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Accident Analysis and Prevention. Vol 133, 2019, 1-6. 0001-4575

The more (sharp) curves, the lower the risk

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ABSTRACT

The risk of accident in horizontal curves is a complex function of at least the following characteristics of the curve: the radius of the curve; the length of the curve (and the resultant deflection angle); the presence of a spiral transition curve; the super-elevation of the curve; the distance to adjacent curves; and whether the curve is on a flat road, a straight gradient or a vertical curve. The interactions between these characteristics in determining accident risk in horizontal curves is only beginning to be understood. This paper summarises the results of studies that have investigated the interaction between the radius of a horizontal curve and the distance to adjacent curves. The shorter the mean distance between curves, the lower is the increase in risk for a given curve radius. The sharper neighbouring curves are, the lower is the increase in risk for a given curve radius. Thus, overall risk may not be higher on a road consisting mostly of sharp curves than on a road consisting mostly of straight sections with a few curves located far apart from each other.

Key words: horizontal curve; radius; adjacent curve; risk; interactions

1 INTRODUCTION

It has been known for a long time that the risk of accident is higher in horizontal curves than on straight road sections. Perhaps the most widely studied characteristic of horizontal curves is their radius, i.e. how sharp the curves are. Although studies have consistently found that accident rate per million vehicle kilometres driven in curves increases as radius declines, there is large variation in estimates of the increase in risk. This is particularly the case when radius is less than 200 metres. Thus, Elvik (2013) noted that when relative risk is set to the value of 1.0 for a curve radius of 1,000 metres, it was found to vary between 2.6 and 8.2 in curves with a radius of 100 metres in six studies made in six different countries. A review of recent North-American studies (Elvik 2017) found that the discrepancy in estimates of risk associated with sharp curves remains. Relative risk in curves with a radius of 150 metres varied between 1.9 and 4.1 when the risk in curves with a radius of 1,200 metres or more was set to 1.0. Clearly, risk in sharp curves is influenced not just by their radius.

In addition to radius, accident rate in horizontal curves has been found to be influenced by: the presence of spiral transition curves (Zegeer et al. 1991, Tom 1995); the length of curves (and the resulting deflection angle) (e.g. Persaud et al. 2000, Saleem and Persaud 2017, Bil et al. 2018); super-elevation in curves (e.g. Sakshaug 1998, Christensen and Ragnøy 2006); road surface friction (Musey and Park 2016); the distance to adjacent curves (Matthews and Barnes 1988, Eick and Vikane 1992, Eriksen 1993, Stigre 1993, Hauer 1999, Findley et al. 2012, Khan et al. 2013, Bil et al. 2018); the radius of adjacent curves (Gooch et al. 2016, 2018); whether horizontal curves are located on flat roads, straight gradients or vertical curves (Bauer and Harwood 2013, Saleem and Persaud 2017); and the use of warning signs or advisory speed limits in curves (e.g. Montella et al. 2015). No study has included all these factors. Hence, their contributions to the safety of horizontal curves is not well known.

The objective of this paper is to summarise evidence from studies of the interaction between the distance between adjacent curves and the increase in risk in curves of a given radius. As noted above, the increase in risk in horizontal curves of a given radius varies substantially, and one of the factors associated with this variation is the distance between curves. The main research questions asked in the paper are:

1. Has an interaction between the number of horizontal curves on a given length of road and the increase in risk for curves with a given radius been found consistently in studies examining this interaction?
2. Does the interaction depend on the radius of a horizontal curve; i.e. is there a radius beyond which the interaction becomes negligible?
3. What may explain the interaction between the number and sharpness of curves and the increase in risk associated with them?

2 STUDY RETRIEVAL

The studies identified by Elvik (2013, 2017) in previous reviews were included. To identify new studies, searches were made of ISI Web of Science, Science Direct and Transportation Research Record online using “horizontal curve” and “radius” and/or “accidents” or “crashes” as search terms occurring in the title, abstract or key words of papers. Studies were included if they: (1) developed models or contained estimates of the association between the radius of horizontal curves and the accident rate (or accident frequency) in the curves, and (2) developed models or contained data shedding light on the interaction between radius and the distance to neighbouring curves in influencing the accident rate in curves with a given horizontal radius.

