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International transferability of accident modification functions for horizontal curves

Rune Elvik

Institute of Transport Economics

Gaustadalléen 21, NO-0349 Oslo, Norway

E-mail: re@toi.no

ABSTRACT

Studies of the relationship between characteristics of horizontal curves and accident rate have been reported in several countries. The characteristic most often studied is the radius of a horizontal curve. Functions describing the relationship between the radius of horizontal curves and accident rate have been developed in Australia, Canada, Denmark, Germany, Great Britain, New Zealand, Norway, Portugal, Sweden, and the United States. Other characteristics of horizontal curves that have been studied include deflection angle, curve length, the presence of transition curves, super-elevation in curves and distance to adjacent curves. This paper assesses the international transferability of mathematical functions (accident modification functions) that have been developed to relate the radius of horizontal curves to their accident rate. The main research problem is whether these functions are similar, which enhances international transferability, or dissimilar, which reduces international transferability. Accident modification functions for horizontal curve radius developed in the countries listed above are synthesised. The sensitivity of the functions to other characteristics of curves than radius is examined. Accident modification functions developed in different countries have important similarities. The functions diverge with respect to accident rate in the sharpest curves.

Key words: horizontal curves, radius, accident modification functions, international transferability, synthesis

1 INTRODUCTION

The international transferability of accident modification functions, i.e. functions describing the effects of highway design elements or road safety measures, is a topic of great interest and was recently examined by an OECD-group (OECD 2012). Small countries cannot always perform national research about every topic, but may have to rely on studies made in other countries. It then becomes important to assess whether knowledge can be transferred internationally.

The topic of this paper is the international transferability of accident modification functions for horizontal curve radius. An accident modification function for horizontal curve radius is a mathematical function that relates accident rates in horizontal curves to the radius of the curves. Since horizontal curves are a design element of highways in all countries, such functions have been developed in a number of countries. The main question to be examined in this paper is whether accident modification functions for horizontal curve radius developed in different countries are similar, supporting a formal synthesis of these functions in the form of an average function, or whether the functions are too different for such a formal synthesis to make sense.

2 STUDY RETRIEVAL

Relevant studies were retrieved by consulting the Handbook of Road Safety Measures (Elvik, Høye, Vaa and Sørensen 2009). In addition, relevant papers were identified from the online archive of Transportation Research Record by using “horizontal curve radius” as search term. A similar search for papers published in Accident Analysis and Prevention was made in ScienceDirect. Studies that have developed models of the relationship between horizontal curve radius and either: (1) The number of accidents per curve; (2) Accident rate (number of accidents per million vehicle kilometres of travel), or: (3) Accident Modification Factors (AMFs) in horizontal curves were identified for ten countries (alphabetically): Australia, Canada, Denmark, Germany, Great Britain, New Zealand, Norway, Portugal, Sweden and the United States. The three measures of safety in curves are not directly comparable; the relationship between them is discussed in section 3 (below).

No attempt was made to identify every study that has dealt with the relationship between horizontal curve radius and safety in curves. Priority was given to obtaining a sample of studies that included as many countries as possible and spanned as long a period as possible. The chief reason for applying these selection criteria was to obtain the largest possible range of replications (Elvik 2012), as a large range of replications permits a more stringent assessment of international transferability than a smaller range of replications.

3 MEASURES OF SAFETY IN HORIZONTAL CURVES

The literature reviewed for this paper contains three measures of safety in horizontal curves:

1. Number of accidents per curve per unit of time
2. Accident rate in curves (accidents per million kilometres of travel)

3. Accident Modification Factors associated with curves (i.e. the ratio: accidents in curves/accidents on straight sections)

These measures of safety do not necessarily produce the same results. To see why, consider Figure 1.

Figure 1 about here

Figure 1 contains two curves with the same deflection angle (90 degrees). The radius of the lower curve is three times the radius of the upper curve. Vehicles travelling in the lower curve will produce three times as many vehicle kilometres as vehicles travelling in the upper curve. To see how the different measures of safety can assume different values, applying the models developed by Persaud, Retting and Lyon (2000) will be instructive. Persaud, Retting and Lyon developed the following accident prediction model for horizontal curves:

Accidents per curve per year = $(AADT)^b (L)^g R^p e^{\left(a+h\left(\frac{L}{R}\right)\right)}$ (1)

AADT is annual average daily traffic. L is the length of the curve in kilometres. R is the radius of the curve in metres. L/R is the ratio of the length of the curve (kilometres) to the radius of the curve (metres) and a, b, g, h and p are coefficients estimated by means of negative binomial regression. For tangent (straight) sections, the following accident prediction model was developed:

Accidents per section per year = $(L)(AADT)^b e^a$ (2)

L is the length of a road section; AADT is annual average daily traffic. These models will be used to compare the safety of curves with radius 100, 300 and 500 metres. The length of curves is highly correlated with their radius. Curves with small radius tend to be shorter than curves with large radius. Persaud, Retting and Lyon provide data on radius and length for 15 curves; omitting one of these as an outlying data point, Figure 2 gives a plot of radius and length for the remaining 14 curves.

Figure 2 about here

The power function fitted to the data points in Figure 2 will be used to describe the relationship between curve radius and curve length. According to this function, a curve with a radius of 100 metres will have a length of 205 metres, a curve with a radius of 300 metres will have a length of 376 metres and a curve with a radius of 500 metres will have a length of 498 metres. Based on Table 5 in the paper by Persaud, Retting and Lyon, an AADT of 6,700 will be assumed. Model coefficients referring to injury accidents will be applied.

Inserting the values into equation 1, the model-predicted number of accidents was estimated to be 0.868 for a curve with radius 100 metres, 0.455 for a curve with radius 300 metres and 0.399 for a curve with radius 500 metres. The corresponding accident rates (accidents per million vehicle kilometres) were estimated, respectively, to be 1.733, 0.496 and 0.328. For straight road sections of the same length as the curves (205, 376 and 498 metres), applying equation 2 resulted in a model-predicted annual number of accidents of, respectively, 0.101, 0.185 and 0.245. Straight section accident rate (accidents per million vehicle kilometres of travel) was 0.201 in all cases. Based on these numbers, the effects of curve radius on safety in curves can be stated in terms of different estimates of relative risk. Thus, applying the predicted number of accidents:

R (100) : R(300) : R(500) = 0.868 : 0.455 : 0.399 = 2.175 : 1.140 : 1.000.

Curves with a radius of 500 metres have then been used as reference and the numbers indicate how many more accidents are to be expected in curves with radii of 300 or 100 metres. Expressing the same ratios in terms of accident rates gives (100, 300, 500):

5.284 : 1.512 : 1.000.

The increase in accident rate associated with smaller curve radius is considerably greater than the increase in the number of accidents. Finally, the same two comparisons can be made using straight road sections of the same length as the curves as reference. Relying on the number of accidents, this gives (100, 300, 500):

8.603 : 2.462 : 1.627.

This shows that even curves with a radius of 500 metres are expected to have more accidents than a straight road section of the same length as the curves. Applying accident rates (accidents per million vehicle kilometres) gives (100, 300, 500):

8.621 : 2.468 : 1.632.

