XVII International Symposium
"ROAD ACCIDENTS PREVENTION 2026"
Novi Sad, Serbia, 14th and 15th October 2026.

https://doi.org/10.68515/RAP.2026.17.20

ROAD SAFETY ON HORIZONTAL CURVES: A LITERATURE REVIEW

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Abstract: Horizontal curves concentrate a disproportionate share of severe road crashes, with average crash rates about three times higher than on comparable tangent sections. This paper reviews the international literature on road safety at horizontal curves and synthesises three research streams that have developed largely in parallel: geometric design factors, speed and driver behaviour, and crash prediction methodology. Fifty four sources, retrieved through a structured search of Scopus, Web of Science, ScienceDirect, TRID and Google Scholar, are organised by thematic strand and assessed for convergence of findings. Curve radius remains the dominant geometric predictor, while side friction demand, pavement condition, the relationship with adjacent curves and the combination with vertical alignment are established but underused secondary factors. Methodological work has moved towards specifications that address excess zeros, unobserved heterogeneity and spatial structure, whereas evaluation of countermeasures remains the thinnest strand of evidence and rests on a small number of before and after studies. Five research gaps are identified: flat terrain settings, two part crash generating processes, maintenance variables, validation of behavioural surrogates, and the geographical narrowness of the evidence base.

Keywords: horizontal curves; road safety; crash prediction; literature review

1. INTRODUCTION

Road traffic crashes remain a leading cause of premature death worldwide, with approximately 1,16 million fatalities each year and 92% of them occurring in low- and middle-income countries [51]. Within this burden, horizontal curves occupy a distinct position. They represent a small share of network length yet concentrate a disproportionate share of severe outcomes: recent evidence from the United States indicates that more than a quarter of all roadway fatalities are associated with a horizontal curve, and that the average crash rate on curved segments is roughly three times that of other segments [52].

The reasons are structural. A curve imposes a lateral acceleration demand that a tangent does not, restricts sight distance, requires continuous steering correction and frequently arrives after a long tangent on which the driver has already established a speed the curve cannot accommodate. Whether it is negotiated safely therefore depends on the interaction of geometry, speed choice, friction supply and roadside environment. Research on that interaction has accumulated for more than three decades, from the before and after evaluations of geometric improvements [53] to the predictive method of the Highway Safety Manual [3].

What has changed recently is the nature of the evidence rather than the nature of the problem. Automatically extracted roadway geometry from mobile mapping, LiDAR and GIS layers has removed the sample size constraint that limited earlier curve studies, allowing models to be estimated on tens of thousands of curves [32, 52]. Naturalistic driving studies and floating car

data have made it possible to observe what drivers actually do on curves rather than to infer behaviour from crash records [2, 11, 22, 49]. The statistical toolbox has expanded far beyond the Poisson and negative binomial baseline towards random parameter, two part, spatial and machine learning specifications [26, 31, 52, 54].

These three streams have developed largely in parallel and are rarely synthesised, so practitioners face evidence that is rich but fragmented, in which a finding about curve radius, one about operating speed profiles and one about model specification are difficult to place in relation to one another. This paper provides such a synthesis: it reviews the international literature on safety at horizontal curves, examines the convergence between findings obtained in different geographical and methodological contexts, and identifies the gaps that future research should address. Section 2 describes the review approach, Section 3 quantifies the problem, Sections 4 and 5 review geometric and behavioural factors, Section 6 examines crash prediction models, Section 7 reviews countermeasures, Section 8 identifies gaps and Section 9 concludes.

2. REVIEW APPROACH

The review was conducted as a structured narrative synthesis rather than a formal meta-analysis, because the heterogeneity of outcome measures, from crash counts and crash modification factors to operating speeds and surrogate conflict indicators, does not permit a common effect size to be pooled. Literature was identified through Scopus, Web of Science, ScienceDirect, TRID and Google Scholar, combining the terms horizontal curve, curved segment and curve radius with road safety, crash frequency, crash prediction, crash modification factor, operating speed, design consistency and run off road. Reference lists of retrieved reviews were screened and forward citation searching applied to the most cited studies.

Sources were retained under three conditions: they had to address horizontal curves explicitly, as the unit of analysis or as a principal explanatory variable, rather than treating curvature as one covariate in a network level model; they had to report an empirical result, a model specification or a systematic synthesis; and they had to be peer reviewed or issued as official guidance. Priority was given to work published after 2010, with earlier studies retained where they remain the reference point for later work, as with the geometric improvement evaluations of the early 1990s [53] and the empirical Bayes framework [23].

