TITLE: The Effect of Combining Geometric Minima - Findings from Case Studies

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ABSTRACT

Road authorities are regularly faced with constrained situations and funding limitations. In Australia, the application of Context Sensitive Design in complex situations has sometimes led to geometric minima being adopted. Geometric minima are the less conservative geometric values used in road design, and include design exceptions.

Although several international road authorities have developed guidelines that work towards achieving flexibility in design, little guidance is usually given on the potential safety implications of applying more than one geometric minima at a particular location. One of the reasons that so little guidance is provided is that the quantitative effect of combining geometric minima on accident rates is largely unknown. It is quite difficult and time consuming to identify the relationships between individual geometric parameters and accident rates, without introducing various combinations of geometric parameters.

The case studies discussed in this paper were the result of undertaking detailed geometric investigations at some of the worst accident sites in Queensland, Australia. The studies showed that all of the sites assessed had substantial combinations of geometric minima that included several design exceptions.

Based on the findings of the case studies, this paper provides recommendations of what combinations of geometric minima should be avoided.

INTRODUCTION
As part of standard road design practice worldwide, authorities continue to explore alternatives outside of the design domain in order to address site specific constraints and features. In particularly complex situations, it may be necessary to combine geometric minima. Geometric minima are the less conservative values used in road design, and include design exceptions.

When making a decision to adopt a road design solution that includes combinations of geometric minima, consideration of safety should be central to the basis of the risk evaluation. To date, limited research has been conducted to adequately assess the safety effects of combining geometric minima.

The purpose of this paper is to provide to road design practitioners evidence to date of the need to avoid combining geometric minima. This is undertaken by describing the findings of case studies where detailed geometric assessments were undertaken at some of the worst accident sites in Queensland, Australia. The geometric minima found at these sites and their potential effect on the recorded accidents is discussed. This paper is not intended for academic debate, as the findings of the case studies only provide anecdotal evidence of the effects of combining geometric minima. Much more work is required in this area before robust relationships can be established.

DEFINITIONS
The following terms used in this paper are defined in Part 2 of the recently published Austroads Guide to Road Design Series (*1*). These are the primary guidelines for road design throughout Australia and New Zealand.

The Design Domain
The Geometric Design Guide for Canadian Roads (*2*) and Robinson and Smith (*3*) explain Design Domain as a range of values from which a designer selects design criteria. This range of values is shown on the x-axis of the conceptual diagram in Figure 1. Values chosen from the lower end of the domain may be less safe or less efficient, but are usually less expensive than those in the upper regions of the domain. Values towards the upper end of the domain are more likely to be chosen for the more important, higher volume roads than for the less important, lower volume roads. For some parameters, the upper bound will be infinity (eg horizontal curve radius). For other parameters, there will be a practical upper bound (eg median width).

The shape of the relationship in Figure 1 changes for different parameters. For example, the smallest values of some parameters may be associated with the highest cost and benefits with the largest values providing the least cost and benefits (eg longitudinal friction factor). For other parameters, the shape of the relationship for the benefit and the cost may vary. For the parameter ‘lane width’, the benefit relationship may form a peak whilst the cost relationship may be the same as that shown in Figure 1.

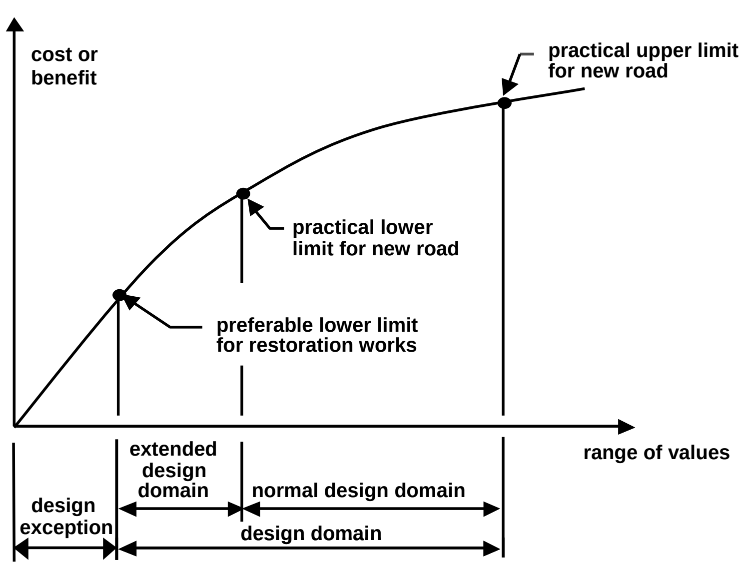

FIGURE 1 Conceptual Diagram of the Design Domain

As shown in Figure 1, the Design Domain is represented by the range of values within the Normal Design Domain and the Extended Design Domain. The Normal Design Domain defines the limits given in road design guidelines of the values of parameters for new roads. In Australia, the Extended Design Domain is a range of values below the lower bound of the normal design domain as listed in road design guidelines. The concept of Extended Design Domain was introduced at the 3rd International Symposium on Highway Geometric Design in 2005 (*4*).

