

EFFECT OF ROAD NETWORK BENDINESS ON TRAFFIC CRASH OCCURRENCE

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Abstract

This paper summarises the findings of a comprehensive study of the effects of road network bendiness on traffic crashes that used GIS (geographical information system) analysis (Fowler 2007). The study was based on previous research that examined the effect of road network "bendiness" on crash occurrence at a TLA level of aggregation (Haynes *et al.* 2007b). It was assumed that the "bendiness measures" used by Haynes *et al.* (2007b) would be more appropriate for predicting crash occurrence, and more useful from a traffic engineering viewpoint, when applied to localised regions. Thus a more appropriate method is presented and illustrated by a case study of New Zealand fatal traffic crashes.

The crash data consisted of the 4019 fatal crashes that occurred on New Zealand roads in the period 1996 to 2006. Sample sets of randomly selected non-crash sites on the road network were also analysed for comparison. The bendiness measures analysed were: bend density (number of "bends" per km); detour ratio (ratio of actual distance travelled between junctions to straight line distance); cumulative angle (degrees per km); mean angle (degrees); and standard deviation of angles. These were applied to areas of influence extending to 1km of travel around each site. Rural and urban environments were analysed separately as it was considered that the two cases would be significantly different.

Many factors complicated attempts to apply the bendiness measures at crash locations. It was difficult to infer the effects of the road travelled on driver behaviour given that the routes taken leading up to crash locations were unknown. Sample sets of flow data were used in some regions to infer likely routes taken. The remaining data was simply weighted according to the number of alternative routes; this proved effective for situations with low variability of flow on surrounding roads.

Binary logistic regression models were developed for both the rural and urban situations to predict the probability of a crash occurring on a section of road with certain bendiness characteristics. The urban model developed did not have a significant goodness-of-fit and so was not discussed further in this paper. It was found that rural roads with numerous but consistent bends were safer than completely straight roads or large individual curves, which indicates that bendiness is a protective quality as long as design consistency is maintained.

1.0 Introduction

Many previous studies have assessed the effects of individual horizontal curves on traffic crash occurrence. Their general consensus is that increasing curvature (decreasing radius) leads to increasing crash occurrence and therefore that horizontal curves are hazardous road elements. However, sections of road with infinite curvature (i.e. straight sections) have been shown to have the same crash rates as medium-sized curves (Gibreel *et al.* 1999).

Many other researchers have noted the importance of the context in which curves are located. Over forty years ago English traffic engineers noted that roads with long straights and few curves generally had higher crash rates than similar roads with many curves (Road Research Laboratory 1965 as cited by Nicholson, 2006), this was supported by Wilson (1968) who identified the danger of having a single sharp curve after a long tangent. Noland and Oh (2004) also suggested that roads with many curves may not necessarily be less safe than straighter roads. This research seems to contradict the findings of studies focused on individual horizontal curves and suggests that more investigation into the effects of curves in context of the wider road environment should be made.

This gives rise to the notion of “curviness” or “bendiness”, which is traditionally known as a measure of the cumulative variation in horizontal direction along a length of road (McLean 1989). Measures of bendiness gauge the combination and placement of several curves as opposed to examining curves individually. Many different measures of bendiness that gauge the proportions and sizes of curves and tangents (straight sections of road) that exist along a stretch of road or for a whole road network have been used, but no one formula for bendiness has been defined.

The importance of design consistency has also been recognised. Hauer (2000) attributed the high crash frequencies of sharp curves that follow long straight tangents to driver behaviour and the road’s unexpectedness. Mahalel and Szternfeld (1986) showed that crashes occur when the demand placed on a driver by the nature of the road environment is greater than the driver’s level of awareness (or performance).