The retained sources distribute unevenly across thematic strands, and the distribution is itself informative. Methodological work on crash frequency modelling dominates numerically, since the curve is a convenient and well defined unit for testing new count data specifications, while evaluation of countermeasures is the thinnest strand and rests largely on a few before and after studies still cited two decades after publication. This imbalance between the effort invested in predicting crashes at curves and the effort invested in measuring what happens when a curve is treated is one of the central findings of the review.

3. THE SCALE AND NATURE OF THE PROBLEM

The elevated risk of curved alignment is among the most robust findings in road safety research, reproduced across countries, road classes and analytical methods; a systematic ranking of infrastructure related risk factors placed horizontal curvature among the highest ranked design variables [39]. The magnitude of the excess depends on how the comparison is constructed. Compared with tangents on the same road, crash rates on curves are typically one and a half to four times higher, with recent large scale analysis placing the average ratio near three [52]. Compared across roads with different curvature densities the picture reverses instructively: Elvik

[14] found that the shorter the mean distance between curves, the smaller the increase in risk associated with a given radius, so that overall risk need not be higher on a road consisting mostly of sharp curves. The pattern is usually interpreted through driver adaptation and expectancy, since a sequence of demanding curves keeps expectancy calibrated while an isolated curve on an otherwise straight alignment violates it.

The crash types are equally consistent. Single vehicle run off road events dominate, followed by head on collisions caused by departure towards the opposing lane. Both carry high severity, because departure angle and the presence of rigid roadside objects govern the energy dissipated in impact [20, 27]. Analysis of driver injury severity in single vehicle crashes at curves confirms a higher probability of serious or fatal outcome than on tangents [45], and geometric design of curves has also been shown to influence risk for cyclists and pedestrians [15].

Exposure is not uniform. Two lane rural roads account for most curve related fatalities in the majority of jurisdictions, combining high operating speeds with narrow cross sections, limited recovery space and alignments often designed to superseded standards, while in mountainous terrain the combination of grade and curvature amplifies both frequency and severity [4, 10].

4. GEOMETRIC DESIGN FACTORS

4.1. Radius, length and transition design

Curve radius is the most consistently significant geometric predictor of crash frequency, and the relationship is strongly non linear: risk rises slowly as radius decreases from large values, then sharply below a threshold that most studies place between 200 and 400 metres depending on design speed and terrain. This relationship is embedded in the predictive method of the Highway Safety Manual, where the crash modification factor of a curved segment is a function of radius, curve length and the presence of spiral transitions [3], a formulation derived from the early evaluations of geometric improvements [53].

Later work refined rather than overturned this formulation. Gooch et al. [21] quantified the safety effect of curves on two way two lane rural roads and concluded that both the presence of a curve and its degree of curvature must be accounted for, while also examining how neighbouring curves modify the estimated effect. Chakraborty and Gates [8] found that curve geometry retains explanatory power for single vehicle crashes even on rural secondary roads with modest volumes. The most comprehensive test to date is the Norwegian study of 63.969 curves by Elvik and Haugvik [15], which included more curve characteristics than any previous study. Most coefficients agreed with earlier findings, but two were unexpected: compound curves, in which radius varies along the curve, proved safer than circular curves, and a steeper grade before a curve was associated with fewer crashes. Both point to the same mechanism, namely that features signalling the presence and severity of a curve to an approaching driver improve outcomes even when they depart from conventional design ideals.

4.2. Superelevation, side friction and pavement condition

Stability in a curve depends on the balance between superelevation and side friction demand. Himes et al. [24] developed a roadway departure crash modification function for rural two lane highways in which side friction demand enters through an interaction between radius and speed, alongside a direct superelevation effect, with crash frequency increasing for smaller radii, higher speed limits and lower superelevation. The formulation is notable because it expresses risk through the demand placed on friction rather than through radius alone. Parsa et al. [40] revisited

maximum superelevation from the perspective of side friction factor and lateral acceleration and concluded that a single maximum value applied uniformly across a network is unlikely to be optimal across radius and speed combinations.