It was not possible to statistically combine the results of different studies by means of standard techniques of meta-analysis. However, the results of the studies reviewed in the next section have been made comparable by: (1) Converting estimates of accident frequency to accident rate (i.e. accidents per million vehicle kilometres); (2) Converting accident rates to accident modification factors by setting the value of the lowest estimated accident rate in any study to 1.0 and expressing other accident rates as a multiple of this value. The results of the studies are then summarised in terms of functional relationships and the shape of these relationships is compared graphically.

3 ESTIMATION OF RISK – FREQENCY OF CURVES

A total of five functional relationships using distance between neighbouring curves as the independent variable and relative risk in curves with a given radius have been developed. This section explains how these relationships were estimated.

3.1 Matthews and Barnes (1988) – re-analysed by Hauer (1999)

The oldest study that examined the interaction between the distance between curves and curve radius in influencing accident rate was reported by Matthews and Barnes (1988). Hauer (1999) re-analysed the study, fitting the following models to describe its results:

Accident rate =

$$e^{(1.73 \cdot 10^{-6} R^2 - 4.17 \cdot 10^{-3} R)} \cdot e^{(-(6.2 \cdot 10^{-4} - 1.2 \cdot 10^{-6} R) \cdot (1200 - T))} \qquad (1)$$

$$\text{Accident rate} = e^{(1.73 \cdot 10^{-6} R^2 - 4.17 \cdot 10^{-3} R)} \qquad (2)$$

R denotes the radius of a curve in metres and T denotes the length in metres of the tangent (straight) section preceding a curve. Equation 1 applies to curves with a radius less than 500 metres and a tangent length less than 1,200 metres. Equation 2 applies to curves with a radius of 500 metres or more. No correction for tangent length was applied to curves with radius larger than 500 metres. Accident rate was stated as the number of accidents per million vehicle kilometres of travel. Estimates of accident rate developed by means of equations 1 and 2 have been tabulated in Table 1.

Table 1 about here

It is seen that the length of the tangent (straight) section ahead of a curve has a larger influence on accident rate the sharper the curve is. The accident rate for a tangent length of 1,200 metres and curve radius of 700 metres (0.126, lowest rightmost cell of Table 1) is given the value of 1.0. The highest estimated accident rate (0.671) then gets the value of 5.32 (0.671/0.126).

3.2 Findley et al. (2012)

The next study exploring how accident rate depends both on the distance between curves and their radius was reported by Findley et al. (2012). The study applied the CMF (crash modification function) developed for the Highway Safety Manual:

$$\text{CMF} = \frac{(1.55 \cdot L_C) + \left(\frac{80.2}{R}\right) - (0.012 \cdot S)}{(1.55 \cdot L_C)} \tag{3}$$

In equation 3, L_c is the length of a curve in miles, R is the radius of the curve in feet and S is an indicator for the presence of a spiral transition curve, equal to 1 if there is a transition curve at both ends of a curve, 0.5 if there is a transition curve at one end only, and 0 if there is no transition curve. When applying the equation in this paper, it was assumed that there is no transition curve. It was further assumed that the length of a curve is equal to its radius, which implies that the deflection angle is equal to one radian (57.3 degrees). Equation 3 estimates a crash modification function, i.e. a multiplicator showing how much higher the accident rate per million vehicle miles is in a horizontal curve compared to a straight section.

Findley et al. added a correction term to equation 3, defined as follows:

$$\text{Correction} = \text{CMF} \cdot e^{[B_0 + (B_1 \cdot D) + (B_2 \cdot P) + (B_3 \cdot (D \cdot P))]} \tag{4}$$

The correction term is an exponential function containing a constant term (B_0), a term for the distance to the distal curve(B_1) (i.e. the neighbouring curve furthest away from a given curve), a term for the distance to the proximal curve (B_2) (i.e. the neighbouring curve closest to a given curve) and a term (B_3) for the interaction between distances to distal and proximal curves. Distances to distal and proximal curves were measured in miles. The results for distance to proximal curve of 0.3 miles and distances to distal curve between 0.3 and 2.1 miles have been extracted. The multipliers (the exponential function in equation 4) ranged from 1.267 for a distance of 0.3 miles to the distal curve to 2.138 for a distance of 2.1 miles to the distal curve. Risk in a curve with radius 1,200 metres was used as reference (i.e. set to 1.0) when estimating accident modification factors.

