This is an unedited draft reflecting my personal opinions. Ezra Hauer

4. Road Grade and Safety

E. Hauer. Draft[1], April 17, 2001

The purpose of this section is to summarize what the accumulated literature tells us about the effect of grade on safety. The arrangement of this literature review is approximately chronological. In section 4.1 we review the accumulated empirical evidence about how grade alone affects safety. In section 4.2 we examine how the combination of grade and horizontal curvature affects safety. Section 4.3 is an attempt to draw conclusions.

4.1. Grade and safety on straight road sections.

1953. The evidence available by 1971 has been assembled by Leisch & Associates (1971). The earliest paper mentioned in this review of the literature is by Raff (1953) who concluded that: " on tangent highway sections there does not appear to be any relation between grade and accident rates.". He adds that: "In these analyses the roads have been classified only by grade, so it remains possible that grade may have some effect on the accident rate when the appropriate other features are held constant". One should also add that data were pooled from 15 states and this created a difficulty because: "It was difficult to decide how to combine the detailed data from different states. The reporting requirements vary, and it cannot be assumed that the reporting laws are fully complied with in every state."(p.22) This difficulty could not be fully overcome and, at least for 'grade' the results are erratic and uncertain.

1956. Bitzel using data about German freeways, reports the results in Table 1.

Table 1

Gradient [%]	Accident Rate [accidents/MVM]
0-1.9	0.75
2-3.9	1.09
4-5.9	3.06
6-8	3.39

1 Earlier drafts of this papers were prepared in the course of a project for UMA Engineering (for the new Canadian Geometric Design Guide) and for DELCAN (in ORSAM 98).

In this oft-quoted study the results seem quite clear. However, the indicated increase of the accident rate is about 40% for each percent of grade. This is out of line with all other study results.

1958. Bowman, in a study of accidents on the Ohio Turnpike, concluded that downgrades even when lesser than 3.14% have accident rates slightly higher than those on level sections, and that upgrades even if less than 2% produce additional accidents.

1961. Mullins and Keese made up continuous collisions diagrams of 54 miles of freeways in five Texas cities using some 10,000 accident reports. Their findings are given in Table 2.

Table 2

	Location	Accidents/MVM*
Crest	On upgrade of crest	2.33
	At peak of crest	1.96
	On downgrade of crest	1.92
Sag	On downgrade of sag	3.57
	At bottom of sag	2.45
	On upgrade of sag	2.39

*Million Vehicle Miles

On first examination, the results appear to be mixed. There is no self-evident simple pattern that might be perceived to be in accord with expectations. To illustrate, note that the crest and the downgrade that follows are the least dangerous while the downgrade part of the sag has the highest rate. One explanation that may be consistent with these findings is through the link between vertical profile and likely speed profile on it. Speed is likely to be largest on the downgrade portion of a sag where the accident rate is highest. It then gradually diminishes through the bottom of the sag→ the upgrade part of the sag →the upgrade part of the crest→the peak of the crest. After the peak, average speed begins to increase again. As shown in Figure 1, the observed change in accident rates (from Table 2) seems to follow the postulated change in average speed.

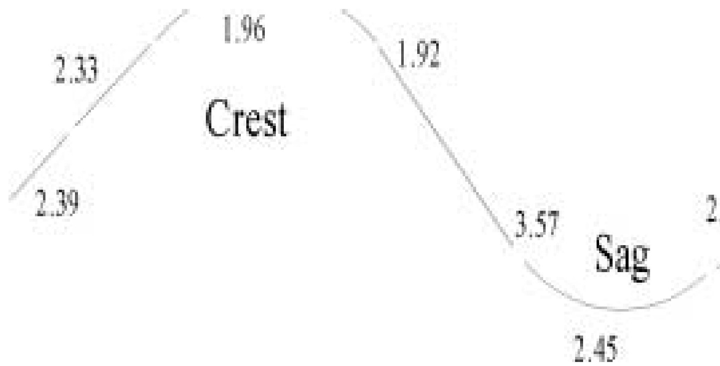

Figure 1

Also noteworthy is the finding by Mullins and Keese (1961) that "no apparent relationship existed between the number of accidents and the sight distance as an independent contributing factor."(p.45. and Figure 17). This is also supported by Figure 1 here. The sight distance on crest curves is shortest just ahead of the peak. Were sight distance important, this is where more accidents would be expected to occur. However, the peak is where the accident rate is seen to be the second lowest.

