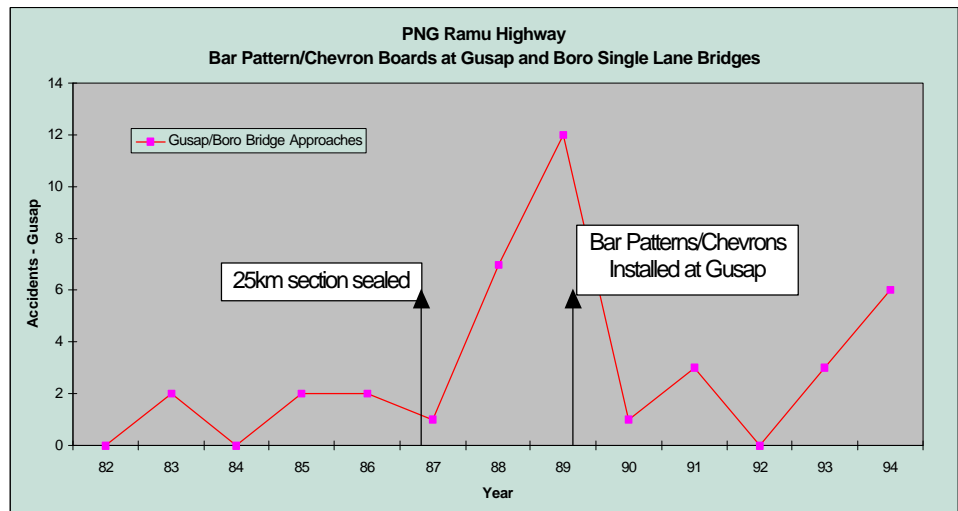
Visual appearance:

The visual appearance of a road can become a safety hazard if the combination of the vertical and horizontal curvature leads to the driver not being able to discern the approaching road geometry in time to change his behaviour to suit the conditions. Visual problems are of most significance on high speed roads and small radius curves. Many problems can be avoided by separating out vertical curvature from horizontal changes or by adjusting their lengths so that vertical and horizontal curves begin at a common chainage and end at a common chainage.

Phasing: Hazardous situations	
The vertical curve overlaps one end of the horizontal curve	Vert. - Horiz. -
The vertical curve overlaps both ends of the horizontal curve	Vert. - Horiz. -

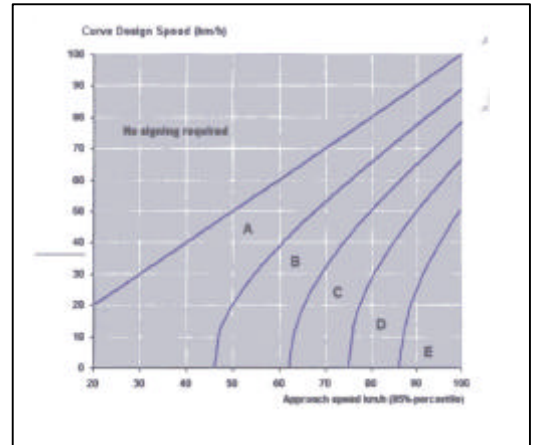
Longitudinal alignment:

Studies show that isolated curves and 'the first in a series of curves after a straight or almost straight section' are the most dangerous. If these are unavoidable then, where possible, the curve should be designed to be navigable at a speed close to the speed maintained over the preceding straight section and it may be possible to introduce a medium curve before a very sharp bend in order to achieve a gradual reduction in approach speed. Several curves in sequence do not generally pose a problem if a constant navigable speed can be maintained throughout. Curves should be separated by a 3-second driving time gap to allow the driver opportunity to assess the forward situation.