Two previous studies provided the motivation for this research. The first, Haynes *et al*’s (2007a) study of the effect of road network bendiness on traffic crash occurrence in Britain used Geographical Information Systems (GIS) to compute five bendiness measures for all 403 local authority districts in England and Wales. It was concluded that bendiness was not hazardous but protective on a large scale, although individual bends were still more hazardous than individual straight sections. It was hypothesised that this was due to a combination of decreased speeds on curves, increased driver vigilance and a discouragement of risk-taking behaviour.

However, when applying the same methodology to roads in New Zealand’s 74 territorial local authority regions (TLAs) Haynes *et al* (2007b) found no significant relationships between road bendiness and crash occurrence, except that, on urban roads, detour ratio and cumulative angle measures indicated bendiness may be slightly protective.

From a traffic engineering perspective, the methodology used by Haynes *et al* (2007b) (which shall hereafter be termed “the motivating study”) seems somewhat dubious. While it was not the intention of the motivating study to examine the effects of bendiness on a “micro-level”, the high level of aggregation used means that it is not obvious whether or not crashes occurred on the bendy parts of “bendy regions”.

Section 2 of this paper presents a more appropriate method of analysing the effect of road bendiness on crash occurrence. Section 3 details results from when this method was

applied in a New Zealand case study. Section 4 summarises the conclusions made and section 5 suggests areas for further research.

2.0 Study Method

In order to find a more conclusive understanding of the effects of road bendiness on traffic crash occurrence, a new methodology was developed based on that of the motivating study. Specific details are not given here but can be found in Fowler (2007).

The main assumption of the method was that crashes should be analysed individually, rather than at an aggregated level. An “influence area” of 1km travel around each crash was chosen. It was assumed that this would be the distance of travel that affected drivers’ perceptions of the roads on which the crashes occurred. As no information was given regarding the routes taken by drivers involved in crashes, the bendiness measures were calculated for all possible routes between a crash and the extent of its influence area.

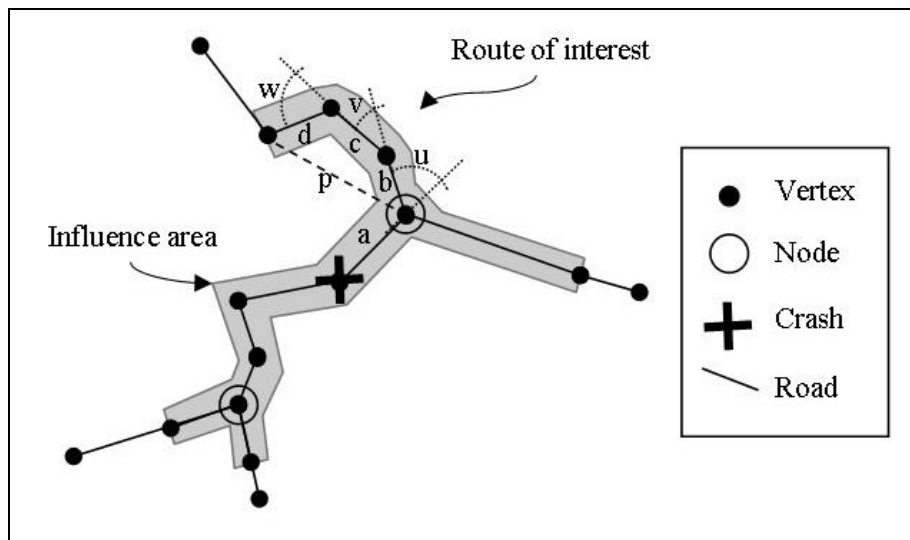


Figure 1 Bendiness Measure Diagram

Figure 1 shows the influence area of a particular crash. It can be seen that four possible routes between the crash and the extents of its influence area exist. Parameters for the calculation of bendiness measures for one of these routes are shown to illustrate the application of the measures and correspond to the parameters in equations 1 to 5. The bendiness measures used were:

Bend density (BD) – defined as the number bends per kilometre of road. This does not include the bends at intersections, i.e. includes only vertices which are not also nodes in its analysis. Bend density was calculated with equation 1:

$$BD = \frac{N_v - N_n}{a + b + c + d} \quad (1)$$

where: N_v = number of vertices within the study region;
 N_n = number of nodes within the study region; and
 a, b, c, d = road link lengths.

