

# A remedy for accidents at bends

by Douglas Stewart and Christopher J. Cudworth  
Department of Engineering, Aberdeen University

About 30 per cent of all accidents on rural roads occur at bends. This may not appear surprising, because of the influence of centrifugal force and restricted visibility, but more subtle factors can determine their safety.

Investigation of 'safe' and 'hazardous' bends had indicated that the main difference between them was not whether their curvature was large or small, but whether it was constant or variable. This led to the hypothesis that drivers have more difficulty in perceiving the curvature of a transitional bend, because it can deceive them into maintaining an excessive speed.

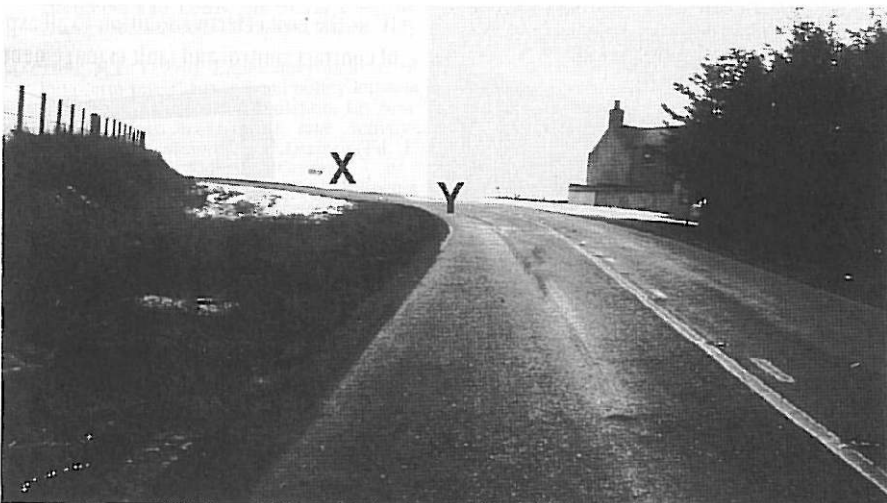
Three acute, accident-prone bends were therefore converted from transitional to circular alignment. Comparing equal before-and-after periods, accidents have been reduced significantly, by about 80 per cent, and cost-effectiveness has also been high. These results suggest that widespread prevention of accidents at sub-standard bends would be simple and inexpensive, and that design codes should no longer recommend the use of transition curves.

It is also proposed that 'accident migration' could be countered by selective retention of sub-standard bends.

## INTRODUCTION

It is a dull, wet day. You are driving along a quiet, country road, rather faster than usual, because you are late. In the distance you see a gentle bend. Not until you enter it do you realise that only the initial curvature is small (Fig 1). You turn the wheel to try to follow the bend as it tightens (Fig 2, 'accident' path), but you are travelling too fast. You brake, and the accident causation is complete — speed, wet road, centrifugal and deceleration forces, driver error. But also, as will be demonstrated, design error. Your car skids and spins across the road. Another accident has started to happen.

Fig 1. Entering a transitional bend: curvature is much greater at apex X than that perceived at Y.



## DESIGN OF BENDS

Most drivers can probably identify with that accident situation, because deceptive curvature is common. A simple remedial measure was proposed in an earlier paper<sup>1</sup> which discussed this deception more fully, but before investigating its effect on accidents we should briefly review the evolution of bend design.

Until about 60 years ago bends normally had constant curvature, i.e. they were circular arcs. Today, however, a bend usually comprises two types of curve, as in Fig 2: a transition curve at entry, followed by a circular curve, then another transition at exit. Wholly transitional curves, with no circular element, are also common.