3.3 Khan et al. (2013)

Khan et al. (2013) estimated a set of models to predict accident rates in curves. All models were negative binomial regression models of the following basic form:

$$\text{Number of accidents} = e^{(Coefficients_i \cdot Predictor\ variables_i)} \qquad (5)$$

The predictor variables included in the model referring to the largest accident data set (the ALL crash data set; N = 15,097 accidents) were:

1. Curve radius in feet
2. Curve length in feet
3. Ln(AADT)
4. Posted speed limit
5. Average IRI (International Roughness Index)
6. Difference between posted and advisory speed
7. Upstream tangent of 0-600 feet (dummy)
8. Upstream tangent of 601-1200 feet (dummy)
9. Upstream tangent of 1201 – 2600 feet (dummy)

When applying the equation, curve radius was varied between 328 feet (100 metres) and 3937 feet (1200 metres). Mean curve radius in the data was 2920.4 feet and mean curve length was 914.8 feet. Based on this, curve length was set to a proportion of curve radius = 914.8/2920.4 = 0.313. All other variables were entered at their mean values. The mean values of the three levels for the length of the upstream tangent, using the midpoint of the range as an estimate and converted to metres was, respectively, 91 metres, 274 metres and 579 metres. Risk in curves with a radius of 100 metres was found to increase sharply as the length of the upstream tangent increased.

The model (equation 5) predicts the number of accidents. However, as AADT and the ratio of curve length to curve radius were kept constant when applying the model, the results can be interpreted as estimates of accident rate at the mean traffic volume (an AADT of 1338). In the comparisons of accident rates for different distances to upstream curves, everything else was kept constant. A curve with radius 1,200 metres was used as reference for the accident modification factors.

3.4 Bil et al. (2018)

A paper by Bil, Andrasik, Sedonik and Cicha (2018) presented a GIS-tool used to identify curves and compute curve radius on Czech highways. The paper contained an accident prediction model for one class of road. The authors were contacted and asked if they could supply similar models developed for other classes of road. The answer was positive, and prediction models for four classes of road were provided. All these models had the following form:

Number of accidents per curve per year = $e^{\beta_1+\beta_2(\frac{L}{R})} AADT^{\beta_3} L^{\beta_4} R^{\beta_5}$ (6)

The first coefficient (β_1) is a constant term. The next coefficient (β_2) refers to the ratio of the length of a curve to its radius, with both length and radius measured in metres. The final three coefficients refer to AADT (Annual Average Daily Traffic), Curve length (L) and curve radius (R). Note that the model predicts the number of accidents. To obtain the accident rate, used as estimator of safety by the other studies included, the number of vehicle kilometres performed in curves with different radii was estimated using an AADT of 2,000 and assuming that each curve had the same length as its radius (L/R = 1).

One of the four classes of road included in the study was motorways, where the mean distance between horizontal curves was considerable larger than in the other three classes of road. This class was omitted. In the other three classes of road, the mean number of curves per kilometre of road was 2.4382, 4.9232 and 5.2230, corresponding to mean distances between curves of 410, 203 and 191 metres. The accident rate in curves with a radius of 100 metres was found to increase as the distance between curves increased.

3.5 Re-analysis of Eick and Vikane (1992), Eriksen (1993) and Stigre (1993)

A number of Norwegian studies (Eick and Vikane 1992, Eriksen 1993, Stigre 1993) evaluated the road safety effects of signing of hazardous curves. In these curves, background and/or directional signs were put up. All curves were identified by means of a computer programme (Amundsen and Lie 1984). The purpose of this programme was to identify surprising curves. Curves scoring high for degree of surprise were selected for special signing. These curves did not all have the same radius, but data on the radius of each curve was not provided in the studies quoted above. However, data provided by Sakshaug (1998) show that the mean radius of the signed curves was 110 metres. Thus, no great inaccuracy is introduced by treating the curves as having a radius of 100 metres to be consistent with the studies quoted above.