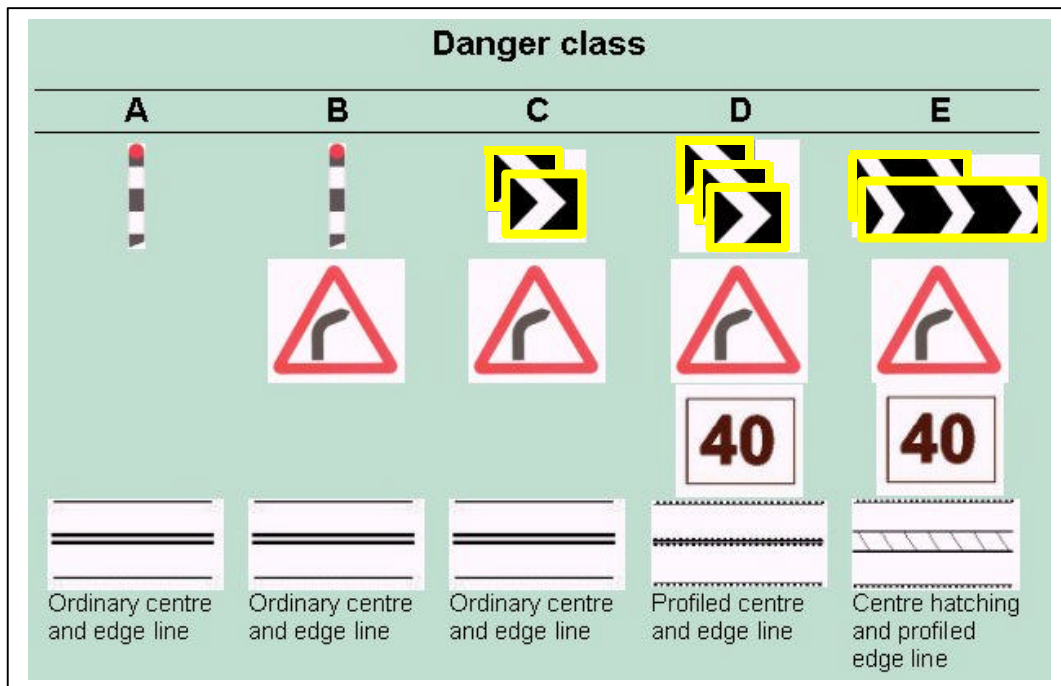
A model for Signing and Marking Horizontal Curves:

Herrstedt and Greibe (2001) developed a model for determining the risk category of a bend, using a five point risk category scale A, B, C, D and E, where A is very slight risk and E is very high risk. The risk of the curve is assessed by determining the degree by which the kinetic energy of a vehicle has to reduce in order to navigate a bend safely. This means that a reduction in speed from 80 km/h to 70 km/h is just as dangerous as a reduction from 50km/h to 32 km/h. The risk category is thus based on the assumption that only small changes in speed are acceptable at high speed levels, whilst larger changes in speed are acceptable at lower speed levels for curves of the same risk category.