1966. Hillier and Wardrop studied accidents on 55 miles of the London-Birmingham motorway. Their results are shown as circles in Figure 2.

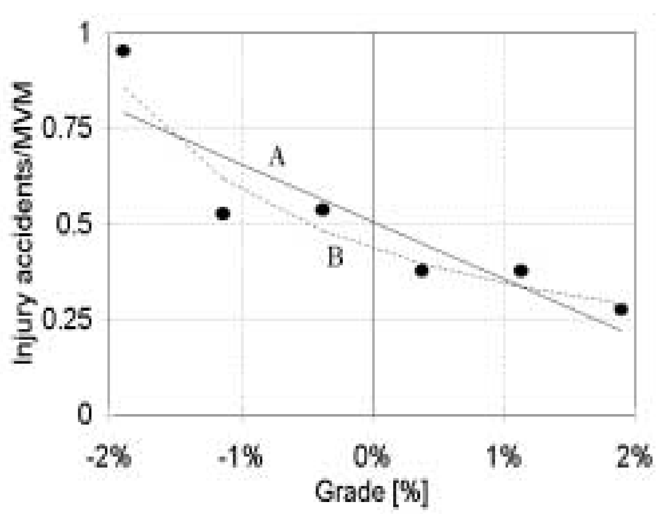

Figure 2

It is difficult to establish from their data whether the underlying relationship is best represented by a straight line such as A, or a non-linear function such as B. Yet this may be the main issue at hand. If a line such as A represents the underlying phenomenon, then the excess accidents on the downgrade lanes of a road section is exactly offset by the accident savings on the upgrade lanes. If so, the safety effect of grade is nil (as has been claimed by Raff). If, on the other hand, curve B represents the true relationship, then the safety harm of a downgrade exceeds the beneficial effect of the upgrade. Also, if B is approximately correct, then the larger the grade the larger its detrimental effect as is illustrated in Table 3 which has been prepared using curve B.

Table 3

Gradient	Uphill Accidents/MVM*	Downhill Accidents/MVM	Average Accidents/MVM
0%	0.43	0.43	0.43
0.5%	0.38	0.50	0.44
1%	0.34	0.59	0.47
1.5%	0.31	0.71	0.51
2%	0.29	0.91	0.60

* Million Vehicle Miles

The relationship in the last column is $1/(2.3-0.156\times g^2)$ where g is the grade in percent and does not exceed 2%. Using this equation the Accident Modification Factors in Table 4 are obtained.

Table 4. AMFs based on Curve B in Figure 2.

From\To	0.50 %	0.75 %	1.00%	1.25%	1.50%	1.75%	2.00%
0.50%	1.00	1.02	1.05	1.10	1.16	1.24	1.35
0.75%	0.98	1.00	1.03	1.08	1.14	1.21	1.32
1.00%	0.95	0.97	1.00	1.04	1.10	1.18	1.28
1.25%	0.91	0.93	0.96	1.00	1.06	1.13	1.23
1.50%	0.86	0.88	0.91	0.95	1.00	1.07	1.16
1.75%	0.81	0.82	0.85	0.89	0.93	1.00	1.09
2.00%	0.74	0.76	0.78	0.82	0.86	0.92	1.00

Thus, e.g., an increase in grade from 1% to 2% will increase accidents by a factor of 1.28.

Hillier and Wardrop explain that: “Gradient would be expected to effect accident rates for several reasons, the most important being its effect on speed.” This is consistent with our interpretation of the results by Mullins and Keese (1961). However, if it is true that the effect of grade on safety is mediated through speed, that is, if grade influences speed and speed influences safety, then it is unlikely to be useful to examine the simple relationship between grade and accident rate. Surely a short and a long road section which have the same grade will have a different effects on speed. Therefore, in spite of the grade being the same, they are likely to differ in their safety. Also, while the bottom of the sag and the peak of the crest will tend to be nearly horizontal, the average speed in the sag is likely to be larger than at the crest. This is why, if the 'speed explanation' is correct, widely different accident rates can be expected on crests and in sags.

1968. In an examination of a Chicago expressway (by Crosstown Associates, 1968) the results in Table 5 were obtained for straight road sections.