Detour ratio (DR) – defined as the ratio of actual road distance to straight distance between nodes (where the crash location and extent of influence area are also considered to be

nodes for the purposes of calculation). This was computed for the network as a whole. By definition the detour ratio must be greater than or equal to one. The detour ratio was calculated according to equation 2:

$$DR = \frac{a+b+c+d}{p+a} \quad (2)$$

where: p = straight distance between two nodes (as shown in Figure 1).

Cumulative angle (CA) – defined as the cumulative angle turned per kilometre, computed according to equation 3:

$$CA = \frac{u+v+w}{a+b+c+d} \quad (3)$$

where: u, v, w = angles at vertices.

Mean angle (MA) – defined as the mean angle of each bend in the network. This was calculated by dividing the sum of all angles by the number of angles in the network according to equation 4:

$$MA = \frac{u+v+w}{Na} \quad (4)$$

where: Na = number of angles between links in the study region.

Standard deviation of angles (SD) – the standard deviation of all angles along a route, according to equation 5:

$$SD = \sqrt{\frac{\sum (\theta - MA)^2}{(n-1)}} \quad (5)$$

where: θ = an angle between two links;
 MA = the mean angle for the route; and
 n = the number of angles the a route.

Weightings were applied to the bendiness values of each route to give an overall estimate of the influence area's bendiness, according to the formula:

$$BM_{Crashj} = \sum_{i=1}^R \left[BM_{Routejr} \times \frac{1}{X_1} \prod_{n=2}^{N-1} \frac{1}{X_n - 1} \right] \quad (6)$$

Where: BM = type of bendiness measure (detour ratio, mean angle etc);
 $Crashj$ = one particular crash;
 $Routejr$ = a route belonging to the influence area of $crashj$;
 R = the total number of $routejrs$ in the influence area;
 X_n = the number of links joining to a node; and
 N = the total number of nodes along a route (first node = crash position, last node = influence area edge).

It was recognised that a more appropriate weighting process would include the flows along each route but, as these were not available for the whole road network, equation 6 was considered the best option.

The method specified that the same calculations should be applied to “comparison sites”, locations randomly selected from the parts of the studied road network that were not within any of the crashes’ influence areas.

Values for other possible non-bendiness influencing variables such as traffic flow, road elevation, rainfall, junction density and intersection/mid-block classification were also calculated for the influence areas of each crash and comparison site.

The method then specified that some type of statistical analysis should be performed to distinguish between the characteristics of crash and comparison sites. Binary logistic (or “logit”) regression was seen as the most appropriate method as it is based on data of two possible outcomes (in this case crash or non-crash) and several influencing variables. The general form of the binary logistic regression model is shown in equation 6.

$$\log it[Y] = \log\left(\frac{Y}{1-Y}\right) = \beta_0 + \beta_1 B_1 + \dots + \beta_f B_f + \dots + \beta_F B_F \quad (6)$$

where: Y = the probability of a crash occurring over the study period ($0 \leq Y \leq 1$)

B_f = influencing factor (for $f = 1$ to F)

β_f = coefficient applied to factor B_f from (Agresti 1996)

When applied in this method, the influencing factors should include different bendiness measures as well as other non-bendiness related factors. Variables should be chosen to be part of a model based on:

- Their individual correlations with crash occurrence (desire a high absolute Pearson product moment correlation coefficient with low associated p-value);
- Their individual correlations with other predictor variables (desire low correlations with low associated p-values between predictor variables);
- Their p-value when included in the model; and
- The effect they have on the general model evaluation statistics (number of concordant pairs, chi-squared statistics etc) when included in the model.

3.0 Case Study

A case study using New Zealand roads is presented to illustrate application of the method.