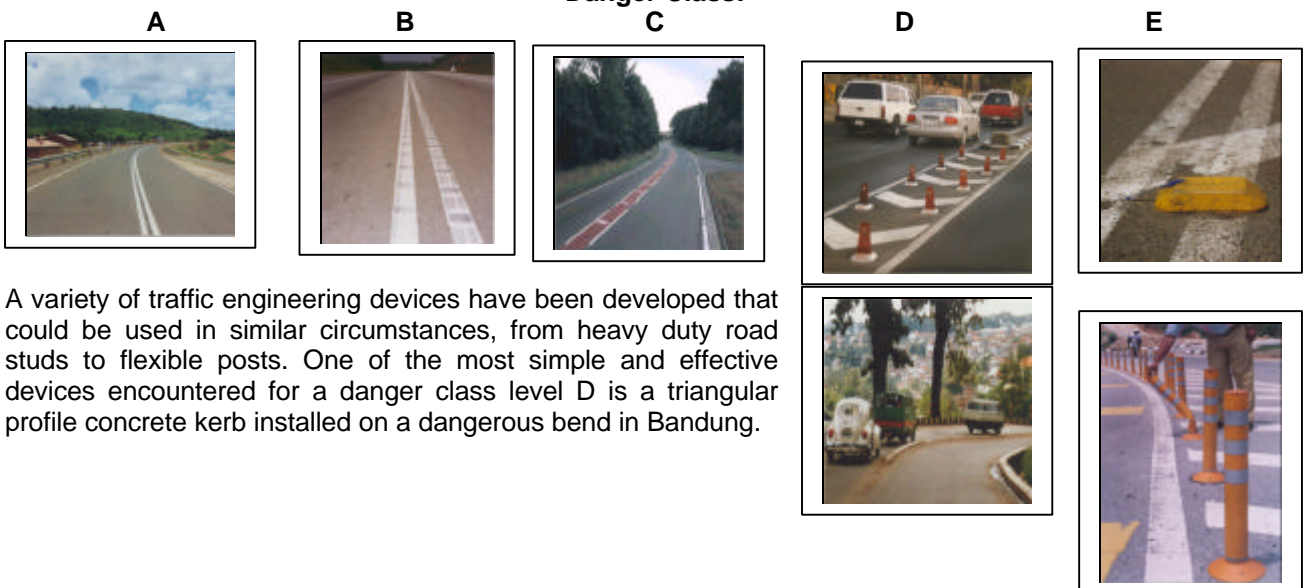


Central Dividers on Bends:

In many countries where line markings are ignored more physical deterrents to crossing the centre line are required. A suggested alternative is shown below:



Danger Class:



A variety of traffic engineering devices have been developed that could be used in similar circumstances, from heavy duty road studs to flexible posts. One of the most simple and effective devices encountered for a danger class level D is a triangular profile concrete kerb installed on a dangerous bend in Bandung.

Driver Alerting Features:

Forward visibility is important to ensure that drivers have sufficient time to react to a change in the road alignment so that they can navigate the road safely. Where it is not possible to provide sufficient stopping sight distance, signs placed in front of a hazard will provide a driver with the additional time needed to change their driving behaviour. Signs can serve two functions: (i) to advise the driver of how the horizontal road alignment changes and (ii) to inform the driver of how to navigate the hazard safely.

Hazardous bend signs placed in front of the bend inform the driver of how the forward road alignment changes. The conspicuity of a sign is very dependent upon its size and background. The adjacent photo, taken in Nepal, shows that the single chevrons on the crown of the bend are lost in the daytime visual background. Edging the signs with fluorescent (yellow) strips or using yellow backing boards can improve conspicuity.

Advisory information can be written on the road or placed on 'speed limit' signs. The information should inform the driver of how severe the hazard is and provide readily understandable advice on how to navigate the hazard safely.

Safety Considerations

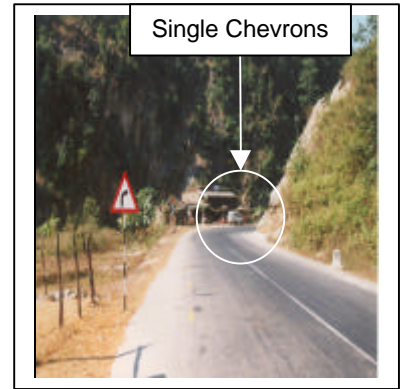
- The Daytime conspicuity can be improved by increasing the number of chevrons and by edging the board with fluorescent material and / or yellow backboards.
- Chevron boards should be reflectorised with material to provide improved night-time visibility.
- The signs should be placed at least 80m in advance of the junction and at least 1.5m from the carriageway edge.
- Advisory signs should provide clear information in a quickly understandable format. Where literacy may be a problem, pictorial information should be used in preference to text.

Road edge and centreline delineation provide important forward road information for drivers and can be used to help position vehicles correctly when poor visibility exists and on curves. White lining provides a cheap engineering measure for preventing accidents. Double solid centre lines on bends discourage overtaking or lane 'drifting' and prevent Head-on and Sideswipe accidents whilst edge lines help the driver discern the forward road alignment and reduce run-off-the-road accidents. However, in many countries such line markings are ignored and more physical deterrents are required.