Table 5. Accident rates on straight road sections

	Accidents/MVM
Up-grade	1.87
±0.5%	1.10
Down-grade	2.49

Unlike the data in Figure 2, here the upgrade has a higher accident rate than nearly level sections. This finding too, may be consistent with the 'speed explanation' since nearly horizontal sections at the bottom of sags may be expected to have more accidents than upgrades.

1976. An OECD publication (OECD, 1976, p.26)) citing evidence in Leisch et al. (1971) claims that accident involvement tends to be higher at crest and sags. My reading of the same reference leads me to conclude that while accident rates in sags are higher than on long and level road sections, the same is not true for crests. The OECD report says that what they claim "is mainly due to speed variations. Slow moving vehicles on upgrades spread the traffic speed distribution and thus represent a potential hazard while, in a similar manner, faster moving vehicles on steep downgrades are more likely to be involved in accidents. These situations are made more critical by the geometric sight restriction introduced at crests of vertical curves and by vehicles slowing beyond the sags." The speculation in the quote rests on belief that the accident rate at crests is significantly higher than usual. There is little evidence to support this speculation. Thus, e.g., Fitzpatrick (1997, p. 1) finds that "Crash rates on rural two-lane highways with limited stopping sight distance (at crest curves) are similar to the crash rates on all rural highways." The speculation that 'speed variation' causes high accident rates at crests has, at present, only weak support in fact.

1964. Following Leisch et al (1971), the next review of the literature is by Roy Jorgensen Associates (1978). Two studies (in addition to those already reviewed) are mentioned in this review. The first study is by Vostrez and Lundy (1964). For straight freeway sections in California the results are given in Table 6.

Table 6. Accidents/MVM for California Freeway Sections.

	4%-5% trucks	11% trucks
Straight, Level	0.84	1.12
Straight, Up-grade	0.71	1.51
Straight, Down-grade	1.07	1.29

As in earlier evidence, down-grade sections have higher accident rates than straight level sections. The new factor in this study is the proportion of trucks. The indication is that when the proportion of slower moving vehicles is large, the accident rate on the upgrade also tends to be large.

1969. The second study identified in Roy Jorgensen Associates (1978) is by Cirillo et al. (1969). This is a first study recognizing that accident occurrence is affected by many road features such as road width, horizontal curvature, grade, sight distance and many others. Since these tend to be correlated (e.g. wide lanes and shoulders often go with mild grades), single variable tabulation such as those given above, are subject to confounding. That is, what seems to be the effect of grade may be a reflection of an entirely different variable that is correlated with grade (e.g., large grade and narrow shoulders). Thus, unless the effect of all important variables is properly accounted for, studies are not likely to yield credible results. Multivariable statistical models and analysis intend to account for the effect of many variables at once. Cirillo et al. found that grade was an statistically significant variable in one of two such models. According to this model, annual accidents increase by 0.01 for each 1000 vpd for each % of grade.

1978. The next study is by Dunlap et al. (1978). The intent was to study the combined influence of grade and horizontal curvature on skidding. Although an indication of a possible combined influence was found, the study yielded useful data about the relationship between grade and accident rate on the Ohio and Pennsylvania turnpikes as shown in Figure 3.

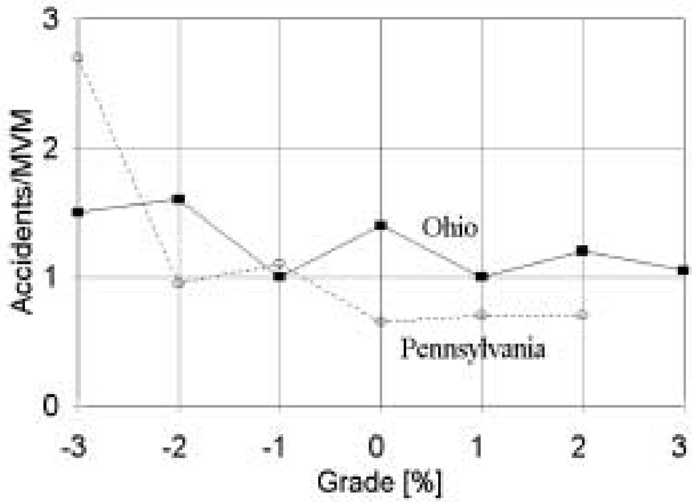

Figure 3

It appears that on both facilities accident rate increases with the downgrade slope. However, there is no noticeable change of accident rate with the upgrade slope.