The original purpose of transition curves is rather obscure. They were recommended for road design as long ago as 1908, by the First International Road Congress, 'to reduce the abruptness of change from a straight line to a

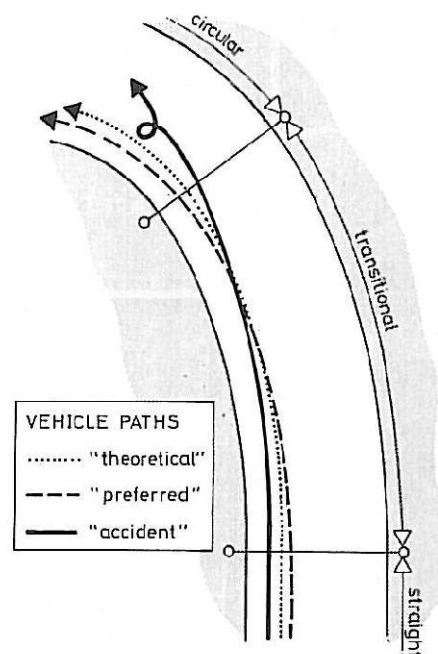


Fig 2. Vehicle paths on transition curve.

curve'. Whether their intention was to improve comfort, safety or appearance is not clear, but these benefits have all been claimed for transition curves.

The main impetus for the use of transition curves on roads came, however, from railway engineering. A circular curve linked directly to a straight causes a train to lurch as centrifugal force is suddenly applied. As rail speeds increased this became unacceptable, so the concept of transition curves of the approximate form  $y=kx^3$  was introduced, to produce a gradual change in curvature and therefore in centrifugal acceleration. Application of the same principle to road design stimulated a profusion of theoretical discourses which debated, sometimes with considerable acrimony, the merits of alternative criteria for transition design, and promoted various transition geometries, such as spirals, cubic parabolas, lemniscates and clothoids. The heat of this academic debate did not, unfortunately, generate much light, because there was virtually no practical evaluation of transition curves. Incredibly, the effect of transition curves on safety seems neither to have been questioned nor examined.

There had been some awareness, however, that this technology transfer from rail to road was inappropriate because the vehicle guidance systems are completely different. Laurence and Oglesby, for instance, pointed out that 'Railroad trains must follow the precise alignment of the tracks, and the discomfort (of entering a bend) . . . can be avoided by using easement (transition) curves. On the other hand, the motor vehicle operator is free

to alter his lateral position on the road and can provide his own easement curves by steering into circular curves gradually<sup>12</sup>.

It was generally considered, however, that this lateral movement was undesirable, that a road vehicle should precisely follow the line of a bend just as a train does. Yet it is readily apparent, simply by observing vehicles on bends, that they do not do so. Drivers 'cut the corner' (Fig 2, 'preferred path'), a manoeuvre commended as good driving practice because it increases cornering radius and visibility distance, and hence safety. The more acute the bend, the greater this deviation tends to be, as confirmed by Godthelp<sup>3</sup>. Deviation tends to be greatest if the acute bend is transitional, probably because this strategy reduces the need to rapidly change direction and also improves perception of the curve. Hence we have the curious paradox that transitional alignment on acute bends encourages the lateral movement which it is intended to prevent.

To try to overcome this 'problem' of drivers deviating from the line of the road it has been suggested<sup>4</sup> that curve design should be based on drivers' actual paths. But this would be self-defeating. As soon as a road is realigned to match vehicle paths these paths will change, to diverge again from the road line. As long as a driver is free to deviate from the line of the road he is likely to do so, because he prefers to. His vehicle will, of course, trace a transitional path as he turns the wheel, but there is no need for the line of the road to parallel this path because an infinite variety of vehicle paths can be fitted within any one bend.

The thesis presented by the author, however, was not just that transition curves are unnecessary and ineffectual. It was also that they are potentially dangerous because of visual deception, and that this could readily be remedied. Shinar *et al.*<sup>5</sup> have proposed that deceptive curves could be corrected by introducing counter-illusions to reduce vehicle speeds, but although they achieved reductions in speed these tended to dissipate within a few weeks. This suggests that rather than introduce corrective illusions, it is preferable to eliminate deception by minor realignment to create uniform, or circular, curvature, as proposed in the author's previous paper. For brevity this technique will be termed 'circlation'<sup>6</sup>.