These comparisons show that it is not unimportant how safety in curves is measured. To meaningfully synthesise models developed in different countries, it is essential that safety has been measured the same way in all studies. Unfortunately, this is not the case for the studies reviewed in this paper. Most studies report accident rates (accidents per million vehicle kilometres) in curves. The following rules were adopted to make functions based on other estimators as comparable as possible to accident rates:

1. The estimates developed for Canada (Persaud, Retting and Lyon) have been stated as accident rates, applying a uniform AADT of 6,700.
2. The AMF for Great Britain (McBean 1982) was developed by applying a case-control approach which is quite different from the other studies included. It was assumed that case sites and control sites were matched by traffic volume, so that estimated relative risks can be interpreted as relative accident rates.
3. The predicted number of accidents in the models for Germany were converted to accident rates by assuming that curve length was proportional to curve radius.
4. The AMF for Portugal has traffic volume in the denominator and is therefore interpreted as a relative accident rate.
5. The AMF for the United States was re-estimated as an accident rate; see more details in the section about the United States below.

The available accident modification functions for all other countries included in this study are stated in terms of accident rates.

4 ACCIDENT MODIFICATION FUNCTIONS DEVELOPED IN DIFFERENT COUNTRIES

This section presents the accident modification functions that have been developed in each of the ten countries included in the study.

4.1 Australia

Jurewicz and Pyta (2010) present a model developed to predict the number of single-vehicle run-off-road accidents to the left. The model was specified as follows:

$$\text{Number of accidents} = e^{(\beta_0 + \beta_1 AADT_{one} + \beta_2 Radius + \beta_3 Grade + \beta_4 TLSS + \beta_5 CZ + \varepsilon)} \quad (3)$$

Here e denotes the exponential function, the βs are coefficients estimated by means of negative binomial regression, $AADT_{one}$ is Annual Average Daily Traffic in one direction only, radius is horizontal curve radius in metres, grade refers to whether the road is flat or on a slope, TLSS is the width of the traffic lane plus sealed shoulder, CZ is clear zone width category and ε is the error term. Horizontal curve radius was included as a categorical variable with three values: less than 600 metres, between 600 and 1,500 metres and more than 1,500 metres. Precise values for curve radius were not stated. The dependent variable was the number of run-off-the-road accidents to the left on sections with a length of 60 metres.

If the number of accidents in curves with a radius of more than 1,500 metres is set equal to 1, the corresponding values were 1.422 for curves with a radius between 600 and 1,500 metres and 2.437 for curves with a radius less than 600 metres.

This model was not included in the synthesis of accident modification functions developed later in this paper. There are three reasons for not including the model in the synthesis: (1) The model refers only to a particular type of accident, whereas the other models reviewed in this paper refer to all accidents. (2) Curve radius is only represented as a categorical variable; precise values are not stated. (3) The accident sample was only 217 accidents with a mean value as low as 0.067 accidents per section.

4.2 Canada

An accident prediction model for horizontal curves on rural two-lane roads in Ontario, Canada, was reported by Persaud, Retting and Lyon (2000). The function was fitted to data for 585 curved sections with a total length of 144 kilometres. Curved sections consisted of curves only and did not have any straight segments. The number of accidents per curve per year was modelled as follows:

Accidents per curve per year= $(AADT)^b (L)^g R^p e^{\left(a+h\left(\frac{L}{R}\right)\right)}$ (4)

AADT is annual average daily traffic. L is the length of the curve in kilometres. R is the radius of the curve in metres. L/R is the ratio of the length of the curve (kilometres) to the radius of the curve (metres) and a, b, g, h and p are coefficients estimated by means of negative binomial regression.

The application of this function was discussed in section 3 above. Based on information given in the paper, curve length was modelled as a function of curve radius (see Figure 2):

Curve length (metres) = $16.109 \cdot curve\ radius^{0.5521}$ (5)

A value of 6,700 was applied for AADT and the predicted number of accidents per curve converted to an accident rate by estimating vehicle kilometres of travel in curves, applying equation 5 to estimate curve length. According to Table 5 of the paper, radii in the range from 87 metres to 1150 metres were included. Accident rate was therefore estimated for horizontal curves with a radius ranging from 100 metres (minimum) to 1000 meters (maximum), in steps of 100 metres. The model coefficients for injury accidents were applied.

4.3 Denmark

Rasmussen, Herrstedt and Hemdorff (1992) present a study of the relationship between horizontal curve radius and accident rate (accidents per million kilometres of driving) on Danish motorways (freeways). No mathematical model of the relationship was developed, but the following accident rates were presented:

Curves with a radius < 1,000 metres:	0.30 accidents per million veh. km
Curves with radius 1,000-2,500 metres:	0.15 accidents per million veh. km
Curves with radius >2,500 metres:	0.12 accidents per million veh. km
Straight sections:	0.20 accidents per million veh. km

Despite the few data points, the study is interesting for two reasons. First, it shows that accident rate is related to the radius of horizontal curves even when radius is more than 1,000 metres. Second, straight sections appear to have a higher accident rate than curved sections when curve radius is more than 1,000 metres.

This study was not included in the synthesis of models developed in different countries. The chief reasons for this were that curve radius was only represented as a categorical variable and precise values were not stated, and that the study referred to freeways, where the relationship between curve radius and safety is not necessarily the same as on rural two-lane roads.

4.4 Germany

Dietze and Weller (2011) developed accident prediction models for horizontal curves on rural two-lane roads in Germany. The following model was proposed for single curves:

$$\text{Number of accidents per curve} = AADT^{\alpha} L^{\beta} e^{(\gamma + \delta R)} \qquad (6)$$

Accident data for three years was used in developing the model. AADT is annual average daily traffic, L is the length of a curve in metres, R is the radius of a curve in metres and α, β, γ and δ are coefficients estimated by means of negative binomial regression. When plotting this function on graphs, Dietze and Weller used an AADT of 1,000. The same value has been used in this paper. Curve radius ranged from 30 metres to 495 metres. Curve length ranged from 40 metres to 559 metres. Based on information given in the report, the mean length of a curve can be estimated at 116 metres. The function in equation 3 was fitted for curves with radii between 50 and 500 meters, keeping AADT constant at 1,000 and curve length growing from 40 metres in curves with radius 50 metres to 550 metres in curves with radius 500 metres. The predicted number of accidents was converted to accident rates based on curve length.

4.5 Great Britain

McBean (1982) reported a case-control study of the relationship between horizontal curve radius and the probability that a certain curve would belong to the case group. A total of 197 sites on rural two-lane roads where accidents had been recorded were matched to 197 sites located nearby where accidents had not been recorded. 97 of the accident sites were straight sections, 100 were curves. The curves were classified in four groups according to radius: < 500 feet, between 500 and 1500 feet, between 1500 and 3000 feet and > 3000 feet. One foot equals 0.3048 metres. A log-linear model was developed to predict the change in the probability that a site would belong to the accident (case) group associated with changes in curve radius. A coefficient, v_i, was estimated for each group of curves. The interpretation of this coefficient was as follows:

$$P(\text{accident} \mid \text{radius in group}_i)/P(\text{accident} \mid \text{straight section}) = e^{v_i} \qquad (7)$$

As an example, the coefficient for the tightest curves was 2.05. The exponential of 2.05 is 7.768. This means that accidents were about 7.8 times more likely to occur in tight curves than on straight road sections.