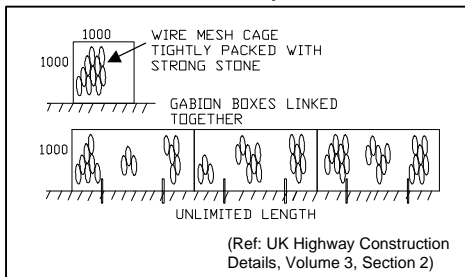
Improved safety can be achieved by combining aural delineation with visual measures. Rumble strips (profiled line marking eg raised rib lines) applied as long edge or centre lines have proved to be effective in reducing run-off-the-road accidents particularly related to driver fatigue. Profiled lines (Vibrallines) have been used in Malaysia to enhance the effectiveness of the double white line and were found to reduce crossovers by 40%. In Europe, there has been a rapid increase in the use of coloured paving to enhance centre line marking.

When the road passes through hilly terrain, a bend in the road alignment can lead to the road appearing to drop off the hillside. Physical delineation (e.g. with guide posts) can provide a visual marker for drivers so that they can discern the change in alignment.

Without any signing, the visual cues available to a driver approaching a bend will frequently be insufficient for him/her to judge whether it is a gentle or sharp curve, usually because the road surface beyond the start of the bend is concealed from the driver's view in some way. The driver will therefore depend upon the expectancy that this bend will be similar to those just encountered. When this is not the case, signing is essential, and in certain circumstances over-signing may be necessary to overcome 'perceptual inertia' (Hills, 1979).

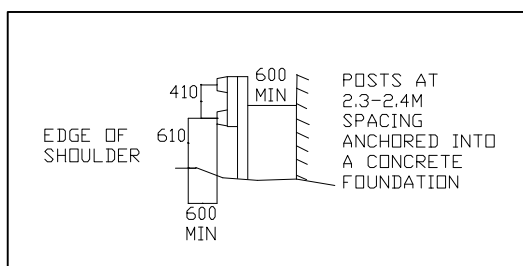


Gabions and Barriers on Dangerous Bends There are many situations where it is necessary to protect errant drivers with a barrier of some form to reduce the severity of an accident.



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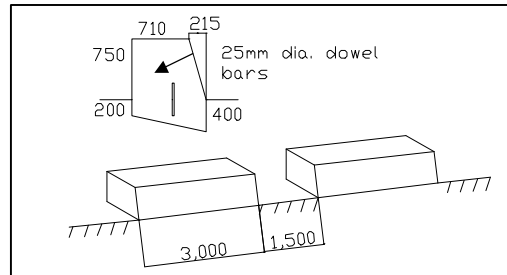
An innovative and successful barrier design has been the development of the concept of linked gabions, whereby 2m x 1m x 1m gabions filled with stones (usually from the adjacent river) are linked to form a continuous barrier. They form a heavy mass but because they are not rigid and the stone can move on impact, they absorb energy thus giving additional safety benefits. They are particularly useful as a low cost solution on high speed roads. On lower volume roads, the gabions can be spaced and painted white to give a level of protection somewhere between delineation and a barrier.



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Whilst steel w-shaped barriers are used extensively on dangerous bends in developing countries, they often have to be imported resulting in a high economic cost. This is because the design of such barriers is a relatively complex subject and installations usually require specialist advice. Furthermore, because of this, the replacement of any section damaged in an accident can take many months. Care should be taken in hill areas and along high speed roads to ensure the barrier restrains errant vehicle. Two cross-beams should be provided to withstand the impact of a heavy-laden truck or large bus and on curves >120m radius, more effective restraint can be provided by tensioning the barrier between its anchorages. This type of barrier is not appropriate for curves <50m radius.

Reinforced cement concrete barriers can be used as an alternative to gabions when the road width is very



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limited. This type of barrier is generally not strong enough to prevent high impact vehicles leaving the road carriageway (and unreinforced concrete has considerably worse performance), but the barrier will improve the delineation of the roadway and present a visual deterrent to motorists. Care should be taken with solid barriers that the drainage of the carriageway is not impaired. This can be accomplished by leaving regular intervals between the barrier blocks or alternatively providing gaps at the bottom of the barrier to allow surface water and dirt to be washed away.