Pavement condition interacts with this balance directly, since friction supply determines how much of the design assumption is realised. Choudhary et al. [10] analysed geometric and pavement parameters jointly on mountainous roads and found condition variables significant alongside geometry. Condition is a maintenance variable modifiable at far lower cost than alignment, yet it is absent from most curve crash prediction models, largely because condition data are rarely available at curve level.

4.3. Curve context: adjacent curves, grades and roadside

A curve is part of a sequence, and its performance depends on what precedes it. Findley et al. [16] demonstrated the statistical significance of spatial considerations, with the distance to adjacent curves proving a reliable predictor of crash frequency, and Awasthi et al. [4] extended this to severity in mountainous terrain. The combination with vertical alignment is a further source of risk: Bauer and Harwood [5] derived crash modification factors for curve and grade combinations that are generally larger than the factors obtained by applying the two elements separately, and Wang et al. [50] confirmed the interaction for freeway combinations of horizontal and crest vertical curves using hierarchical negative binomial models with temporal correlation. Finally, the roadside governs the consequences of a departure. Gong and Fan [20] analysed run off road severity in rural areas, and Khan et al. [27] showed that roadside hazard type interacts with design consistency in determining severity, confirming that geometric and roadside variables should be modelled jointly.

5. SPEED, DESIGN CONSISTENCY AND DRIVER BEHAVIOUR

5.1. Operating speed and design consistency

Design consistency formalises the intuition that a curve becomes dangerous when it differs from what the driver expects on the basis of the preceding alignment. Consistency is assessed operationally by comparing operating speeds on successive elements, and considerable effort has gone into predicting speed profiles from geometry. Camacho-Torregrosa et al. [7] proposed a consistency model based on continuous operating speed profiles rather than discrete element comparisons, allowing the speed differential to be evaluated at any point of the alignment. Llopis-Castelló et al. [29] calibrated the inertial consistency index, which compares the operating speed of an element with the average speed over the preceding section, and demonstrated its association with crash frequency on two lane rural roads.

Montella and Imbriani [37] incorporated consistency variables directly into safety performance functions and showed them to be significant explanatory variables alongside geometry. Khan et al. [26] applied a random parameters negative binomial Lindley specification and confirmed that consistency measures remain significant once unobserved heterogeneity and excess zeros are accounted for, and Ghorbani et al. [18] combined consistency with self explaining characteristics using zero truncated data, finding both groups of variables to contribute. The proliferation of indices has not, however, been matched by cross validation between them, so the choice of index remains largely a matter of local convention.

5.2. Evidence from simulators and naturalistic driving

Crash data describe outcomes but not the mechanism that produced them, and two approaches observe the mechanism directly. Driving simulators allow controlled manipulation of curve characteristics: Bella [6] examined performance on approach to and departure from curves, while Charlton [9] compared advance warning signs, delineation and road markings and found that treatments highlighting perceptual cues were the most effective means of moderating curve speeds, whereas advance warning signs alone had little effect. These findings are consistent with the self explaining road concept [47], according to which design should elicit appropriate behaviour without requiring conscious interpretation of signs.

Naturalistic data provide the complementary picture in real traffic. Wang et al. [49] compared crash and near crash events with matched baseline traversals of rural two lane curves and found high risk behaviours, notably speeding and visual distraction, to combine with curve design elements and pavement surface condition in producing these events. Hallmark et al. [22] characterised driver behaviour on rural curves using the SHRP 2 naturalistic driving study, and Dhahir and Hassan [11] used the same source to question the common modelling assumption that vehicles traverse a curve at constant speed. Floating car data offer a network scalable alternative, demonstrated by Ambros et al. [2] for proactive identification of problematic curves before crashes accumulate, and surrogate measures combined with machine learning classifiers extend the same logic [38]. A review of driver performance at curves [44] nonetheless concludes that the link between behavioural indicators and crash outcomes remains insufficiently validated, which limits their operational use.

6. CRASH PREDICTION MODELS FOR HORIZONTAL CURVES

6.1. From the base model to contemporary specifications

The predictive method of the Highway Safety Manual [3] established the reference structure for curve level analysis: a safety performance function for base conditions, multiplied by crash modification factors accounting for departures from those conditions, combined with observed counts through the empirical Bayes procedure [23] to correct for regression to the mean. The literature has since concentrated on whether the functional form is adequate and whether calibration transfers between jurisdictions.