When combining this function with functions developed in other countries, the following mean values for curve radius in meters were applied in the groups formed by McBean: < 500 feet = 100 metres; 500-1500 feet = 300 metres; 1500-3000 feet = 700 metres; > 3000 feet = 1,000 metres. Relative risks were interpreted as relative accident rates.

4.6 New Zealand

Matthews and Barnes (1988) presented a detailed study of the relationship between characteristics of horizontal curves on rural two-lane roads in New Zealand and the number of injury accidents per million vehicle kilometres of driving. They fitted the following function to the data relating accident rate to curve radius:

Accident rate = $8.5 \cdot R^{-0.64}$ (8)

R denotes curve radius in metres. The function in equation 8 was applied to estimate how accident rate depends on the radius of a curve. Values from 100 to 1,000 metres were used. There is no need to account for different curve lengths, as curve length enters the calculation of the denominator used for accident rates.

Hauer (1999) re-analysed their data and developed the following accident modification functions:

$$\text{Accident rate} = e^{\left(1.73 \cdot 10^{-6} R^2 - 4.17 \cdot 10^{-3} R\right)} \cdot e^{\left(-\left(6.2 \cdot 10^{-4} - 1.2 \cdot 10^{-6} R\right) \cdot (1200 - T)\right)} \quad (9)$$

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

R denotes the radius of a curve in metres (four values were used: 100, 300, 500 and 700 meters) and T denotes the length in metres of the tangent (straight) section preceding a curve. Equation 9 applies to curves with a radius less than 500 metres and a tangent length less than 1,200 metres. Equation 10 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. The functions developed by Hauer will be discussed as part of the sensitivity analysis of study findings.

4.7 Norway

Sakshaug (1998) presented data on radius and injury accident rate per million vehicle kilometres for 10,870 curves on rural two-lane roads in Norway. He did not fit a function to the data, but the following function has been found to best fit the data:

Accident rate = $2.334 \cdot R^{-0.421}$ (11)

R denotes radius of curve in metres. The fitted function does not account for other characteristics of curves than their radius. The data give a hint that accident rate has a minimum value at a radius of about 500 metres and increases slightly for larger radii. However, analyses in which a polynomial function was compared to the power function in equation 8 indicated that the power function fitted best.

4.8 Portugal

Two studies by Cardoso (1997, 2005) model the relationship between characteristics of horizontal curves on rural two-lane roads in Portugal and the excess risk associated with curves. There were three stages of model development. The first stage was to develop a model of unimpeded driving speeds on tangent sections. The second stage was to model how speed changed in curves as a result of curve radius and curve length. The third stage was to estimate the ratio of accident rates in curves to accident rates on tangent sections as a function of several variables. In this paper, the function developed for roads with paved shoulders in the most recent study has been applied, as paved shoulders are more common than unpaved shoulders. This function is shown in equation 12:

$$\frac{AR_{curve}}{AR_{tangent}} = e^{-4.565} \frac{(\Delta V_M)^{0.129} V_{MR}{}^{1.923}}{L_C{}^{0.303} AADT^{0.181} L_F{}^{0.129}} \qquad (12)$$

AR denotes the number of accidents per million vehicle kilometres of driving (accident rate), e is the exponential function, ΔV_M is the reduction in speed associated with horizontal curves, V_{MR} is the average unimpeded speed on the preceding tangent, L_C is curve length (metres), AADT is annual average daily traffic, and L_F is road width (metres).

To apply equation 12, representative values were selected for the variables included. The change in speed associated with a curve was estimated as follows:

$$\text{Speed reduction } (\Delta V_M) = 16.44 - \frac{158.05}{\sqrt{R_C}} + 2.12L_F + 0.705V_{MR} \qquad (13)$$

R_C is the radius (in metres) of a curve, L_F is road width in metres and V_{MR} is unimpeded approach speed on the tangent section. Curve radius was varied between 50 and 1,000 metres. Road width was assigned a value of 6.75 metres and maximum approach speed was set to 105 km/h. Based on the first study, a mean AADT of 3,017 was applied. The reduction in speed (ΔV_M) was entered in the model as a positive number.

4.9 Sweden

Brüde, Larsson and Thulin (1980) developed two accident modification functions for rural roads in Sweden; one for roads with a speed limit of 90 km/h, one for roads with a speed limit of 70 km/h. In this paper, the function developed for roads with a speed limit of 90 km/h will be applied. The roads were rural two-lane roads, but some of them were wider than two-lane roads tend to be in most countries. The functions had the following general form:

$$\text{Accident rate (y)} = \bar{y} \cdot B \cdot K \cdot L \qquad (14)$$

Here $\bar{y}$ denotes mean accident rate (accidents per million vehicle kilometres) for all roads with a speed limit of 90 km/h, B is a correction term for road width, K is a correction term for horizontal curve radius, and L is a correction term for vertical grade. These correction terms can be interpreted as accident modification factors with which the mean accident rate is multiplied to obtain the accident rate for a specific road. Curve radius was given the values of 300, 500, 700, 900, 1500, 3000 and 99,999 meters. The latter value was intended to indicate a straight road. The factor K was obtained as:

K =

$$0.292 - 1.9067 \cdot 10^2 \cdot \frac{1}{R} + 3.4202 \cdot 10^5 \cdot \left(\frac{1}{R}\right)^2 - 1.5881 \cdot 10^8 \cdot \left(\frac{1}{R}\right)^3 + 2.4276 \cdot 10^{10} \cdot \left(\frac{1}{R}\right)^4 \quad (15)$$

In equation 15, R denotes curve radius in metres and the equation applies to curves with radius 300 metres or larger.

4.10 The United States

The Highway Safety Manual (2010) presents an accident modification function (referred to as a crash modification function) for horizontal curves. The function is shown in equation 16:

$$\text{Accident modification function} = \frac{(1.55 \cdot L_C) + \left(\frac{80.2}{R}\right) - (0.012 \cdot S)}{(1.55 \cdot L_C)} \quad (16)$$

In equation 16, L_C is the length of a curve in miles (1 mile = 1.609 kilometres), R is radius in feet (1 foot = 0.3048 metres) and S is the presence of a spiral transition curve (S = 1 if there is a transition curve at both ends of the curve; 0.5 if there is a spiral transition curve at one end of the curve; 0 otherwise).

The function given in equation 16 is based on a study by Zegeer et al. (1992). It was therefore decided to rely on the original source in order to estimate an accident modification function for horizontal curves for the United States. Zegeer et al. (1992) developed the following model to predict the number of accidents in horizontal curves:

$$\text{Number of accidents} = [\alpha_1(L \cdot V) + \alpha_2(D \cdot V) + \alpha_3(S \cdot V)](\alpha_4)^W + \varepsilon \qquad (17)$$

In equation 17, L denotes the length of a curve in miles, V is volume of vehicles (in millions) in a 5-year period passing through the curve, D is degree of curve, S is the presence of a spiral transition curve, W is the width of the road (feet) and ε is an error term. The following parameters were fitted:

$$\text{Number of accidents} = [1.55\,(L \cdot V) + 0.014(D \cdot V) - 0.012(S \cdot V)](0.978)^{W-30}$$

The radius of a horizontal curve in metres equals 1748/D (Hauer 1999). Hence, to represent curves with a radius (in metres) between 50 and 1,000 metres, D was assigned values between 35 and 1.75. A uniform deflection angle of 50 degrees was assumed. Based on this assumption, the length of curves varied between 0.027 miles (for D = 35) and 0.541 miles (for D = 1.75). Mean AADT was set to 2,000. The number of vehicle passages in five years then becomes 3.65 million. No spiral transition curve was assumed to be present. Road width was assumed to be 30 feet. The final term of the equation then becomes 1.