Safety Considerations
<ul style="list-style-type: none"> • The barrier should be located in front of as many roadside obstacles or steep slopes as possible that pose a hazard to motorists in such a way as to allow the continued movement by pedestrians. If long sections of barrier are provided a gap should be provided every 30m to allow pedestrians to take refuge. • The end of the barrier first met by approaching traffic should be angled away from the road carriageway and taper off to the ground to prevent causing a further obstacle to traffic. • Barriers should be placed as far back from the carriageway as reasonably possible and where necessary painted a conspicuous colour to prevent the barrier becoming an obstacle itself. • The barrier height should be a minimum of 710 mm to prevent overtopping by cars and 760mm for heavy goods vehicles.

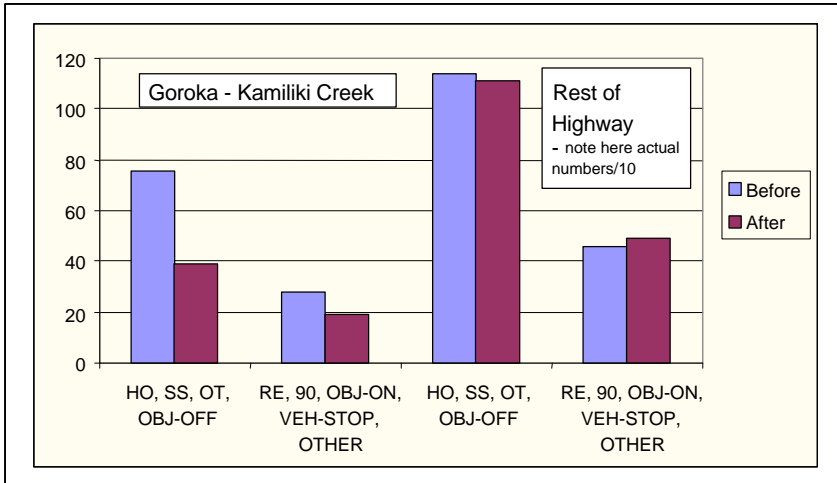
Cost and Safety Effective Design:

In Papua New Guinea in 1988 a section on the Highlands Highway had been identified as having a high number of accidents with almost 50% of the accidents being Overturn, 'Hit an Object Off the Road' or Head On collisions. 43% of these accidents occurred at night and alcohol was a common factor.



A reflectorised chevron board was placed at the bend to warn drivers of the change in alignment. Following implementation of the measure, head on (HO), sideswipe (SS), overturn (OT), and hit object off road accidents (OBJ-OFF) in the section were 40% lower in the

after period whereas other accidents (ie. rear-end (RE), hit object on road (OBJ-ON) and hit stopped vehicle (VEH-STOP)) were only 10% lower. For the rest of the Highlands Highway over the same period, the two groups of accidents were 3% lower and 7% higher respectively (see bar chart). The data suggests that over the six-year period, the chevrons have saved about 4 accidents per year.



	Reduction	Cost/acc (US\$)	Savings (US\$)
Hospitalised Accidents	9	9,680	87,120
Injury Accidents	8	3,020	24,160
Damage Accidents	4	1,800	7,200
Saving over 6 years			118,480
Savings/year			19,746
Approximate Cost			2,000
Approximate First Year Rate of Return			1000%

A Cost-Benefit analysis found that the First Year Rate of Return indicated a ten-fold return overall on the cost of installing the chevron boards.