While the effectiveness of circlation might also be examined by measuring change in vehicle speeds, there is no guarantee that this is a reliable measure of safety at bends. The following evaluation will, therefore, be based primarily on change in accidents, rather than speed. Statistical significance will be denoted by confidence level; (\*) for 95 per cent, (\*\*) for 99 per cent, always using two-sided probabilities.

#### ACCIDENT PATTERNS AT TRANSITIONAL BENDS

The accident situation described in the introduction is most evident on bends whose radii are sub-standard and which are largely or wholly transitional. Such bends are common except on major roads, and three in Grampian Region, Scotland, were realigned, as tabulated in Table I.

Table I. Modified bends (sizes in metres)

Bend location and grid reference	Approx. inner radius (m)		Intersection angle (deg)	Injury accidents	
	Before	After		Before	After
A 952, NK105487	70	110	50	4	0
A 96, NJ481447	220	295	37	7	3
A 947, NJ842248	150	200	28	8	1

Accidents at the bends had been very frequent, despite appropriate warning signs and road-markings. Fortunately only a very small proportion involved injury, because lack of crash barriers or other roadside obstacles resulted in most vehicles coming to rest with only minor damage. Despite incomplete documentation of some of the earliest accidents, which reduces sample size for some of the factors considered, analysis of factors recorded on the Stats 19 forms for the 'before' accidents helps to confirm and clarify the influence of transitional alignment:

#### Number of vehicles

Nine of 13 accidents involved two vehicles, and the remaining four just one. This reflects the relatively low risk of injury when a single vehicle left the carriageway at these bends. Only if the driver had the misfortune to encounter an oncoming vehicle was death or injury likely.

#### Severity of injury

Sixty-eight per cent of accidents were fatal or serious, an unusually high proportion which again results from the predominant type of injury accident — a frontal collision at speed. The high 'cost' of these accidents in relation to the low cost of circlation is why the cost-effectiveness of this remedial treatment is so high.

#### Direction of travel

The earlier paper<sup>1</sup> suggested that left-hand transitions were more dangerous than right-hand due to greater difficulty in correctly perceiving curvature if driving on the inside of the bend. This bias was confirmed (\*\*), as all 13 accidents whose direction was recorded were on the left-hand bend.

It should be noted, however, that right-hand accidents may be recorded at transition curves for at least two reasons. At S-bends an accident initiated on the left-hand bend is liable to terminate on the right-hand bend, and thus be recorded as 'right-hand'. And 'right-hand' accidents can also result from a different type of visual deception. If the vertical alignment of a bend is a valley curve which is misperceived as being in the horizontal plane rather than in the vertical, a bend will appear less acute than it actually is, which can induce accidents at both left and right-hand bends. None of the three bends was of this type, but right-hand accidents are discussed later in relation to control of accident migration.

In countries with right-hand rule of the road, it would be expected that these directional biases would reverse.

#### Light condition

On rural roads in Britain one accident in three is at night, but all of 13 accidents had been in daylight, a significant (\*) difference. Three explanations can be offered. One is that on an unlit road at night a driver has a good view of reflective advance warning signs but not of a bend, hence he is more likely to heed the sign and less likely to be deceived by the bend itself. The second is that a driver has earlier warning of an oncoming vehicle at night, because its headlights illuminate the bend before the vehicle itself can be seen. And thirdly, that illumination falls on the outside of the bend, which tends to be less deceptive than the inside<sup>1</sup>.

#### Tyre adhesion

Centrifugal force due to excessive cornering speeds is resisted primarily by adhesion between tyre and road, so it is to be expected that bend accidents will be more prevalent on wet roads. Of the 12 accidents for which road condition had been recorded, nine were 'wet', two were 'ice' and only one was 'dry'.