A recent paper by Findley et al. (2012) has extended the accident modification function by including a correction for the distance between adjacent curves. The implications of this correction term will be discussed as part of the sensitivity analysis presented later in this paper.

5 SYNTHESIS OF ACCIDENT MODIFICATION FUNCTIONS

5.1 Overview of results for eight countries

Each of the functions presented in section 3, except those for Australia and Denmark, was applied to estimate the relationship between the radius of a horizontal curve and accident rate. Accident rate in the curve having the largest radius was set equal to 1.000. Table 1 shows the resulting estimates of the relative accident rates associated with shorter radii.

Table 1 about here

There are differences in the shapes of the functions. These differences are most noticeable for curve radii of 300 metres or less. Functions that cover the range between 100 meters and 1000 meters are available for Canada, New Zealand, Norway, Portugal and the United States. Table 1 shows that the relationship between horizontal curve radius and relative accident rate varies considerably between these countries. The values of relative accident rate for Canada and New Zealand are fairly close, but diverge for curves with a radius of 200 meters or less. The functions for different countries also differ in terms of the range of curve radii they apply to.

5.2 Developing a summary accident modification function

It is, unfortunately, not straightforward to apply standard techniques of meta-analysis for the purpose of developing a summary accident modification function based on the accident modification functions presented in section 4. In standard meta-analysis, each estimate is assigned a statistical weight which is inversely proportional to its sampling variance (Elvik 2005). However, the standard errors of the terms entering the accident prediction models in section 4 are not always stated. A different approach has therefore been taken for developing a summary accident modification function. The key steps of analysis are as follows:

1. The marginal gradient of relative accident rate with respect to curve radius was estimated for each accident modification function. By marginal gradient is meant the increase in accident rate associated with moving from one point on a function to the next point (see example below).
2. For accident modification functions fitted to data points that increase in steps of 200 or 300 metres, values were interpolated for steps of 100 metres.
3. A simple arithmetic mean of the marginal gradient was estimated for each step of 100 metres.
4. The variance of individual estimates around the arithmetic mean was estimated.
5. Each estimate was assigned a weight inverse proportional to the variance associated with it.
6. A weighted marginal gradient was estimated.
7. The weighted marginal gradients were multiplied in order to form the summary accident modification function.

The first two of these steps will be illustrated by reference to Table 2.

Table 2 about here

The left part of Table 2 shows the accident modification function fitted for Norway, giving relative accident rate according to horizontal curve radius, when the relative accident rate in curves with a radius of 1000 metres is given the value of 1.000. The marginal gradient of the function denotes the change in relative accident rate for each change in curve radius, i.e. the increase in relative accident rate when going from a radius of 1000 to 900 metres, 900 to 800 metres, and so on.

The right part of Table 2 shows the accident modification function fitted for Great Britain. There were only four data points for this function (the original data points were stated in feet; these were converted to metres). The marginal gradients for the function fitted for Great Britain span across several steps. Values for these steps were interpolated by assuming that marginal gradients display the same pattern as in the countries where all marginal gradients are known and combine multiplicatively. These assumptions are most consistent with the evidence for other countries. Thus, relative accident rate was 0.932 for a curve radius of 700 metres and 4.759 for a curve radius of 300 metres. The marginal gradient for the 300/700 metres ratio is 4.759/0.932 = 5.106. This gradient spans across the radii of 600, 500, 400 and 300 metres. Assuming that gradients increase at the same rate as in other countries, the marginal gradients become 1.455 (for 700 to 600 metres), 1.473 (for 600 to 500 metres), 1.509 (for 500 to 400 metres and 1.578 (for 400 to 300 metres) The product of these gradients is $1.455 \cdot 1.473 \cdot 1.509 \cdot 1.578 = 5.106$ (to the third decimal point). Table 3 shows the marginal gradients that were used to develop the summary accident modification function. Note that the data for Australia and Denmark were not included and that curve radii larger than 1000 metres were not considered.

Table 3 about here

The third step of analysis was to compute the simple mean of the marginal gradients listed in Table 3 row-by-row. Thus, the simple mean of the gradients associated with a reduction of curve radius from 200 to 100 metres was (2.352 + 2.306 + 1.427 + 1.558 + 1.338 + 1.326 + 2.269)/7 = 1.797. The simple means are listed in the next to rightmost column of Table 3. The simple mean can be greatly influenced by outlying data points. To account for this, the values were weighted in inverse proportion to their residual variance:

$$\text{Statistical weight} = \frac{1}{(x_i - \bar{x}_i)^2} \qquad (18)$$

Thus, the residual variance for the Canadian data point for a radius of 100 metres was: $(2.352 - 1.797)^2 = 0.308$, and the weight assigned to it 1/0.308 = 3.242. The weighted mean estimates of the gradient in accident rate associated with shorter curve radius are shown in the rightmost column of Table 3. A summary accident modification function was developed by multiplying the marginal gradients. The summary accident modification function is shown in Figure 3.

Figure 3 about here

The data points of the summary accident modification function for horizontal curve radius closely fit a power function. The function is:

Relative accident rate = $127.1658X^{-0.7099}$

X is curve radius in metres. In figure 4, this function is compared to the accident modification functions for horizontal curve radius in the eight countries whose functions served as the basis for the weighted mean function.

Figure 4 about here

The summary accident modification function is located in the middle of the accident modification functions developed in the eight countries and can, in that sense, be interpreted as an average of the functions developed in each country. The only exception to this is the very high accident rate associated with curves with a radius of 100 metres or less in the German model.

6 SENSITIVITY ANALYSES AND PREDICTIVE VALIDITY

The safety of horizontal curves depends not just on their radius, but also on other characteristics, such as length, presence of adjacent curves, the presence of transition curves and super-elevation. The previous sections have focused on radius. Some of the studies quoted in section 4 permit a sensitivity analysis of the relationship between the radius of a horizontal curve and its safety with respect to some of these characteristics. In this section, sensitivity analyses of the findings reported in sections 4 and 5 are performed with respect to:

1. Excluding countries whose accident modification functions differ markedly from the rest of countries.
2. Other characteristics of horizontal curves than their radius.
3. Using the summary accident modification function to predict the results of new studies of safety in horizontal curves

6.1 Sensitivity to countries included

The shape of the accident modification functions reviewed in section 4 and synthesised in section 5 varied. A particularly steep function was found for Germany. When the accident rate at a radius of 500 metres was set to 1.000, relative accident rate in curves with a radius of 100 metres was 13.707 and relative accident rate in curves with a radius of 50 metres was 24.363. These values are considerably higher than those reported in other countries, but not out of line with what previous studies of horizontal curves in Germany have found (Lamm et al. 1999, 2007). The increase in accident rate in the sharpest curves in the United States was also larger than found in other countries. It is therefore of some interest to see how much the summary accident modification function is changed by the omission either of Germany, the United States, or both countries. Table 4 reports the results of the analysis.