1982. The review by Roy Jorgensen and Associates (1978) was followed by the publication of the Synthesis (1982). This review document furnishes no new evidence based on data. The Synthesis was followed by another review of the literature on the subject of the relationship between alignment design and safety (Zegeer et al., 1992). It too gives no additional information about the safety effect of grade, except for mentioning a study by Zador et al. (1987) which pertains to safety on sharp curves preceded by downgrades which will be reviewed in section 2. Thus, it appears that the momentum of research on this matter that produced valuable information till about 1970 came to a halt.

1990. Hedman (p. 231) mentions a study by Brüde et al. (1980) that found that "Grades of. 2.5% and 4% increase accidents by 10% and 20% respectively, compared to near horizontal roads." From $X^{2.5}$=1.10, X=1.038. From X^4=1.20, X=1.046. Thus, the Swedish results point to an AMF of 1.044.

1994. Two additional multivariate statistical models have been identified. Li et al. (1994), using data for 560 km of the British Columbia provincial primary two-lane highway system calibrated a multivariate model for fatal+injury accidents in which grade is one of the variables. Based on their model, the accident modification function is:

$$AMF(\Delta_{\%grade}) \cong 1+0.136\ \Delta_{\%grade} / \sqrt{Accid/km}$$

To illustrate, if the designer contemplates a decrease of a grade from 2.3% to 2.1% ($\Delta_{\%\ grade}$=-0.2%) on a road which at a grade of 2.3% is expected to have 1.7 accident/km, AMF(-0.2)=1+0.136×(-0.2)/√1.7=0.979. That is, the safety gain is a reduction from 1.7 to 1.7×0.979=1.66 accidents/km. According to this a change of 1% in grade results in a change of approximately 10% in accident frequency.

1995. Miaou (1995) using data from 11,539 road sections and 6680 single-vehicle-off-the-road accidents in Utah finds that

$$AMF(\Delta_{\%\ grade}) = e^{0.081 \times \Delta\%grade} \simeq 1+0.081\times\Delta_{\%\ grade}$$

That is, a decreasing the grade by 1% diminishes the number of accidents by 8.1 %. This value is likely to be used in the IHSDM (Interactive Highway Safety Design Model).

4.2. Grade and horizontal curvature in combination.

1953. For two lane roads with volumes up to 10,000 vpd, Raff (1953, Table 21) gives the results in Figure 4.

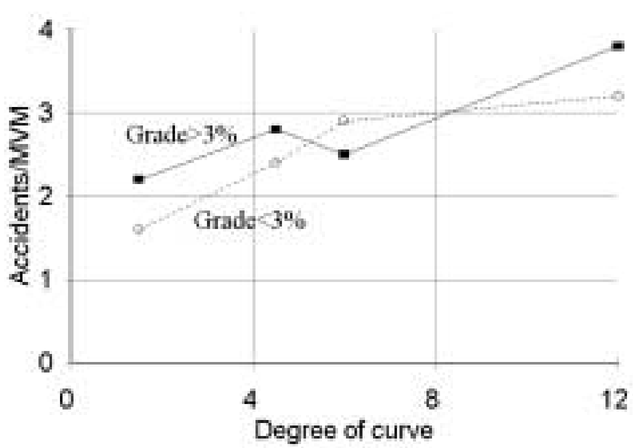

Figure 4

The result is consistent with what we know to be the effect of degree of curve on accidents rates and also with Raff's finding for tangent sections, namely that grade has no effect on the accident rate.