It is unfortunate that the point on a transition curve where adhesion is most desirable is also where skid-resistance tends to be lowest. The polishing effect of centrifugal forces increases with decrease in curve radius, and polishing by braking forces is also likely to increase. A driver is unlikely to detect this reduction in skid-resistance, hence he cannot predict the speed or degree of braking which would initiate a skid. If circlation is impractical, therefore, improvement in skid resistance is highly desirable.

#### RECTIFYING TRANSITIONAL BENDS

At the three bends conventional realignment to increase their radii to normal design standard would have been possible, but very costly because of the length of new road required. It was concluded from these accident patterns, however, that the deceptive appearance of the bends, rather than their radii, was the prime hazard. The inner edge of carriageway of each bend was therefore realigned to change curvature from transitional to circular. This shifted the apex of each bend by no more than 3 m (Fig 3), and cost about 95 per cent less than conventional realignment.

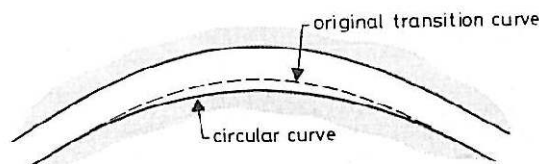
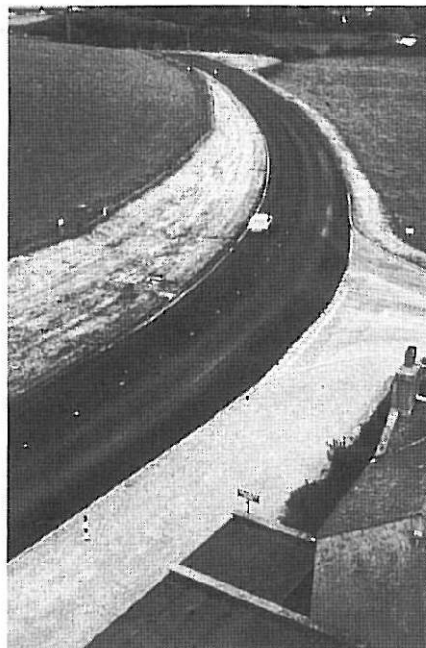


Fig 3. 'Circlation' of transitional bend.



A transitional bend before (Fig 4, left) and after (Fig 5, right) 'circlation'.

After circlation drivers reported that it was much easier to negotiate the bends. Observation and filming confirmed that vehicles could more easily follow the circular alignment, as is demonstrated by comparison of Figs 4 and 5 (the bend on A952, also seen in Fig 1 before circlation). In Fig 4 the margin of grit on the carriageway, opposite the car, is evidence of the lateral drift of drivers unable to follow the transitional curve. After conversion to circular alignment (Fig 5) that margin almost disappeared.

Evidence that accidents had also disappeared was more elusive. Non-accidents, accidents which would have occurred but for remedial treatment, cannot be counted or demonstrated. Instead it is necessary to wait, often for several years, for the reduction in accidents to become statistically significant, a prime reason that improvement in road safety engineering is so slow and erratic.

Despite the preponderance of damage-only accidents at the bends, only injury accidents will be analysed, because most damage-only accidents are not reported to the police. Change in accident rate was based on  $\chi^2$  testing of equal 'before' and 'after' periods of seven years, during which the only significant change at any of the bends was their realignment. There had been no other improvement, and although traffic growth in this period would have been expected to give a slight increase in accidents, there were actually far fewer after circlation.

'Before' and 'after' injury accidents totalled 19 and 4 respectively, a 79 per cent reduction. It is apparent from Fig 6, however, that the real improvement may be slightly less, because the accident peak in year -2 is probably a random one which helped to initiate the schemes. If this peak is given a regression correction of, say, two accidents the overall accident reduction is still 76, and remains very significant (\*\*) in comparison with the 10 per cent reduction in accidents throughout Grampian Region over the same period.