Table 4 about here

It is seen that when Germany, the United States or both countries are omitted, relative accident rate in the sharpest curves, with radius less than 200 metres, drops considerably. Thus, the accident modification functions developed in Germany and the United States predict a larger increase in accident rates in sharp curves than the accident modification functions developed in the other countries included in this study. Reasons for the difference are not known, but it suggests that international transferability could be problematic as far as the sharpest curves are considered. For curves with a radius of 200 metres or more, the slopes of the functions developed in different countries are more consistent.

6.2 Sensitivity to other characteristics of curves

The Canadian model (Persaud, Retting and Lyon 2000) included, in addition to the radius of a curve, AADT, curve length and the ratio of length to radius. The shape of the function relating curve radius to the expected number of accidents is not sensitive to AADT. It is, however, very sensitive to the length of a curve. If curves are assumed to be twice as long as assumed in the main analysis, accident rates increase dramatically and the slope of the accident modification function becomes a lot steeper. In other words, longer curves are associated with an increased accident rate.

The US model (Zegeer et al. 1992) also includes curve length. If all curves are assumed to be twice the length applied in the main analysis, the accident modification function becomes flatter. This means that longer curves are associated with a smaller increase in accident rate as radius becomes smaller; this is the opposite tendency of that found in the Canadian model.

A third study including length of curve as a variable is the German study (Dietze and Weller 2011). According to the German model, the relationship between the radius of a curve and accident rate was not influenced by the length of a curve.

Finally, the Portuguese model (Cardoso 2005) included length of curve. Again, however, a sensitivity analysis with respect to curve length found that the shape of the relationship between curve radius and accident rate was not influenced by the length of curve.

Another characteristic included in some studies is the distance between adjacent curves. Hauer (1999) re-analyzed the New Zealand study (Matthews and Barnes 1988). He developed a set of accident modification factors that account for the effects of tangent length. The shorter the tangent section ahead of a curve of a given radius, the lower is the estimated number of accidents in that curve. The accident modification factors indicate that the effects of a shorter curve radius are larger the longer the straight road section ahead of a curve is.

The German model (Dietze and Weller 2011) also included a term representing the length of a straight section ahead of a curve. The coefficient for this term shows that the longer the straight section ahead of a curve with a given radius, the higher is the accident rate in the curve. According to the model specification, however, there is no interaction between the length of a tangent section and the shape of the relationship between horizontal curve radius and accident rate.

Findley et al. (2012) developed a model of how the number of accidents in horizontal curves, as predicted by the Highway Safety Manual model, is influenced by the distance to adjacent curves. The model shows that the closer curves are spaced the lower becomes the number of accidents in each curve. Their model confirms the findings of Hauer for New Zealand and Dietze and Weller for Germany.

6.3 Predictive accuracy

At least two American studies modelling the relationship between various characteristics of horizontal curves and accident occurrence in curves have been published after publication of the Highway Safety Manual (Bauer and Harwood 2013; Khan, Bill, Chitturi and Noyce 2013). How well does the accident modification function presented in the Highway Safety Manual, based on the work of Zegeer et al. (1992), predict the findings of these more recent studies?

In order to answer this question, the functions developed by Bauer and Harwood (2013) and by Khan et al. (2013) were fitted to the same combinations of values for curve radius and curve length as used in the main analysis. Both functions were found to be very close to the function developed by Zegeer et al. (1992) for curve radii larger than 200 metres. For smaller curve radii, the function developed by Bauer and Harwood (for level sections) indicated an accelerating increase in accident rate, yet a considerably smaller increase than found by Zegeer at al. (1992). Thus, relative accident rate for a curve radius of 50 metres (1,000 metres = 1.00) was 4.89 according to Bauer and Harwood (2013), versus 12.35 according to Zegeer et al.(1992). Khan et al. (2013) found an even smaller increase in accident rate in curves with a radius of 50 metres, giving a relative accident rate of only 1.74.

It would therefore seem that sharp curves are associated with a smaller increase in accident rate now than at the time when Zegeer et al. collected their data (1982-86). Although reasons for this difference are not known, one may speculate that a higher share of very sharp curves are warned and marked today than about 30 years ago, that vehicle steering has improved, that electronic stability control has reduced the risk of running off the road, and that drivers are collectively more experienced today than thirty years ago.

7 DISCUSSION

Does the radius of a horizontal curve influence the accident rate in the curve the same way in all countries? That was the main research problem that motivated the research reported in this paper. The answer is yes and no. Yes, in all countries that have developed accident prediction models for horizontal curves, a tendency is found for accident rate to increase as curve radius gets smaller. The increase in accident rate is monotonic, i.e. it does not have turning points, and accelerating, i.e. reducing curve radius from 200 to 100 metres is associated with a larger increase in accident rate than reducing curve radius from, say, 600 to 500 metres. In these respects, the relationship between the radius of a curve and its accident rate appears to be the same in all countries.

There are, however, important differences between countries too. In particular, the accident prediction functions differ greatly for curves with a radius smaller than about 200 metres. The functions developed for Germany and the United States predict a considerably sharper increase in accident rate in these curves than the functions developed in other countries. Reasons for these differences are not known. Moreover, the relationship does not appear to be stable over time. Recently developed accident predictions model for horizontal curve in the United States predict a much smaller increase in accident rate in the sharpest curves than the model that was implemented in the Highway Safety Manual. Again, reasons for this change are not known, but one can speculate that the most hazardous curves are better signed than before and that vehicle steering and handling has improved over time.

As for the differences between countries, a possible reason could be the general alignment of the road system. It is noteworthy that the relative accident rate in curves with a radius of 50 metres is lower in Norway than in the other countries included in the study. Norway has a very high frequency of curves on many roads. Norwegian drivers are used to driving in curves and expect roads to have many of them.

The study has a number of limitations. The sample of countries was small; only eight countries were included in the formal synthesis of accident modification functions. Except for Portugal and the United States, only one accident modification function had been developed in each country. Ordinary techniques for meta-analysis could not be applied, because the precision of model coefficients was not always stated. It was not possible to test for the presence of publication bias.

8 CONCLUSIONS

The main conclusions of this study can be summarised in the following points:

1. Horizontal curves are associated with an increased number of accidents, the more so the sharper a curve is.
2. Models of the relationship between horizontal curve radius and accident rate in curves (accident modification functions for horizontal curve radius) have been developed in many countries. Models developed in ten countries are reviewed in the paper.
3. Accident modification functions in different countries differ both in terms of their mathematical form (exponential, power, etc) and in terms of the variables included.
4. An attempt was made to synthesize the accident modification functions developed in different countries. To the extent the summary accident modification function can be compared with the national accident modification functions, it appears to be a representative summary of these functions.