Based on the data provided by Eick and Vikane (1993), Eriksen (1993) and Stigre (1993), five groups have been formed with respect to the mean distance between curves. Accident rates (injury accidents per million vehicle kilometre) in these groups are shown in Table 2.

Table 2 about here

The estimates of risk in Table 2 show that not only the risk in curves declines as the distance between them gets shorter, but that the risk on straight section between curves also declines. This is perhaps not so surprising, as higher density of curves means that the straight sections become shorter, and short straight sections may be associated with a lower speed than long straight sections. Nevertheless, the relative increase in accident rate (rate in curves/rate on straight section) tends to be smaller on roads with many curves than on roads with few curves, consistent with what the studies above have found. The following function was fitted to the relative accident rates:

Relative accident rate (curve/straight) = $3.652X^{0.2555}$ ($R^2 = 0.4775$) (7)

This function will be applied along with the results of the other studies reviewed above.

4 ESTIMATION OF RISK – SHARPNESS OF NEIGHBOURING CURVE

Two studies by Gooch et al. (2016, 2018) included data on the presence and radius of proximal and distal curves to a given curve. Models were developed including these variables in addition to the radius of a subject curve. These models were applied to estimate how the accident rate in a subject curve depends on the presence and radius of a proximal curve. The following estimates were developed, all for a subject curve with radius 100 metres:

1. No proximal or distal curves (intended to represent an isolated curve).
2. A proximal curve within 0.75 miles with radius 1,200 metres.
3. A proximal curve within 0.75 miles with radius 100 metres.
4. A proximal curve within 1.25 miles with radius 1,200 metres.
5. A proximal curve within 1.25 miles and radius 100 metres.
6. A proximal curve more than 0.75 miles away with radius 1,200 metres.
7. A proximal curve more than 0.75 miles away with radius 100 metres.

The distances of less or more than 0.75 miles were used by Gooch et al. (2016). The distance of 1.25 miles was used by Gooch et al. (2018). The extreme values for radius (1,200 and 100 metres) were used to probe whether the distance or the sharpness of a proximal curve had the greatest influence on the accident rate of the subject curve.

5 RESULTS

Figure 1 shows results of the five studies that were reviewed in section 3, dealing with how accident rate in a curve with a given radius depends on the distance to a neighbouring curve. A sharp curve with a radius of 100 metres is used as case. It is seen that all studies find that accident rate in a sharp curve increases as the mean distance between curves increases.

Figure 1 about here

The shape of the functions showing how accident rate in a sharp curve increases as the distance to neighbouring curves increases differs considerably. The functions developed by Hauer (1999) and Khan et al. (2013) rise steeply at an increasing rate. The function developed by Findley et al. (2012) is close to linear, whereas the functions fitted to the Norwegian and Czech studies (Eick and Vikane 1992, Eriksen 1993, Stigre 1993, Bil et al. 2018) increase steeply at first and then become flatter. It would therefore not be informative to try to developed a synthesised function based on the five functions shown in Figure 1.

The intercept of the functions also differs considerably. The function fitted to the study by Bil et al. (2018) suggests a negative accident rate when the distance between curves goes toward zero; this is implausible, but possibly attributable to the fact that Bil et al. included only curves in their models, not straight sections. When applying their models, a radius of 1,200 metres was treated as a straight section. Had a value of, say 12,000 been applied for a presumably straight section, relative accident rate for a radius of 100 metres would have been considerably higher.

Despite the rather wide dispersion of intercepts and different functional forms seen in Figure 1, all studies agree that the more curves there are on a road, the lower is the risk in a curve with a given radius. In other words: the more common this risk factor is, the lower is the risk associated with it.

Figure 2 shows estimates developed on the basis of the two studies by Gooch et al. (2016, 2018). The results of the studies were very similar, but the coefficients for radius (degree of curvature) of proximal curves did not apply the same values for distance in the two studies. The first study applied distances of less than or more than 0.75 miles from a subject curve. The second study only applied a distance of less than 1.25 miles from a subject curve.