Removal of perceptual error would be expected to change not only the number of accidents but also their type. Common factors of the 'before' accidents were 'left-hand', 'wet' and 'daylight'. All three were present in nine of 12 'before' accidents, but in none of the four 'after' accidents, a difference which is close to significance (\*). It is also significant (\*) that ice was reported for three of the 'after' accidents, but for only two of 12 'before' accidents. This suggests that after circlation the critical driver error was no longer misperception of alignment, but rather of road surface condition.

It is necessary, of course, to consider other possible explanations for accident reduction at the three bends. One is the greater road width created by the removal of transitions. Inadequate width, however, had never been cited as a problem at any of the bends, nor is there any consensus from previous research that accident rate improves with increase in width of carriageway.

Improvement might also have been anticipated due to the increase in radius as alignment is changed from transitional to circular. While safe cornering speed must thereby have increased, this cannot plausibly account for the reduction in accidents. It has been shown by McBean<sup>6</sup> that as bend radius decreases there is a marked rise in accident risk at about 500 m, but that further increase in risk at smaller radii is relatively small. As the radii of all three bends were well below 500 m, even after circlation, it is therefore not

surprising that their degree of improvement does not seem to be related to radius.

Another cause of improvement might have been the resurfacing necessitated by realignment. Although this would have improved skid-resistance, it has been found<sup>7</sup> that these roadstones reach an equilibrium skid-resistance, apart from seasonal variation, within one year. Hence only in the first year after realignment might the resurfacing have influenced accident rate.

The effect of warning signs must also be considered. As discussed by Wright and Boyle<sup>8</sup>, signing should help to compensate for any underestimate of risk by a driver by increasing his awareness of risk, and thus compensate for underestimation of actual risk. But signs can give only a simple warning of the presence of a bend; they cannot help a driver to perceive whether a bend is circular or transitional. Extensive signing had not remedied the poor accident record of the three bends, and there seemed no justification for retaining most of the signs after circlation. Most signs at the bends, such as hazard chevrons, skid warning signs and SLOW road-markings were therefore removed, though advance warning signs were retained because alignment remained below the Department of Transport's Design Speed Standard.

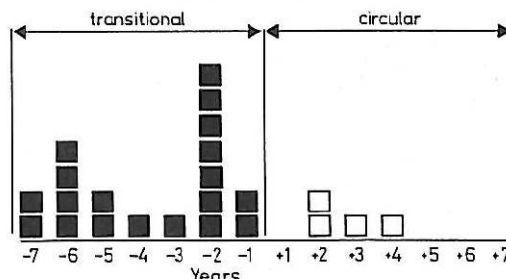
#### DISCUSSION

All evidence affirms that transitional alignment had been an essential factor in most accidents at the three bends. If so then it might be expected, from risk-compensation theory, that accident rate on the bends would now be little greater than if the bends did not exist. That is, if the risk of their sub-standard alignment is now perceived correctly, drivers will adequately compensate for it and hence be no more liable to accident than they would elsewhere on the road.

Analysis of the injury accident record supports that expectation. Before improvement the accident rate per unit length of bend had been about 10 times greater than that along the 5 km of road centred on each bend, a significant (\*\*) difference. After circlation the disparity reduced to just two, and was not significant.

This radical improvement in safety is particularly topical in view of the Department of Transport's shift in emphasis from time savings to accident savings in evaluating road schemes<sup>9</sup>. Considering accident reduction at the three bends in cost-benefit terms, the 'before' accidents (four fatal, eight serious and seven slight) are valued at £2.8M, compared with about £60 000 for the 'after' accidents (two serious and two slight)<sup>10</sup>. If this average saving of £390 000 per year is relat-

Fig 6. Effect on accidents of rectifying transitional alignment.



ed to the £16 000 total cost of the schemes, at current prices, it represents an 'economic rate of return' of about 2400 per cent per year, which may be compared with DTP guidelines of 50 per cent for accident remedial schemes and 7 per cent for capital expenditure on major road schemes. It is apparent, therefore, that transfer of funding from conventional realignment to circlation would radically increase both the rate at which hazardous bends can be made safe, and the cost-effectiveness of doing so.