5. Accident rates in horizontal curves are influenced by other characteristics of the curve, such as the length of the curve and the distance to neighbouring curves. A sensitivity analysis with respect to these characteristics found that the shorter the distance is between adjacent curves, the lower is the accident rate in each curve. Findings were inconsistent as far as the length of curves is concerned. Some studies indicate that shorter curves have higher accident rates than otherwise identical longer curves, some studies indicate the opposite and some studies indicate that accident rate in curves is unrelated to the length of the curve.

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LIST OF FIGURES AND TABLES

Table 1:

	Relative accident rates in horizontal curves with different radii in eight countries. Accident rate in curves with largest radius = 1.000							
Radius (metres)	**Canada**	**Germany**	**Great Britain**	**New Zealand**	**Norway**	**Portugal**	**Sweden**	**United States**
50		24.360			3.525	5.640		12.348
100	8.227	13.707	7.099	4.365	2.634	4.415		3.816
200	3.498	5.943		2.801	1.968	3.330		1.682
300	2.353	3.074	4.759	2.161	1.659	2.796	2.167	1.285
400	1.844	1.712		1.798	1.470	2.449		1.148
500	1.555	1.000		1.558	1.338	2.191	1.539	1.085
600	1.368			1.387	1.240	1.981		1.050
700	1.236		0.932	1.256	1.162	1.781	1.360	1.029
800	1.138			1.154	1.098	1.603		1.016
900	1.061			1.070	1.045	1.399	1.240	1.006
1000	1.000		1.000	1.000	1.000	1.000		1.000
1500							1.086	
3500							1.000	

Table 2:

	Accident modification function for Norway		Accident modification function for Great Britain		
Radius of curve (metres)	Relative accident rate	Marginal gradient of accident rate	Relative accident rate	Marginal gradient of accident rate	Interpolated marginal gradient
100	2.634	2.634/1.968 = 1.338	7.099	7.099/4.759 = 1.492	1.427
200	1.968	1.968/1.659 = 1.186			1.045
300	1.659	1.659/1.470 = 1.129	4.759	4.759/0.932 = 5.106	1.578
400	1.470	1.470/1.338 = 1.099			1.509
500	1.338	1.338/1.240 = 1.079			1.473
600	1.240	1.240/1.162 = 1.067			1.455
700	1.162	1.162/1.098 = 1.058	0.932	0.932/1.000 = 0.932	$0.977^3 = 0.932$
800	1.098	1.098/1.045 = 1.051			$0.977^2 = 0.955$
900	1.045	1.045/1.000 = 1.045			0.977
1000	1.000		1.000		1.000

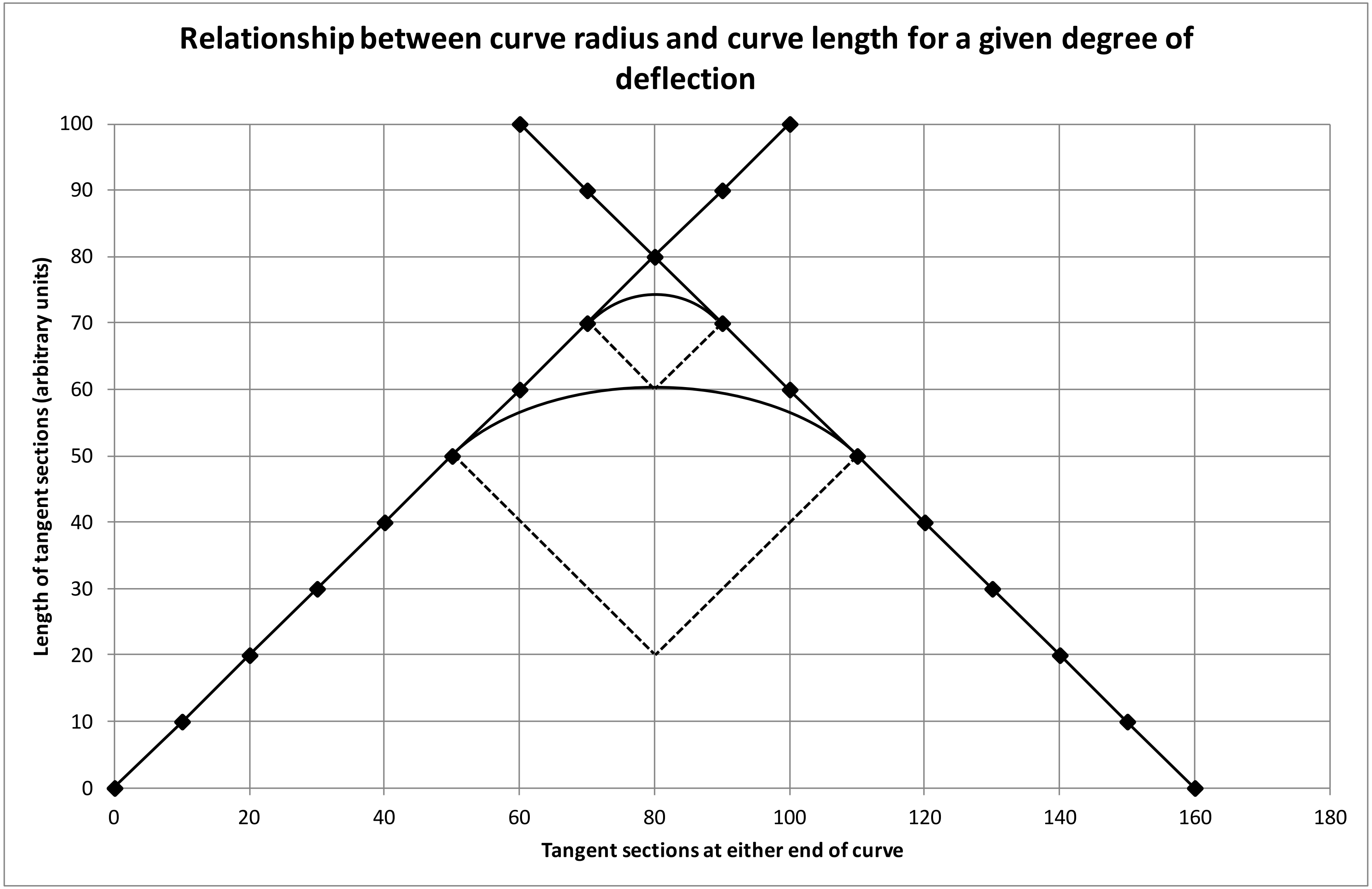
Table 3:

Marginal gradients for effects of shorter horizontal curve radius on accident rate and mean values of gradients										
Curve radius (metres)	**Canada**	**Germany**	**Great Britain**	**New Zealand**	**Norway**	**Portugal**	**Sweden**	**United States**	**Simple mean**	**Weighted mean**
50		1.777			1.338	1.277		3.236	1.907	1.750
100	2.352	2.306	1.427	1.558	1.338	1.326		2.269	1.797	1.680
200	1.487	1.933	1.045	1.296	1.186	1.191		1.308	1.350	1.304
300	1.276	1.795	1.578	1.202	1.129	1.142	1.213	1.119	1.307	1.260
400	1.186	1.712	1.509	1.154	1.099	1.118	1.161	1.058	1.250	1.169
500	1.137		1.473	1.124	1.079	1.106	1.071	1.033	1.146	1.132
600	1.107		1.455	1.104	1.067	1.112	1.057	1.020	1.132	1.105
700	1.086		0.977	1.089	1.058	1.111	1.047	1.013	1.055	1.056
800	1.072		0.977	1.078	1.051	1.146	1.047	1.010	1.054	1.051
900	1.061		0.977	1.070	1.045	1.399		1.006	1.089	1.062
1000	1.000		1.000	1.000	1.000	1.000		1.000	1.000	1.000