1956. Using data from German expressways, Bitzel (1956) gives the results in Figure 5.

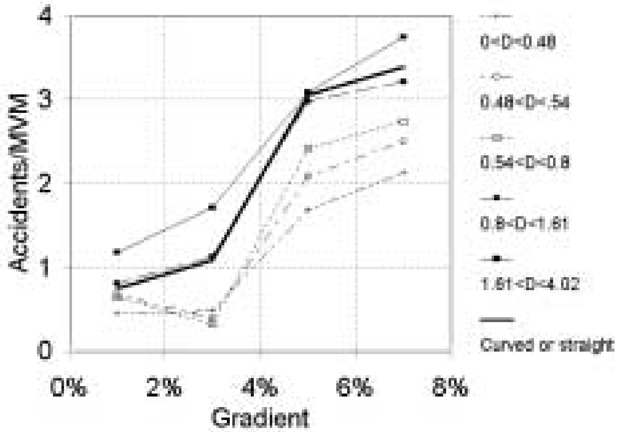

Figure 5

Note that this study does not represent upgrades and downgrades separately. It seems clear from Figure 5, that on curves, as on tangents, the larger the gradient the higher the accident rate . Also, for any given gradient, the larger the degree of curve, the higher the accident rate. Were the curves parallel one would conclude that a unit increase in gradient adds the same amount to the accident rate, irrespective of the degree of curve D. Except for the two low points at the averag e gradient of 3%, the data in Figure 5 are not inconsistent with this hypothesis. Were the curves fanning out uniformly, one might conclude that a unit increase in the gradient multiplies the accident rate by the same proportion irrespective of the degree of curve. This too is a tenable hypothesis in view of the data in Figure 5. Thus, the data in figure 5 do not give a clear indication of some special interaction between gradient and curvature. They only show that accidents increase with degree of curve and accidents in crease with grade and the two effects are merely superimposed without being reinforced.

1964. Next comes the study of California freeways by Vostrez and Lundy (1964). The results are shown in Table 7.

Table 7. Accidents/MVM for California Freeway Sections

	4%-5% trucks	11% trucks
Straight, Level	0.84	1.12
Straight, Up-grade	0.71	1.51
Straight, Down-grade	1.07	1.29
Curved, Level	0.86	1.83
Curved, Up-grade	1.78	1.69
Curved, Down-grade	2.10	1.88

On straight road sections the % trucks seemed to have a clear effect. This clarity vanishes when curved sections are considered. Rather than seeking ad-hoc explications why trucks matter on straight upgrades but not on curved ones, one is well advised to ascribe this anomaly to the aforementioned inadequacies of univariate tables - there are other important variables that may explain these numbers and these were not accounted for.

1966. The results by Hillier and Wardrop (1966) for straight sections of the London-Birmingham Motorway were presented earlier. However, as shown in figure 6, for curved sections the results were different. The data here are for sections with three lanes in each direction and asphalt pavement. While on downgrade sections the presence of a curve does not seem to matter, there is an indication that on upgrade sections where a

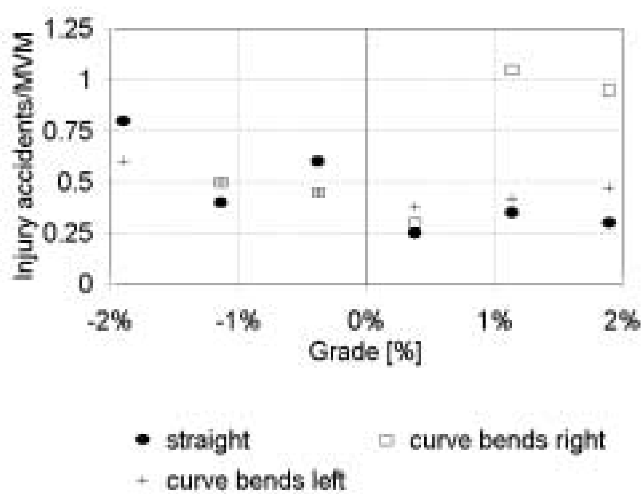

Figure 6

curve bends right[2], the accident rate is unusually high. Since the reference does not give the precision of the data points in figure 6, it is difficult to judge how reliable this finding is.

1968. The comparison of straight and curved road sections based on data from the Chicago Expressway system (Crosstown Associates, 1968) is given in Table 8.

Table 8

	Curved Roadway Accidents/MVM	Straight Roadways Accidents/MVM
Level	2.29	1.10
Upgrades	2.25	1.87
Downgrades	2.56	2.49

It appears, as is usual, that curvature affects safety and grade affects safety. However, there is no intimation here that the combination of grade and curvature presents an unusual hazard.

1978. The influence of the combined grade and horizontal curvature on accidents was studied by Dunlap et al. (1978). They conclude that : "The analysis of the turnpike accident data shows no evidence of effects that can be attributed to grades and curves in combination. p.4".