Figure 2 about here

A gentle proximal curve within 0.75 miles of a subject curve hardly influences accident rate in the subject curve. However, if the proximal curve has a radius of 100 metres, accident rate in the subject curve is 8 % lower (relative risk 0.92). Proximal curves located more than 0.75 miles from a subject curve appear to influence accident rate in the subject more than proximal curves located less than 0.75 miles from the subject curve. This is inconsistent with the functions presented in Figure 1, all of which show a positive relationship between distance between curves and relative risk in a subject curve with a given radius. However, a sharp proximal curve is associated with a reduction in the accident rate of a subject curve for all distances specified by the two studies. It is noted that some of the coefficients estimated by Gooch et al. (2016, 2018) were highly uncertain and that results could have been different with different values for these coefficients

6 DISCUSSION

Many risk factors that are associated with accidents display a dose-response pattern. The higher the speed, the higher the risk of accident and the more severe its outcome. The higher the blood alcohol concentration, the higher the risk of accident. The larger the mass of a vehicle, the higher its potential for causing damage to others in case of an accident. Horizontal curves appear to display the opposite pattern: the more there are of them, the lower the risk in each curve.

Based on the studies presented in this paper, one cannot rule out that a road with many curves will have a lower total accident rate than a road with few curves. A simple numerical example has been developed to illustrate this. A road section of 1 kilometre with a constant traffic volume is considered. The section is assumed to have either 7, 5, 3, or 1 horizontal curves. Each curve has a radius and a length of 100 metres. It is assumed that the beginning and end of the road section consists of a curve, except for the case of 1 curve, which is located at the beginning of the road section. Table 3 shows hypothetical relative accident rates for the curves and the straight sections between them.

Table 3 about here

Accident rate for the shortest straight sections has been given the value of 1. All other accident rates are relative to this value. The section with seven curves will have six straight sections located between the curves, each with a length of 50 metres (0.05 kilometres). For the shortest straight sections, speed is not expected to increase compared to the speed kept in curves. For the longer straight sections, an increase in speed has been assumed, leading to an increase in accident rate. Since traffic volume is assumed to be constant throughout the length of the road section, the expected number of accidents can be estimated simply by multiplying the length of curves and straight sections by their respective relative accident rates. The estimated total number of accidents is shown in the rightmost column of Table 3.

It is seen that the estimated expected number of accidents tends to increase as the number of curves goes down. This obviously follows from the assumptions made, but as these are not altogether implausible, the hypothetical estimates may nevertheless predict real data. The results for the two bottom rows of Table 3 show a case of Simpson's paradox. This denotes a situation where an effect in each of two groups, A and B, goes in one direction, whereas the effect when the groups are added (A + B) goes in the opposite direction. While the accident rate is higher both in curves and on straight sections in the bottom row than in the row immediately above it (3.6 vs. 2.7 and 1.3 vs. 1.1), the expected number of accidents is slightly lower than in the next-to-bottom row (1.53 vs. 1.58).

One potential source of bias in comparisons using accident rate, is that accident rate depends on traffic volume and traffic volume could be different on roads with different frequency of curve. Roads with many curves tend to have low traffic volume and the accident rate tends to be higher at a low traffic volume than at a high traffic volume. Nevertheless, it is unlikely that differences in traffic volume between roads with many curves and roads with few curves can explain the findings of this paper. Applying the coefficient for ln(AADT) in a recent accident prediction model for Norway (Høye 2016) (0.928), it can be estimated that accident rate on a road with an AADT of 1,000 will be about 18 % higher than on an otherwise identical road with an AADT of 10,000. The differences in accident rates associated with horizontal curve radius and distance to neighbouring curves found in the studies reviewed in this paper are far greater than 18 %.

The most likely explanation for the results are behavioural adaptation among drivers. When driving on a road that mostly consists of curves, drivers come to expect that there will be many curves. They adapt their speed and visual search accordingly, but not enough to eliminate the increase in accident rate associated with curves. Even on roads that mostly consist of curve, the accident rate in the curves remains higher than on straight sections.