3.1 Description of Data

The main data sets used in the case study were: a network of road centrelines consisting of individual straight links and vertices; and locations of the 4019 fatal crashes that occurred in the period 1996-2005. Comparison sites, selected randomly from all vertices on the network greater than 1km from a crash location were also used to assess the bendiness of non-crash locations and improve the method’s statistical robustness. Sites were categorised according to whether they occurred on rural state highway, rural non-state highway or urban roads.

Several statistical analysis techniques were trialled in the case study. For example, one analysis attempted to normalise the bendiness measures (and thus remove the need for other variables) by computing the ratio of a bendiness value calculated for the immediate area (taken as 250m) around a site to the bendiness value of the site’s influence area. For the purposes of this paper, however, only the binary logistic regression technique is discussed as this method yielded the most conclusive results.

3.2 Binary Logistic Regression Results

The binary logistic technique was chosen because it distinguishes between two possible outcomes, in this case each site was either classed as “crash” or “not-crash”.

The reason for distinguishing between the rural state highway and rural non-state highway cases was that comprehensive flow data was available for state highways only. The location's census meshblock area was shown to be the best proxy measure for rural non-state highway road flow. The model chosen to predict crash occurrence on rural state highways is shown in Table 1.

Table 1 Rural State Highway Model

Predictor	Coefficient	Standard Error	P-value
Constant	-1.49	1.28	0.243
Detour Ratio	2.60	1.26	0.039
Cumulative Angle (degrees/m)	-6.72	0.95	<0.001
Standard Deviation of Angles	0.0757	0.0163	<0.001
Estimated Average Annual Daily Traffic (veh)	0.000328	0.000040	<0.001
Mean elevation above sea level (m)	-0.000984	0.000377	0.009

The evaluation statistics of the rural state highway model were:

- Test that all slopes are zero: $G = 269$, P-Value <0.001;
- Deviance goodness of fit test: $\chi^2 = 1044$, P-Value > 0.999; and
- Percentage of pairs that were concordant, discordant, tied = 81.3%, 18.3%, 0.4%.

The model chosen to predict crash occurrence on all other rural roads is shown in Table 2.

Table 2 Rural non-State Highway Model

Predictor	Coefficient	Standard Error	P-value
Constant	-1.38	0.42	0.001
Detour Ratio	1.19	0.39	0.002
Cumulative Angle (degrees/m)	-7.54	0.51	<0.001
Standard Deviation of Angles	0.0457	0.0073	<0.001
Mean Rainfall (mm/year)	0.00445	0.00130	0.001
Mean elevation above sea level (m)	-0.00159	0.00045	<0.001
Intersection within 30m	0.963	0.162	<0.001
Meshblock Area (km²)	-0.00632	0.00143	<0.001

The evaluation statistics of the rural non-state highway model were:

- Test that all slopes are zero: $G = 645$, P-Value <0.001;
- Deviance goodness of fit test: $\chi^2 = 2254$, P-Value = 0.998; and

- Percentage of pairs that were concordant, discordant, tied = 82.0%, 17.7%, 0.2%.

Both rural models used the same bendiness measures; detour ratio, cumulative angle and standard deviation. While the first two measures individually had negative Pearson correlations with crash occurrence (indicating that an increase in bendiness would decrease crash occurrence) when included in the model the detour ratio had a positive relationship to crash occurrence. This is an effect of including the two measures together and does not necessarily indicate that bendiness is hazardous. The positive relationship between standard deviation of angles and crash occurrence means that as consistency increases crash risk decreases.

Both models included the mean elevation above sea level term; this may be an indication that the bendiness terms used did not fully account for the effects of bendiness. Elevation was shown to be positively correlated to the bendiness measures, as would be expected given that roads with high elevations are likely to be in mountainous regions with terrain that dictates bendy roads. The mean rainfall variable and intersection dummy-variable were important only in the rural non-state highway model. This may imply that more treatments are required to combat the effects of weather and intersection presence on rural non-state highways, or may simply be a side-effect of not having actual flow data for this model.