1987. Zador et al. collected data on curvature a grade at sites of fatal single-vehicle rollover crashes in New Mexico and Georgia. Two sets of 'comparison sites' were used. In one set were road sections located one mile upstream of the crash site; in the other were 300 sites selected at random in each State. The authors find that sites with sharp left hand curves in combination with steep downgrades are highly over-represented amongst sites with fatal roll-over crashes.

1988. Matthews and Barnes assembled a database including all curves on the 2000 km long state highway in New Zealand. Among other variables, the curve radii and road gradients were recorded.

---

[2] In the original paper, he finding is for 'left hand bends'. Since in the UK the driving is on the left side of the road, I have converted the finding to conditions where driving is on the right side of the road.

Accident counts for 5 years were used. The results (based on Table II, p. 116) are shown in Figure 7.

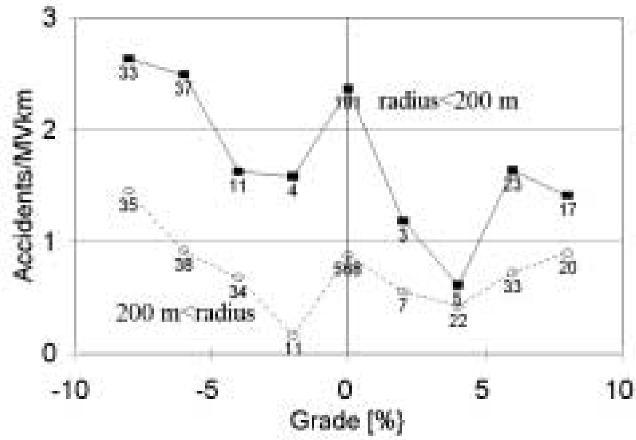

Figure 7

The numbers below the points give the count of accidents from which the accident rate has been calculated. This should allow the reader to assess the precision of each point. Several observations follow. First, it is clear that the point at 0% grade (actually ± 1%) does not belong to the general trend. This is most likely due to the fact that this data point lumps sag and crest curv e sections. As noted earlier, accident rates at sags and crests are very different and should not be considered similar. Only nearly level road sections that are neither crests nor sags should be used in this kind of plot. Second, it is also apparent that the accident rate increases with the gradient on down-grades and that the increase is quite steep. A 10% increase in accidents for every 1% steepening of the downgrade is indicated. It is not very clear whether the accident rate increases with the upgrade slope. Third, it is clear that larger radius curves have a smaller accident rate than short radius curves. This, however, is nothing new. Without further analysis one can not say whether there is something to the combination of curvature and grade.

4.3. Summary.

The grade (gradient, slope) of a road is likely to affect safety by various mechanisms. Vehicles tend to slow down going up-grade and speed up going down the grade. Speed is known to affect accident severity. The more severe an accident, the more likely it is to be reported to the police and thus to enter the official statistics. It follows that the number of reported accidents depends on speed and thereby on grade. In addition, it is possible that the frequency of accident occurrence increases when the diversity of speed increases. Since road grade affects the diversity of speeds, it may affect accident frequency. Also, grade affects braking distance. This too may have an effect on accident frequency and severity. Grade also influences the rate at which water drains from the pavement surface and thus may have an effect on safety.

The existence of several diverse mechanisms working in consort means that the final outcome (accidents) may be a complex superposition of many processes. For some processes (e.g., drainage) the distinction between up-grade and down-grade is immaterial. For other processes (e.g., the change in average speed) the distinction between up and down-grade is crucial. Nor can one hope to adequately understand, describe, or predict the safety effect of a grade without considering the length over which the grade prevails. While speed may be unaffected by a short downgrade it may be significantly affected by a longer one. Yet, there may be no distinction in this respect between 1 km and a 10 km downgrade. Furthermore, while the grade on a crest or in a sag may be similar, the speed distribution at the two locations is likely to be very different. In short, the safety effect of grade can be understood only in the context of the road profile and its influence on the speed distribution profile.

At present our understanding of how grade affects safety is only rudimentary. Even so, good practice is to use at any time the best available knowledge. With this purpose in mind, the following observations are offered.