7 CONCLUSIONS

The main conclusions of the research presented in this paper are:

1. The shorter the mean distance between horizontal curves, the lower the accident rate in curves of a given radius.
2. Neighbouring curves with a small radius (sharp curves) are associated with a lower accident rate in a subject curve of a given radius than neighbouring curves with a larger radius.
3. It cannot be ruled out that, under plausible assumptions, a road with many sharp curves will have a lower accident rate than an otherwise identical road with fewer sharp curves.

ACKNOWLEDGEMENT

This study was made as part on the ongoing revision of the Handbook of Road Safety Measures, funded by the Norwegian Ministry of Transport and the Norwegian Public Roads Administration.

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Department of Transportation, Federal Highway Administration, Turner-Fairbank Highway Research Center.

LIST OF FIGURES AND TABLES

Figure 1:

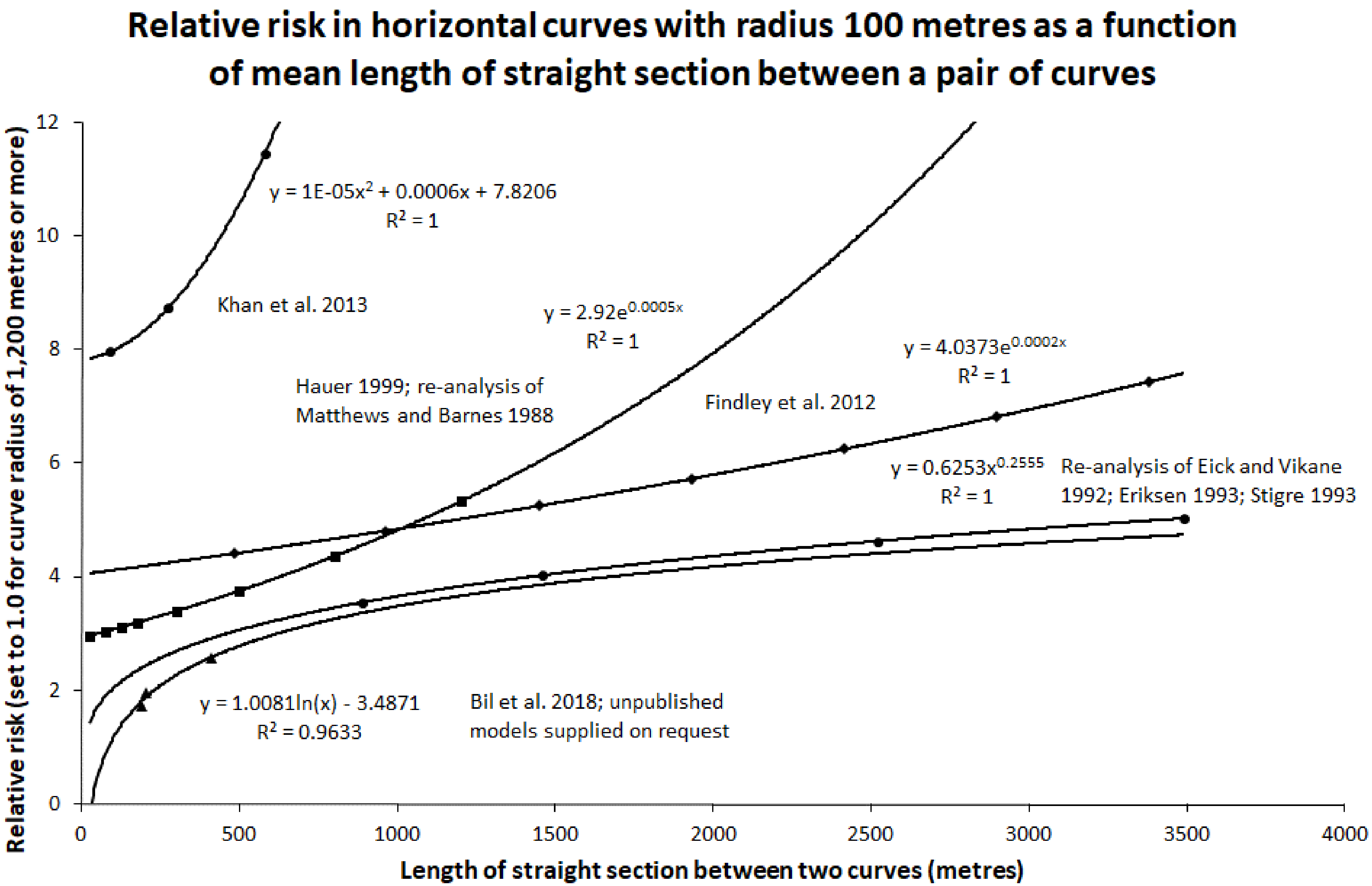
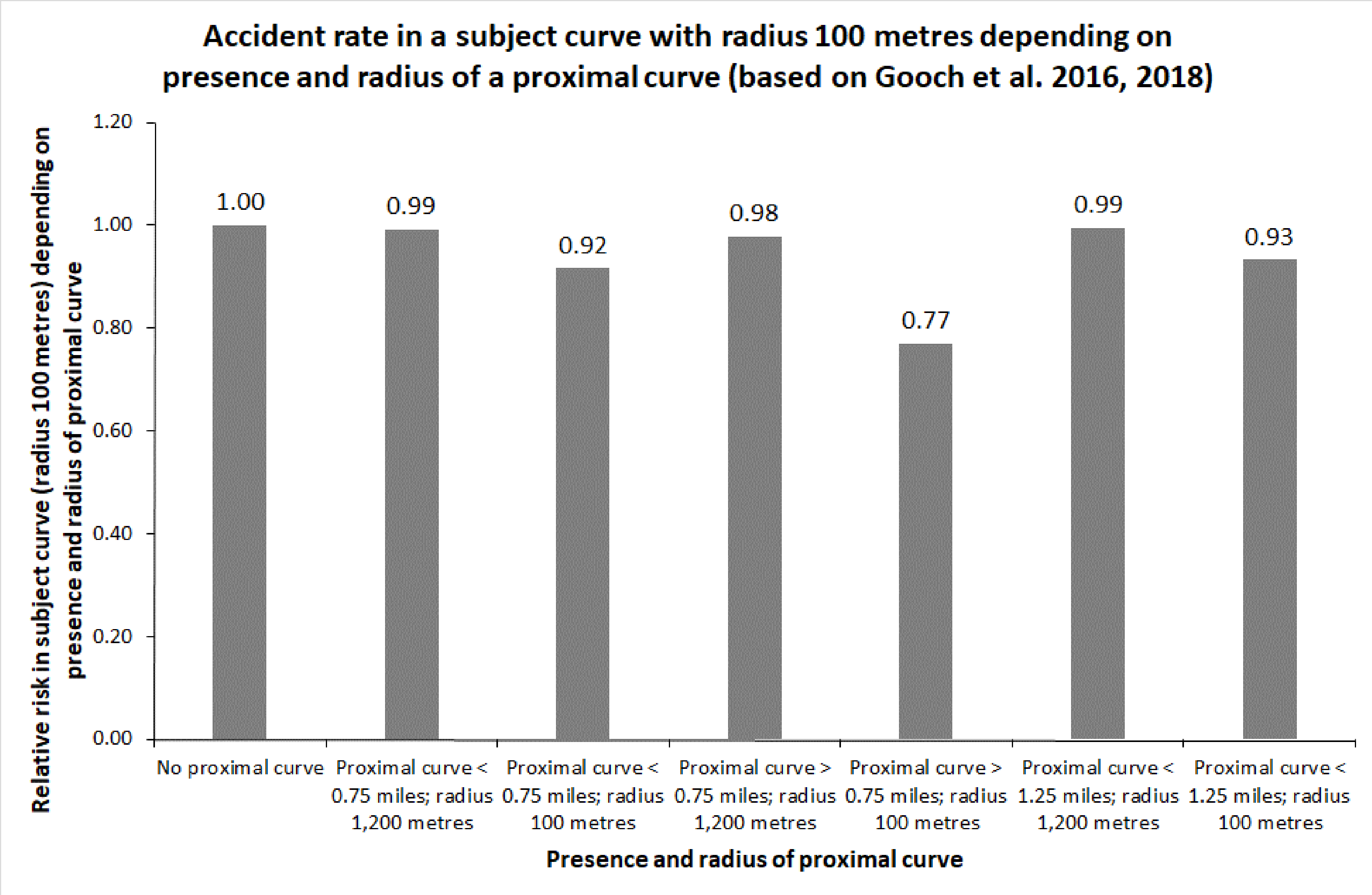