A concordant pair occurs when the probabilities predicted are in line with the observed outcomes (e.g. of the pair, the location that had a crash event was given a higher probability of a crash occurring by the model than the non-crash location the pair would be concordant). A discordant pair occurs when the probabilities predicted are opposite to that of the observed outcomes. A tied pair occurs when the probabilities of both outcome occurring are predicted to be equal. (Minitab Inc 2003) Both the rural models had high percentages of concordant pairs, which shows they were very accurate.

The model chosen to predict crashes on all urban roads is shown in Table 3.

Table 3 Urban Roads Model

Predictor	Coefficient	Standard Error	P-value
Constant	0.389	0.167	0.019
Cumulative Angle (degrees/m)	-4.83	0.31	<0.001
Standard Deviation of Angles	0.0858	0.0051	<0.001
Mean Rainfall (mm/year)	0.00436	0.00132	0.001
Mean elevation above sea level (m)	-0.00236	0.00046	<0.001
Junction Density (junctions per km)	-0.463	0.036	<0.001
[Population + Employment] / Area (people/km²)	0.000130	0.000024	<0.001

The evaluation statistics of the model were:

- Test that all slopes are zero: G = 906, P-Value <0.001;
- Deviance goodness of fit test: $\chi^2 = 4327$, P-Value <0.001; and
- Percentage of pairs that were concordant, discordant, tied = 77.5%, 22.3%, 0.2%.

It was observed that, while the two rural models had excellent goodness-of-fit statistics, the urban model had a p-value well below a 5% significance threshold. Thus, for the purposes of this paper only the rural models shall be examined.

The rural models were applied to several "typical" sections of road to give an indication of the effects of bendiness on crash risk. Non-bendiness variables were held constant at mean values. These sections, along with the probabilities of crashes occurring predicted by the rural models are shown in Figure 2. It is important to note that these probabilities are for a ten-year period, in accordance with the crash data used.

It can be seen from Figure 2 that the safest road type trialled consisted of several similar bends. The most dangerous road type differed slightly between the two cases, with the large individual curve being the worst for rural state highways and the completely straight section being the worst for non-state highways. In both cases there was little difference between these two types. The single curve isolated between two straight sections was also given a high crash risk by both models. This confirms the hypothesis that design consistency is very important to road safety.