On the first question, the negative binomial model has long been the default response to overdispersion, but the reviews of Lord and Mannering [31] and Mannering et al. [33] documented a range of alternatives developed for the specific features of crash data, including unobserved heterogeneity, temporal instability [34] and low sample means [30]. Curve level data are particularly exposed to the last, because disaggregating a network into individual curves produces short units with low expected counts and a high proportion of zeros.

6.2. Excess zeros, heterogeneity and two part processes

The treatment of excess zeros is where curve level modelling departs most clearly from segment level practice. Zero inflated specifications have been criticised conceptually, since they imply intrinsically safe sites, an assumption difficult to defend for a curve carrying traffic. Two part hurdle models avoid it by separating the probability that a curve experiences any crash from the number of crashes conditional on occurrence, allowing different covariate sets to govern the two processes. An alternative response keeps a single equation but enriches the error structure:

Zhang et al. [54] modelled crash frequency on mountain freeways with random parameters negative binomial mixture specifications, the Lindley and generalised exponential variants, which absorb excess zeros and heterogeneity simultaneously and avoid the two stage assumption of zero inflated models. Random parameter specifications more generally let coefficients vary across observations [26, 33], and spatial approaches account for correlation between neighbouring sites [43]. Table 1 summarises representative curve oriented modelling studies.

Table 1. Representative crash prediction studies focused on horizontal curves

Study	Setting	Modelling approach	Principal contribution
Elvik and Haugvik [15]	Norway, 63.969 curves	Accident prediction models	Broadest set of curve characteristics tested
Yang et al. [52]	United States, rural curves	Six statistical and ML models compared	Benchmarking of model families on one dataset
Kronprasert et al. [28]	Thailand, two lane rural roads	Safety performance functions	SPF framework in a middle income context
Chakraborty and Gates [8]	United States, rural secondary roads	Count models, single vehicle crashes	Curve geometry effects on lower class roads
Ghorbani et al. [18]	Iran, two lane rural roads	Zero truncated count models	Consistency and self explaining variables
Wang et al. [50]	China, freeways	Hierarchical negative binomial, temporal correlation	Combined horizontal and crest vertical curves
Zhang et al. [54]	China, mountain freeways	Random parameters NB mixture models	Excess zeros absorbed without zero inflation
Mićić et al. [35]	Serbia, flat rural roads	Negative binomial models	Regional calibration in flat terrain conditions

6.3. Data, transferability and model comparison

The constraint that shaped curve research for two decades was the cost of measuring geometry. Automated extraction from mobile mapping and GIS layers has removed it, and Ma et al. [32] demonstrated crash risk modelling of curves using large scale automatically extracted geometry. The same capability underpins the comparison by Yang et al. [52] of linear regression, Poisson, negative binomial, support vector machine, random forest and neural network models on a single large dataset of rural curves, which separates the contribution of the model from that of the data, a distinction impossible when each study uses its own sample.

Transferability remains unresolved. Elvik [13] examined the international transferability of accident modification functions for horizontal curves and found that functions estimated in one country do not reliably reproduce effects observed in another. Ambros et al. [1] reached a similar conclusion, identifying calibration and data comparability as the principal obstacles. For countries outside the North American and Western European research core the practical consequence is that imported functions require local recalibration, confirmed by regional studies in Serbia [19, 35] and by applications in Asian contexts [28]. In the same regional context, reliability-based formulations have been proposed as an alternative to conventional count models [25].

7. COUNTERMEASURES AND THEIR EFFECTIVENESS

Countermeasures fall into three groups: those that change the alignment, those that change the surface or cross section, and those that change what the driver perceives. International guidance consolidates the evidence into implementation strategies [48] and systematic effect estimates [12], noting that certainty varies widely between treatment types. Table 2 summarises the principal treatments.

Table 2. Reported effectiveness of selected horizontal curve treatments

Treatment	Evaluation context	Reported effect
Curve realignment [46]	Rural two lane roads, three US states, empirical Bayes	68% fewer total crashes, 74% fewer injury and fatal, 78% fewer run off road and fixed object
Chevrons, warning signs and flashing beacons [36]	15 curves on motorway A16, Italy, empirical Bayes	Statistically significant reductions in target crash types
Centreline rumble strips [41]	Rural two lane roads, United States, empirical Bayes	25% fewer frontal and opposing direction sideswipe injury crashes, 14% fewer injury crashes
Centreline and shoulder rumble strips [42]	Rural two lane roads, United States	Further reduction over centreline treatment alone
High friction surface treatment [17]	Horizontal curves, United States	Curve specific crash modification factors developed

Realignment produces by far the largest effects. The empirical Bayes evaluation by Srinivasan et al. [46] on rural two lane roads in California, North Carolina and Ohio reported a 68% reduction in total crashes and a 78% reduction in run off road and fixed object crashes, with the average degree of curve reduced from 18,1 to 6,9. These results define an upper bound on what can be achieved at a curve, and they also explain why realignment is rarely applied, since reconstructing an alignment costs orders of magnitude more than any other treatment.