- All studies using data from divided roads concluded that accident frequency increases with gradient on downgrades. Some studies concluded that the same is true for upgrades, while other studies concluded to the contrary. Estimates of the joint effect (up-grade & downgrade) vary. Use of AMF (+1% increase in grade)=1.08 has been recommended for two lane roads mainly in view of results by Miaou. Thus, increasing the gradient from, say, 2.0% to 2.5% is expected to increase accident frequency by a multiplication factor of $1.08^{0.5}=1.04$. An increase from 2.0 to 3.7% is likely to increase the accident frequency by a factor $1.08^{1.7}=1.14$.

- I tend to disregard the results of the one study of two lane roads (Raff, 1953) that did not find any effect of grade on safety for three reasons. First, the pooling of data from different states has been regarded as a handicap by the author and resulted in erratic findings. Second, Raff did not find a grade effect even on divided roads. Third, there is no logical reasons for which the adverse effect of grade should be confined to divided roads. On the contrary, one may expect that overtaking on upgrades of two lane roads be an additional hazard.

- Researchers looked for deterioration in safety on crests of vertical curves and found none. This may be an indication that vertical curves on existing highway are well built so that no data was available for very substandard crest curves. In any case, collisions with fixed objects on the pavement are vanishingly few.

- The literature abounds with hints that there is an important interaction between grade and curvature. What seems to be true is that downgrades cause an increase in accidents and large horizontal curvature also causes such an increase. When a sharp curve follows a downgrade, the two effects are added. I did not find any convincing evidence of an important effect over and above this superposition. There is, however, an indicat ion that when a right curve follows an upgrade there are unusually many accidents, perhaps due to sight distance limitations. There is also an indication that when a left curve follows a downgrade, unusually many vehicles run-off-the road.

References.

Bitzel, I.F., (1956), Effect of motorway design on accidents in Germany. *Highways and Bridges and Engineering Works*, Vol.24, No. 1161, p.1-4.

Bowman, B.H., (1958). Ohio turnpike accident study. *Traffic Engineering*, Vol. 28, No. 9, pp. 23-26.

Cirillo, J.A., Dietz, S.K., Beatty, R.L., (1969) Analysis and modelling of relationshipsbetween accidents and the geometric and traffic characteristics of the interstate system. Bureau of Public Roads. 95 p.

Crosstown Associates, (1968), Correlation of accident rates and highway geometric features. Draft.

Dunlap, D.F., Fancher, P.S., Scott, R.E., MacAdam, C.C. and Segel, L, (1978), Influence of combined highway grade and horizontal alignment on skidding. National Cooperative Highway Research Program Report 194, Transportation Research Board, Washington, D.C.

Hedman, K.O., (1990), Road design and safety. *VTI Rapport 351A*, Swedish Road and Traffic Research Institute, Linköping, Sweden.

Hillier, J.A. and Wardrop, J.G., Effect of gradient and curvature on accidents on London-Birmingham motorway. *Tra ffic Engineering & Control*. Pp. 617-621.

Hoban, C.J., (1988), Selecting appropriate geometric standards for rural road improvements. *Compendium of Technical Papers*, 58th Annual Meeting, Institute of transportation Engineers, Washington, D.C., pp.332-340.

Leisch, J.E. & Associates (1971), Traffic control and roadway elements - their relationship to highway safety/revised. Chapter 12, Alinement. Highway Users Federation for Safety and Mobility.

Li, J., Abdelwahad, W., and Brown, G., Joint effect of access and geometry on two-lane rural highway safety in British Columbia. *Canadian Journal of Civil Engineering,* XXI (vi) pp. 1012-1 024, 1994.

Matthews, L.R., and Barnes, J.W., (1988). Relation between road environment and curve accidents. *Proceedings, 14th ARRB Conference,* Part 4, pp. 105-120.

Miaou, S-P., Development of adjustment factors for single vehicle run-off-the-road accident rates by horizontal curvature and grade. Oak Ridge National Laboratory. Draft August 3, 1995.

Mullins, B.F.K., and Keese, C.J. (1961).Freeway traffic accident analysis and safety study. Highway Research Board Bulletin 291, pp.26-78.

Organisation for Economic Co-operation and Development (1976), Hazardous Road Locations: Identification and Countermeasures. Paris. p. 108.