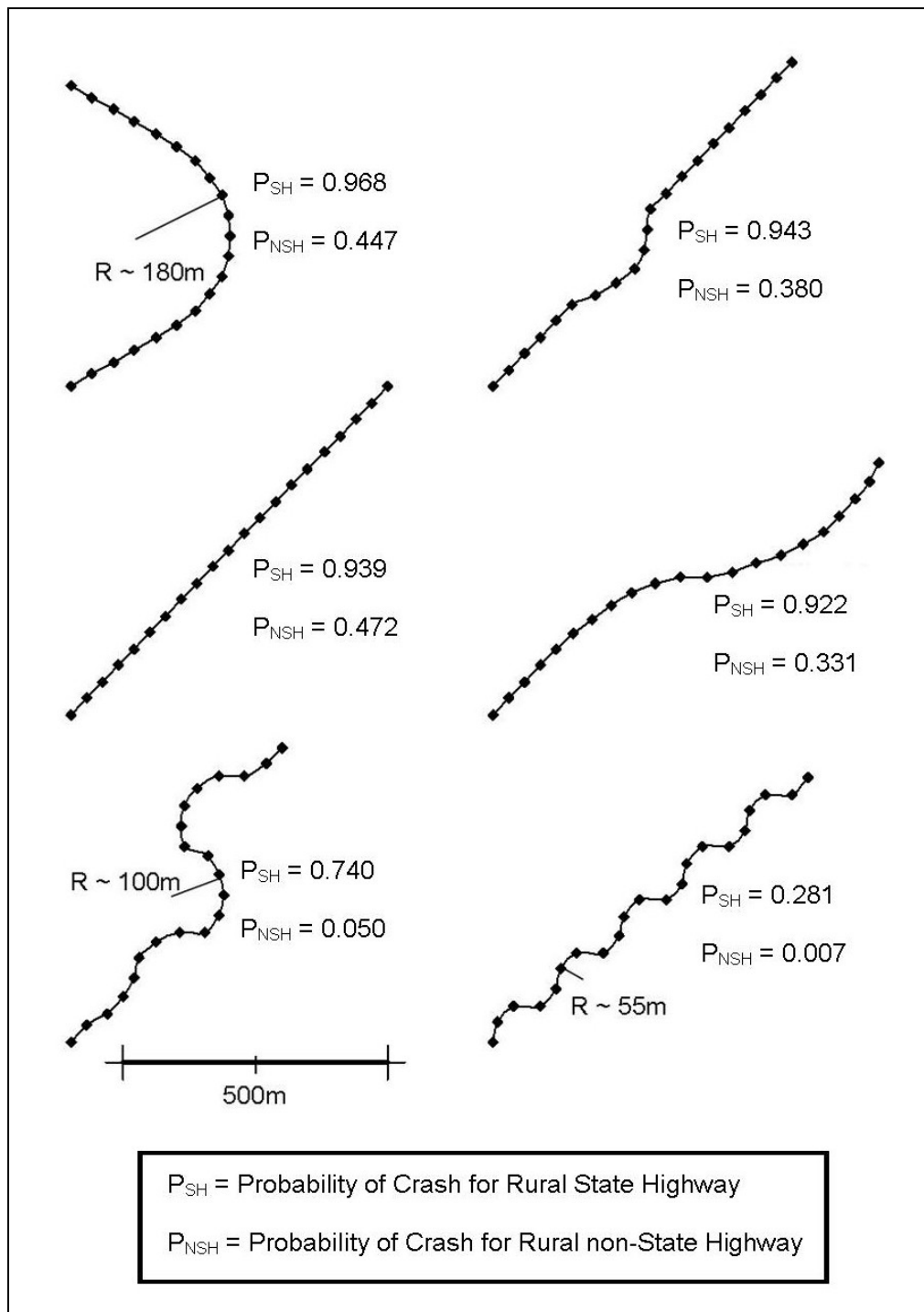


Figure 2 Model Crash Risk Predictions for Typical Rural Road Sections

4.0 Conclusions

This paper has presented a brief overview of an in-depth study; nevertheless some insights can be gained from the information presented here.

A method of calculating bendiness values for influence areas around crash and comparison sites has been presented and applied in a New Zealand case study.

Binary logistic regression models were developed for the rural state highway, rural non-state highway and urban cases to compare the effects of bendiness for crash and non-crash sites while accounting for other, non-bendiness related variables.

The model developed for crash risk on rural state highways had a significant goodness-of-fit test result and high number of concordant pairs, indicating that it was a suitable model. This model showed that large individual curves are the most hazardous, followed by straight sections. The section of road tested with this model that was shown to be the safest was a series of small and consistent bends, indicating the protective effect of bendiness. It has also been shown that design consistency has a high influence on traffic safety, with consistently bendy road sections having much lower crash risks than those of sections containing isolated curves. An advantage of the rural state highway model was that it was based on actual flow data.

The model developed for crash risk on rural non-state highway roads also had a significant goodness-of-fit test result and high number of concordant pairs. It was slightly disadvantaged compared to the rural state highway model, as no actual flow data were available. The census meshblock area (which is defined based on number of residents) was shown to be the most appropriate proxy for flow. The rural non-state highway model predicted straight sections of road to be the most dangerous, followed closely by large individual curves. As for the state highway model the section of road with many small and consistent bends was shown to be the safest. The two models' results should not be compared quantitatively due to the difference in flow measures used.