Low cost treatments are therefore the operational reality. Montella [36] evaluated combinations of chevron signs, curve warning signs and sequential flashing beacons on fifteen curves of an Italian motorway and reported statistically significant reductions. Rumble strips address lane departure directly: centreline treatment reduced frontal and opposing direction sideswipe injury crashes by 25% in an empirical Bayes evaluation [41], and combined centreline and shoulder application outperforms centreline treatment alone [42]. High friction surface treatment addresses the supply side of the stability balance, and curve specific crash modification factors have recently been developed for it [17]. The recurring limitation is that treatments are evaluated in isolation while they are applied in combination, so the interaction between them remains poorly quantified.

8. RESEARCH GAPS AND FUTURE DIRECTIONS

Five gaps emerge consistently. The first concerns terrain. Most curve studies have been conducted in rolling or mountainous terrain, where curvature is imposed by topography. Flat terrain generates a different problem, because curves there are sparse, separated by long tangents that encourage high approach speeds, and therefore violate expectancy more severely. Models calibrated on curve rich alignments are unlikely to represent this mechanism, and studies in flat terrain remain scarce [35].

The second concerns the structure of the crash generating process. Two part formulations rest on the premise that the factors determining whether a curve experiences crashes differ from those determining how many it experiences [31], yet curve level applications remain rare and the alternative responses to excess zeros, from zero inflation to random parameter mixtures [54], are seldom compared on the same data. Systematic comparison of hurdle, mixture and single equation specifications at curve level, with attention to the interpretation of the components rather than to fit statistics alone, is still lacking.

The third concerns maintenance variables. Pavement condition and friction supply are known to matter [10, 40] and friction based treatments produce measurable reductions [17], yet condition variables are absent from almost all curve crash prediction models. This is a data availability problem rather than a conceptual one, and automated condition surveys should make it tractable.

The fourth concerns the link between behaviour and outcomes. Naturalistic driving and floating car data now describe curve negotiation in detail [2, 11, 22, 49] and surrogate measures offer proactive screening [38], but their validation against crash records remains limited [44], so behavioural data still supplement rather than replace crash based analysis.

The fifth concerns transferability and geographical coverage. Functions estimated in high income countries transfer poorly [1, 13], while the countries bearing the greatest share of the global burden are least represented in the literature, and studies from Thailand [28], India [10] and Southeast Europe [19, 35] show that local calibration changes estimated effects appreciably. Expanding the geographical base of curve research is therefore a matter of validity rather than completeness, as is the systematic use of spatial and temporal structure, since both correlation between neighbouring curves [16, 43] and temporal instability of parameters [34] have been shown to matter.

9. CONCLUSIONS

Four conclusions follow. First, the elevated risk at horizontal curves is a robust and internationally reproduced finding, with crash rates averaging about three times those on comparable tangents, but its magnitude depends on driver expectancy as much as on geometry, as shown by the smaller increase in risk where curves follow one another closely. Second, curve radius remains the dominant geometric predictor, while side friction demand, pavement condition, the relationship with adjacent curves and the combination with vertical alignment are established secondary factors that remain underrepresented in operational models. Third, curve level data require specifications capable of handling excess zeros, unobserved heterogeneity and spatial structure, and the alternative responses to these features are rarely compared on common data. Fourth, the evidence on countermeasures is asymmetric: realignment is demonstrably effective but rarely affordable, while low cost perceptual and surface treatments are widely applied, evaluated mostly in isolation, and poorly quantified in the combinations actually used.

For research, the priority is to close the gap between the sophistication of prediction and the weakness of evaluation, and to extend both to the terrain types and regions that current models do not represent. For practice, curve safety management should treat expectancy, friction supply and roadside forgiveness as co equal with radius rather than as corrections to a geometric standard.

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