Raff, M.S., (1953). Interstate highway-accident study. Highway Research Board Bulletin 74, Trafic Accident Studies Washington D.C., pp. 18-45.

Roy Jorgensen Associates Inc. (1978). Cost and safety effectiveness of highway design elements. National Cooperative Highway Research program Report 197, Transportation Research Board, Washington, D.C.

Synthesis of safety research related to traffic control and roadway elements. Vol 1.(1982) Offices of Research and development and Technology, Federal Highway Administration, FHWA-TS-82-232.

Vostrez, J. and Lundy, R.A., (1964) Comparative freeway study A-IV-1. State of California, Division of Highways. 116

Zador, P., Stein, H., Hall, J., and Wright, P., Relationship between vertical and horizontal roadway alignments and the incidence of fatal rollover crashes in New Mexico and Georgia. *Transportation Research Record 1111.* Transportation Research Boards, Washington, D.C., pp. 27-41.

Zegeer, C.V., Twomey, J.M., Heckman, M.L., and Hayward, J.C., (1992).Safety effectiveness of highway design features. Volume II: Alignment. Publication No. FHWA-RD-91-045. U.S. DOT, Federal Highway Administration.

4. Grade.

Year/ Ref.	Method	Size	Accident modification functions	Acc. type	Conf. rating	Conditions	Comments
Raff 1953	C/S Uni and bi-variate	15 states	"on tangent highway sections there does not appear to be any relation between grade and accident rates.	all	0.5	Sample from 15 states	Pooled data does not allow any inferences
Bitzel, 1956	C/S Uni-variate	German Freeways	0%-2% 2%-4% 4%-6% 6%-8% 1.00 1.45 4.08 4.52	all	0.5		Out of line with other results. Most likely due to confounding with other variables
Mullins & Keese, 1961	C/S collision diagrams	54 miles of freeway , 10,000 accidents	Accidents/MVM seem to vary as speed varies: diminish from sag towards crest and then increase towards sag.	All	1.5	Texas cities	
Hillier & Wardrop, 1966	C/S along one road	55 miles of motor-way	If curve B then 0% 0.5% 1% 1.5% 2.0% 1.00 1.02 1.09 1.19 1.39 $AMF=(1-0.068\times\%grade^2)^{-1}$	Injury	2	London to Birmingham Straight sections	Differentiates between upgrade and downgrade lanes
Crosstown Associates 1968	C/S Along freeway	Chicago Expressway	Accidents/MVM Upgrade 1.87 +/- 0.5% 1.10 Downgrade 2.49	All	1		

Year/ Ref.	Method	Size	Accident modification functions	Acc. type	Conf. rating	Conditions	Comments
Vostrez & Lundy, 1964	C/S accident rate		Accidents/MVM 4-5% trucks 11% trucks Level 0.84 1.12 Up grade 0.71 1.51 Down grade 1.07 1.29	All	1.5	Straight freeway sections in California	When proportion of truck is large, upgrade accident rate grows
Cirillo 1969	C/S Multivariate regression	Interstate system	Grade was significant in one of two models. Annual accidents increase by 0.01 for each 1000 ADT for each 1% of grade	all	1		
Dunlap et al., 1978	Ohio and Pennsylvania turnpikes		Accident rate increases with downrade and remains constant with upgrade. AMF is about 1.10/%grade	all	1.5		
Hedman, 1990	C/S	Swedish roads.	Study by Brude at al. AMF = 1.044/%grade	?	?		
Li et al. 1994	C/S Multi-variate	163 sections 560 km	$AMF(\Delta_{\%grade}) \cong 1+0.136\ \Delta_{\%grade}/\sqrt{Accid/km}$ Ex.: Increase of grade from2% to 3% when 0.6 accid/km, AMF=1+0.136/.0=1.23	Fat+InjS EVD*	2		Model equation includes ADT in additive form. This is illogical.

Miaou 1995	C/S Multi-variate	11539 road sections 1985-92 Utah 6680 SV.	0.919±0.009 for 1%	All roads	Single veh.. off-the road	2	mainly rural two-lane but including HPMS 2,6,7,8,9 Non-intersection accident	Lane width is not included in variables. Section length is variable with negative coefficient
			0.960±0.015 for 1%	Speed limit=55 mph				
			0.892±0.013 for 1%	Speed limit<55 mph				