The model developed for crash risk on urban roads did not have a statistically significant goodness-of-fit result which indicates that the method developed in this study may not be applicable to the urban situation.

The results of these three models were very different to those of the motivating study. Whereas this study showed significant trends between bendiness and crash occurrence in rural situations, the motivating study found no such evidence. Conversely, the motivating study found a significant relationship between bendiness and crashes on urban roads whereas this study's urban model was not statistically significant. It was assumed from the start that bendiness may not be a major contributor to urban crash occurrence and, contrary to the results of the motivating study, the models developed here do suggest this is true.

The greatest limitation of this research is considered to be the data used. Much time was spent processing data (mainly the road network, but also crash and traffic flows) into formats applicable to the investigation. Ideally a road network for the whole of New Zealand with comprehensive flow information would have been used. Crash data directly corresponding to the road network, with route information would also be ideal. This would give more accurate results and allow more time to be spent on analysis rather than preparation. Data collection is expensive but perhaps these findings can help steer the decisions as to what data is collected and in what format in the future.

5.0 Recommendations for Further Research

- Investigation of Influence Area Sizes

For this research an influence area of 1km was used. It was anticipated that this value, although loosely based on previous research, would require further investigation. However, given the time taken to perform the computations for the whole of the country, it was not possible for this research to investigate the optimum size of influence areas used. A further investigation, perhaps focusing on a subsection of the data used in this research, should be performed to determine the optimum influence area size. It is suggested that sizes be based

primarily on travel time rather than distance and therefore area covered would be determined by vehicle speeds within the area.

- Determination of Actual Routes Travelled

Attempts were made to predict the most likely routes taken by drivers previous to crashing and weight all possible routes, however exposure may not be the biggest crash influence and in many cases it may have been the route least travelled that was the most hazardous. Therefore, more research into determining the route travelled would be very beneficial to this research and most probably any other road safety investigations. Use of a single route would also allow much faster computations per crash and hence reduce the computing time of the study. This would enable more analysis to be done in the same amount of time and other methods to be tested.

- Include Injury Crashes in Analysis

Having a larger sample size may counteract the effects of under-reporting and produce a more statistically significant model. Future research should be done to compare models for the effects of road network bendiness on injury crash occurrence with those created by this study for fatal crash occurrence. This may also allow a better understanding of the effects of road bendiness on crash severity. For example, one hypothesis may be that although fewer fatal crashes occur on bendy roads this is simply due to lower travel speeds and hence lower severities when crashes do occur.

- Develop Alternative Measures of Design Consistency

With the exception of the standard deviation of angles term used in this study all of the measures used were simply taken from those of the motivating study and applied in different ways. While these measures capture the important aspects of bendiness and are consistent with previous studies it is envisaged that future research could develop new measures, especially some more suited to GIS applications.

One way of doing this might be to pre-process the road network before analysing it with respect to crashes. Individual road links could be regrouped according to the elements (curves or tangents) they belonged to. Each element could be gauged in terms of its length and total curvature or other measures such as inferred radius of curvature etc. Thus, instead of sorting through all the individual links of a route and computing bendiness measures the characteristics of the elements forming the route could simply be aggregated.

6.0 Acknowledgements

We are very grateful to Robin Haynes and Iain Lake (School of Environmental Sciences, University of East Anglia, UK) and Clive Sabel, Simon Kingham and Jamie Pearce (Geography department, University of Canterbury) whose original studies formed the motivation for this research and who were continually helpful in providing advice, clarification and much-needed data.

We are extremely appreciative of the efforts made by Fergus Tate and Jason Wildman (MWH Wellington) to provide the Upper Hutt City Council flow data and to Manu King (Transit New Zealand) who kindly provided state highway spatial flow data. Also, many thanks to John Thyne for his abundant GIS-related advice and Alan Nicholson who has been a wealth of information and inspiration, especially for statistical evaluations.

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