Table 4:

	Relative accident rate in horizontal curves (1.00 for curves with radius 1,000 metres) depending on countries included in synthesis				
Curve radius (metres)	**All countries – simple mean**	**All countries – weighted mean**	**Weighted mean – Germany excluded**	**Weighted mean – United States excluded**	**Weighted mean – Germany and USA excluded**
50	11.87	8.32	6.32	6.10	5.40
100	6.22	4.76	4.15	4.47	4.13
200	3.46	2.83	2.68	2.88	2.67
300	2.57	2.17	2.13	2.21	2.19
400	1.96	1.72	1.75	1.75	1.74
500	1.57	1.47	1.47	1.48	1.48
600	1.37	1.30	1.30	1.32	1.32
700	1.21	1.18	1.18	1.19	1.19
800	1.15	1.12	1.12	1.13	1.13
900	1.09	1.06	1.06	1.06	1.06
1000	1.00	1.00	1.00	1.00	1.00

Figure 1:



Relationship between curve radius and curve length for a given degree of deflection
Length of tangent sections (arbitrary units)
100
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
120
140
160
180
Tangent sections at either end of curve

Figure 2:

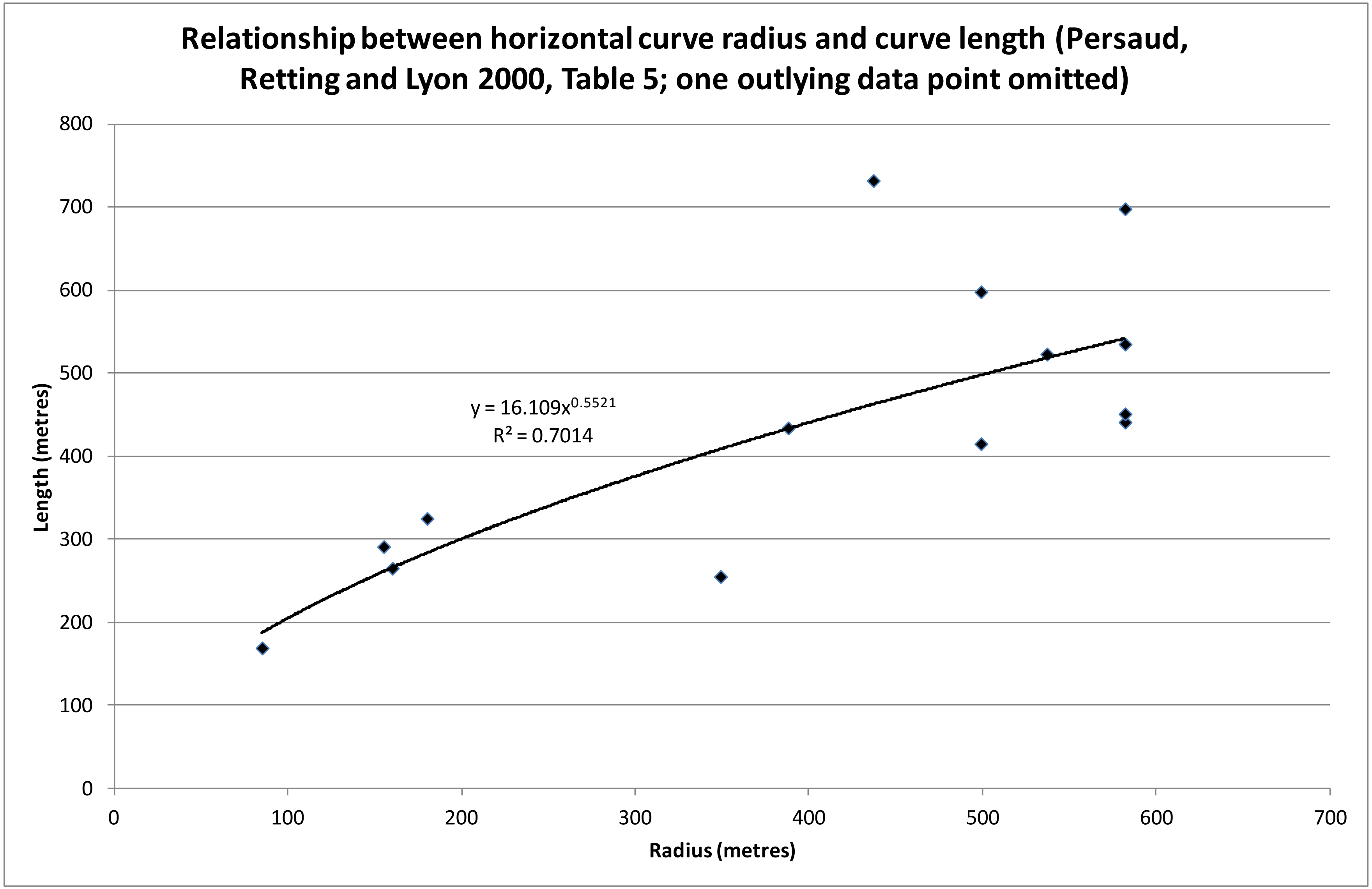

Relationship between horizontal curve radius and curve length (Persaud, Retting and Lyon 2000, Table 5; one outlying data point omitted)
y = 16.109x^0.5521
R² = 0.7014
Length (metres)
Radius (metres)
0
100
200
300
400
500
600
700
800
0
100
200
300
400
500
600
700

Figure 3:

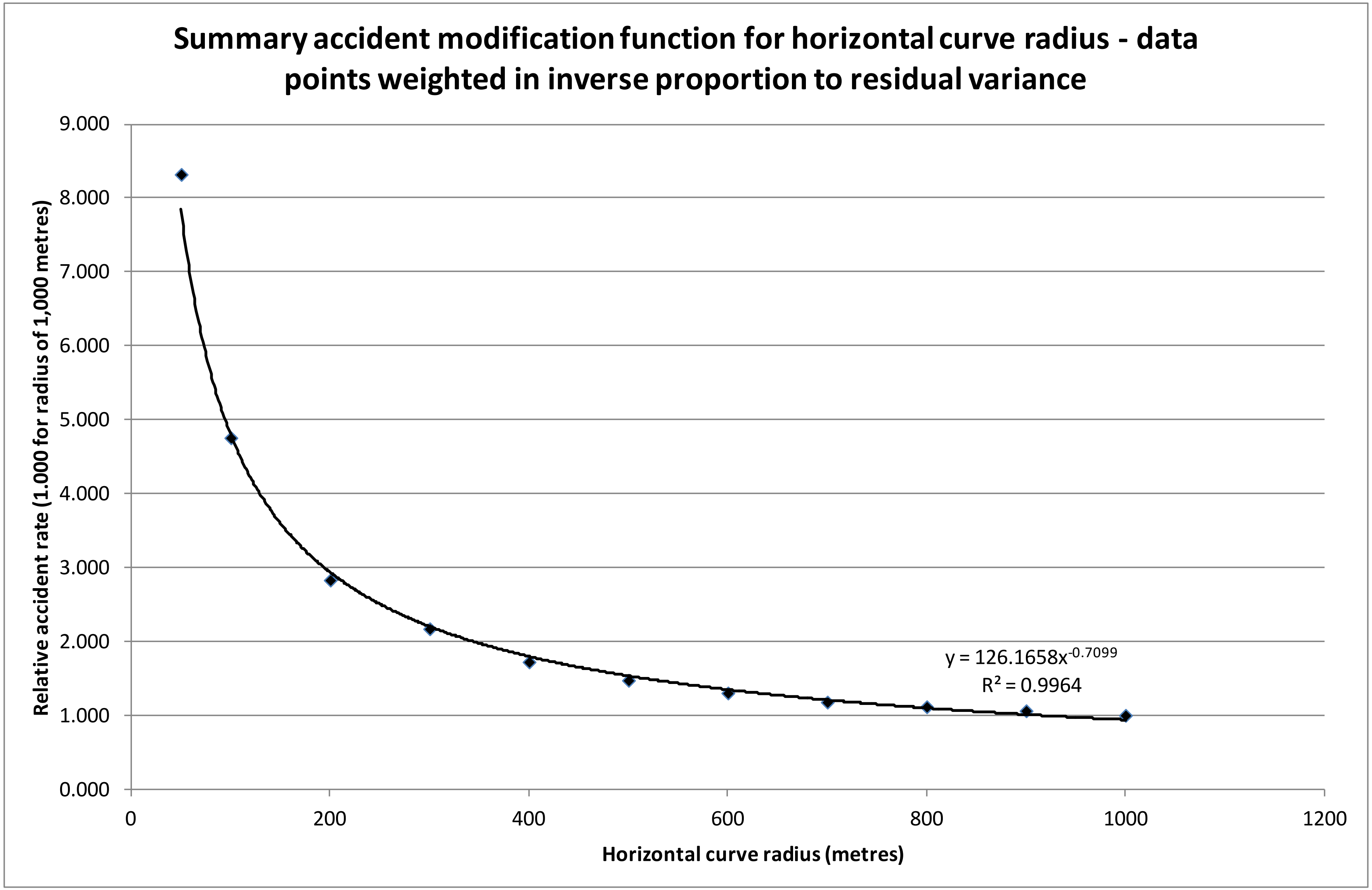
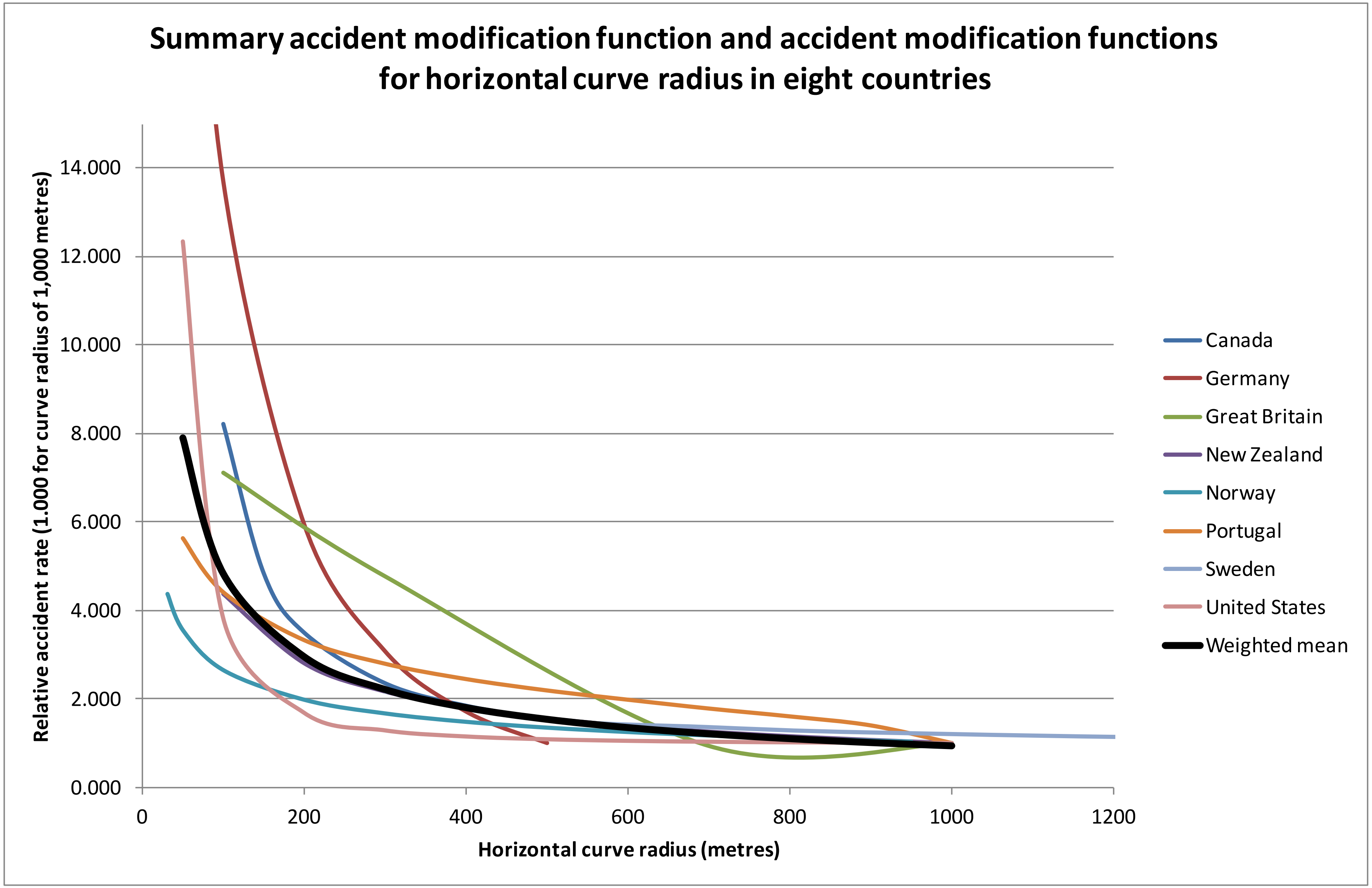

Summary accident modification function for horizontal curve radius - data points weighted in inverse proportion to residual variance
9.000
8.000
7.000
6.000
5.000
4.000
3.000
2.000
1.000
0.000
Relative accident rate (1.000 for radius of 1,000 metres)
0
200
400
600
800
1000
1200
Horizontal curve radius (metres)
y = 126.1658x-0.7099
R² = 0.9964

Figure 4:


Summary accident modification function and accident modification functions for horizontal curve radius in eight countries
Relative accident rate (1.000 for curve radius of 1,000 metres)
14.000
12.000
10.000
8.000
6.000
4.000
2.000
0.000
0
200
400
600
800
1000
1200
Horizontal curve radius (metres)
Canada
Germany
Great Britain
New Zealand
Norway
Portugal
Sweden
United States
Weighted mean