Relative risk in horizontal curves with radius 100 metres as a function of mean length of straight section between a pair of curves
Relative risk (set to 1.0 for curve radius of 1,200 metres or more)
Length of straight section between two curves (metres)
0
2
4
6
8
10
12
0
500
1000
1500
2000
2500
3000
3500
4000
y = 1E-05x2 + 0.0006x + 7.8206
R2 = 1
Khan et al. 2013
y = 2.92e0.0005x
R2 = 1
Hauer 1999; re-analysis of
Matthews and Barnes 1988
y = 4.0373e0.0002x
R2 = 1
Findley et al. 2012
y = 0.6253x0.2555
R2 = 1
Re-analysis of Eick and Vikane
1992; Eriksen 1993; Stigre 1993
y = 1.0081ln(x) - 3.4871
R2 = 0.9633
Bil et al. 2018; unpublished
models supplied on request

Figure 2:



Accident rate in a subject curve with radius 100 metres depending on presence and radius of a proximal curve (based on Gooch et al. 2016, 2018)
Relative risk in subject curve (radius 100 metres) depending on presence and radius of proximal curve
1.20
1.00
0.80
0.60
0.40
0.20
0.00
1.00
0.99
0.92
0.98
0.77
0.99
0.93
No proximal curve
Proximal curve < 0.75 miles; radius 1,200 metres
Proximal curve < 0.75 miles; radius 100 metres
Proximal curve > 0.75 miles; radius 1,200 metres
Proximal curve > 0.75 miles; radius 100 metres
Proximal curve < 1.25 miles; radius 1,200 metres
Proximal curve < 1.25 miles; radius 100 metres
Presence and radius of proximal curve

Table 1:

	Accidents per million vehicle kilometres in horizontal curves with radius between 100 and 700 metres						
Tangent length (metres)	**100**	**200**	**300**	**400**	**500**	**600**	**700**
25	0.373	0.298	0.246	0.211	0.187	0.153	0.126
57	0.382	0.304	0.250	0.213	0.187	0.153	0.126
125	0.392	0.309	0.253	0.214	0.187	0.153	0.126
175	0.402	0.315	0.256	0.216	0.188	0.153	0.126
300	0.428	0.331	0.265	0.219	0.188	0.153	0.126
500	0.473	0.357	0.279	0.226	0.189	0.153	0.126
800	0.549	0.400	0.301	0.235	0.190	0.153	0.126
1200	0.671	0.465	0.334	0.249	0.192	0.153	0.126

Table 2:

	Injury accidents per million vehicle kilometres		
Mean distance between curves (km)	**Accident rate in curves**	**Accident rate on straight sections**	**Ratio of accident rates (Curve/straight)**
6.54	0.420	0.081	5.22
3.49	0.675	0.106	6.36
2.52	0.479	0.123	3.89
1.46	0.188	0.038	4.89
0.89	0.132	0.043	3.05
All	0.410	0.094	4.34

Table 3:

Curves (N)	Straight sections (N)	Length in curves (km)	Straight length (km)	Mean length of straight section (km)	Relative accident rate in curves	Relative accident rate straight	Expected accidents in curves	Expected accidents on straight	Total expected number of accidents
7	6	0.7	0.3	0.050	1.5	1.0	1.05	0.30	1.35
5	4	0.5	0.5	0.125	2.0	1.0	1.00	0.50	1.50
3	2	0.3	0.7	0.350	2.7	1.1	0.81	0.77	1.58
1	1	0.1	0.9	0.900	3.6	1.3	0.36	1.17	1.53