Unfortunately, both the retention of 'sub-standard' radii and the elimination of transition curves conflict with conventional road design philosophy. Hence these departures from Design Speed Standard are considered by the DTP to be inherently dangerous, although neither the safety of transition curves nor the effect of removing them have been investigated by the Department. This conservatism might be understandable if previous research had revealed benefits due to transition curves, but it has not done so.

Lack of information about the effects of transition curves also makes it difficult to decide which transitional geometries are most dangerous. It seems probable that the shorter the transition, the less hazardous it will be. Transition length decreases with increase of bend radius, so the cost-effectiveness of circlation is likely to fall as standard of bend increases. Not all existing bends, therefore, are likely to warrant circlation.

In new design, the length of transition curves is now limited to  $\sqrt{24R}$ , but it would be preferable to eliminate transition curves entirely, because they serve no essential function. Even the application of superelevation, which is commonly cited as their main function, does not actually require transition curves. If superelevation is instead introduced along the straight preceding a circular curve, it can be shown that the induced 'hands-off' drift helps drivers to make the lateral movement which they prefer to apply on entering a bend, and is therefore beneficial.

Fully transitional alignment, the 'cubic spline', is particularly inappropriate. Although this alignment has become practicable due to computer-based design, it inevitably results in much smaller radii than a corresponding alignment comprising only circular curves. It is also less comfortable to drive along, because it necessitates continual adjustment of direction by the driver. At best, therefore, transition curves are unnecessary for safe and efficient design of roads. At worst, they are a dangerous and costly mistake, which we should no longer perpetuate.

#### Accident migration

Optimism about any accident remedial treatment for bends has, however, to be tempered because of a by-product of risk compensation, accident migration. This apparent transfer of accidents from a treated locus to the surrounding road network is a well-established phenomenon. Although the three-bend study was too small for it to be quantified, there was evidence of its influence. At the A952 bend, for instance, accidents became more frequent on a nearby bend. Single-vehicle accidents there were liable to

produce injury because of impact with a bridge parapet, whereas at the first bend they had almost always been damage-only. This situation highlights the need for a more sophisticated philosophy of accident prevention than simply identifying and treating individual 'blackspots'.

Boyle and Wright have argued convincingly<sup>11</sup> that accidents migrate because reduction of risk at one location will reduce driver awareness and therefore induce more accidents elsewhere. That is, rectifying a road hazard also removes the cautionary effect of the accidents and near-accidents which it causes, hence drivers will tend to be more prone to accidents elsewhere, as at that bridge. It seems appropriate, therefore, to revive a concept proposed before accident migration became topical<sup>12</sup>, the creation of 'safe' accidents.

'Safe' accidents will be defined as those which do not cause injury or major damage, and a locus which generates 'safe' accidents will be termed an 'accident whitespot'. It might, for instance, be a right-hand bend where errant vehicles leave the road without crossing the opposing lane, due to some combination of low radius, downhill gradient, deceptive alignment, or other factors. Provision of a gravel arrester bed, or other deceleration system, would result in 'safe' accidents which would still have the desired corrective effect on bad driving. That is, those driving at an excessive risk level would be corrected by their accidents or near-accidents at the 'whitespot', and thereafter would drive more carefully.

If road safety is to be radically improved, it seems necessary to develop such ideas; to consider accident prevention more as management of risk throughout a road system than as treatment of individual hazards. Skilled treatment of hazardous bends could be an effective tool to that end.

#### ACKNOWLEDGMENT

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Mr Stewart's address: Benview, Peterculter, Aberdeen AB1 0NT.