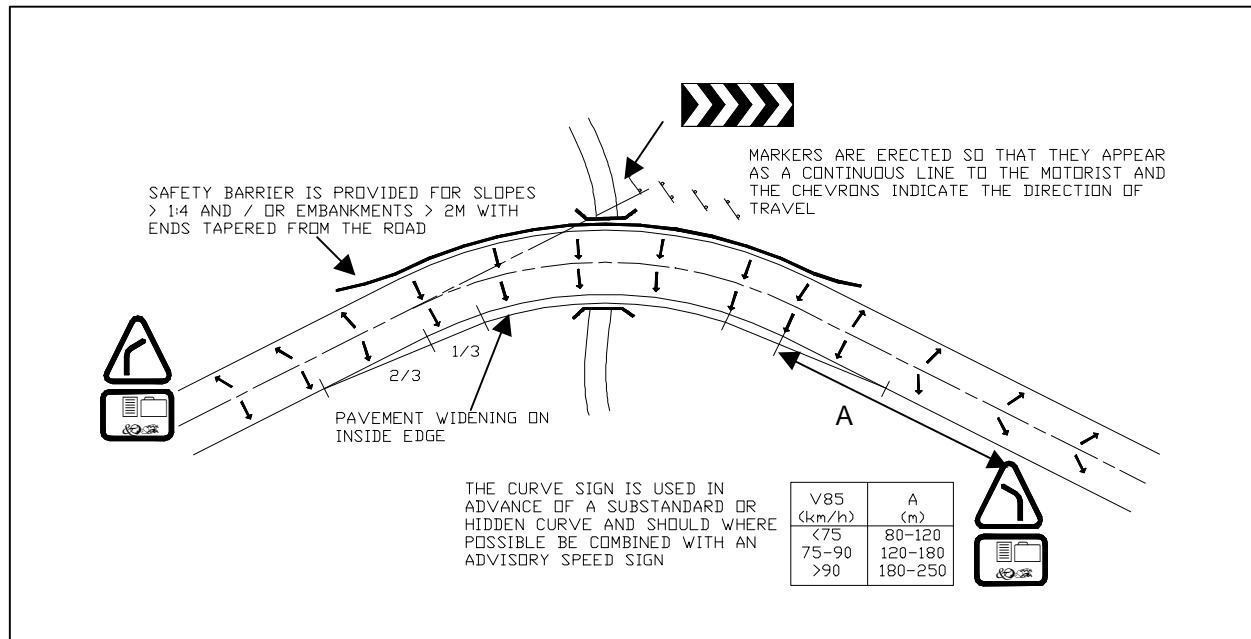
Further Research evidence:

Early research in the US and Australia (Pak-Poy et al, 1988) showed that accident rates rose sharply for bend radii less than 600m. A study of 34 routes in India found that average values of curvature (degrees/km) were significantly correlated to accidents/km/year (CRR1,1982). Kosasih et al (1987) found that a straight road with a single sharp curve has over 5 times the accident rate of more winding roads.

Stewart and Chudworth (1990) have concluded that design codes should no longer recommend the use of transition curves since they can deceive the drivers into maintaining an excessive speed, and they demonstrated that circular arc bends have a lower accident rate. Recent research by TRL for DFID has used Generalised Linear Interactive Modelling techniques (GLIM) to examine survey and accident data for the 480km long Highlands Highway in Papua New Guinea. The road had 180km of flat high speed road and then 300 km in mountainous or rolling terrain. The analysis included a parameter, DEG90, which reflected the presence of a 90 degree (or sharper) bend in a road section: 1 = no 90 degree bends in the section; 2 = single bend; and 3 = 2 or more bends in section.

The analyses found that the single occurrence of a 90 degree bend was the strongest of any highway geometric feature in predicting Overturn and Head On accidents, the two accident types causing high numbers of casualties. Simple measures of curvature were not significant. Multiple 90 degree bends in a section was the most significant for Sideswipe and 'Hit Object Off road' accidents.

Detailed Engineering Drawing:



References:

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Transport Research Laboratory (1988). Overseas Road Note 6 'A Guide to Geometric Design', Crowthorne.

CaSE Design:

The purpose of this project is to identify highway engineering designs that are inherently safe and that fulfil their engineering function at little or no extra cost to alternative designs. It is also concerned with the challenge of making low-cost engineering designs as safe as possible at minimum additional cost. If you have any suggestions for such designs or have comments on this CaSE Note, please contact Stephanie Kirk, Brian Hills or Chris Baguley at International Division, Transport Research Laboratory, Old Wokingham Road, Berkshire, UK RG45 6AU.

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Cost and Safety Efficient Design
for rural highways in Developing Countries