Design Exceptions

Design exceptions are the range of values outside of the design domain, as shown in Figure 1. Design exceptions therefore represent the design values lower than the minimum limits or greater than the maximum limits of geometric parameters listed in road design guides. For numerous parameters though, design exceptions only exist at one end of the design domain where a minimum (or maximum) value has been defined.

Design exceptions have always been part of geometric road design and normally arise in constrained situations where major engineering, environmental and land resumption limitations exist. Alternative terms for design exceptions include Design Variations, Departures from Standards and Design Non-conformances.

Geometric Minima

Geometric Minima are any of the following:

- The less conservative values with the Design Domain, ie a relatively small range of values abutting the least conservative end/s of the Design Domain;
- All values outside of the Design Domain, i.e. Design Exceptions; and
- Where a Design Domain is not specified for a particular parameter, the less conservative values typically used, based on the authors' knowledge of the road network in Queensland, Australia.

Where an increased value of a design parameter produces a higher benefit, geometric minima are the smallest values of the design parameter. Conversely, where an increased value of a design parameter produces a lower benefit, geometric minima are the largest values of the design parameter. Sometimes, geometric minima can be the smallest and largest values (where a lower and upper bound is specified for a design parameter).

SAFETY IMPLICATIONS OF COMBINING GEOMETRIC MINIMA

Understanding the relationship of safety to the road design criteria, the design process, and a desired or expected outcome of the design is important (*5)*.

A review of the safety in geometric standards was conducted by Hauer (*6*) in 2000. This review indicated that design guidelines have an inherent safety level and that little was known about the impacts of using flexibility in applying design guidelines in road design.

Little research has been documented into investigating the safety implications of combined geometric minima. In research studies such as Stamatiadis et al. (*7*), focus has only been placed on evaluating possible safety consequences of design exceptions in an overall design before and after construction. Limited accident data was available for sites where multiple design exceptions had been designed and constructed.

The Federal Highway Administration (FHWA) (*5*) acknowledges the potential for increased risk with the presence of two or more design exceptions at a particular location interacting with each other. The nature of the geometric minima determines whether there is an interaction or cumulative effect that might increase risk. Some combinations of geometric minima may function independently and have no effect on each other. An example given by FHWA is that the radius of a horizontal curve is just one variable that affects the risk of lane-departure crashes on a high-speed roadway. Other contributing factors that can influence this crash risk may include the amount of superelevation, the surface friction of the pavement, and the horizontal and vertical alignments preceding the curve.

A mathematical approach was proposed by Pellegrino (*8*) that evaluates the safety level, in terms of risk when considering one or more geometric minima for a road design solution. The methodology is based on the Interval Analysis technique, and the safety levels are derived from analytical calculations when comparing a number of design solutions. However, this methodology has not yet been validated.

Similarly, Malyshkina et al. (9) conducted an empirical assessment of the impact of highway design exceptions on the frequency and severity of vehicle accidents in Indiana. The modelling results indicated that the approved design exceptions at selected roadway sites did not have a statistically significant effect on the average frequency or severity of accidents. However, it was reported that the process used to determine the frequency of accidents varied between the roadway sites with and without design exceptions.

In 2006, ARRB Group (*10*) identified a need to investigate the combined effects of horizontal and vertical alignment on crash rates and risk following a review of Australian and International research on the link between geometric design elements and safety. More recently, ARRB Group (*11*) has conducted further research on the effectiveness of various treatments in terms of crash reduction in Australia and New Zealand. Similarly, with combinations of geometric minima, it was found difficult to predict the cumulative effect that multiple countermeasures may have. Difficulty was also encountered in validating the calculated combined benefits of treatments with New Zealand crash monitoring data.

The driver's perception of the road alignment and environment plays an important factor in design when evaluating the safety risk at a given road section. With potential to assist road designers, a software system (*12*) has been developed by Universitaet Karlsruhe to evaluate the spatial road alignment quantitatively and to optimise it from the user's viewpoint. The software tool allows the designer to detect insufficiencies in visibility within the electronic road design model.

In lieu of the ability to accurately calculate the safety risk of combined geometric minima at an existing site or proposed road design, road authorities are providing more guidance on the application of suitable mitigating measures into the designs to counteract the potential risks.

Models Linking Geometric Parameters to Accident Rates

A number of well established methods and statistical models are available or are still under development for analysing a given road design for its substantive safety [Hauer (*6*)]. An example of the models and resources available worldwide include:

- The Road Safety Risk Manager (*13*) – developed by ARRB Transport Research Ltd for use by State and Local Government authorities throughout Australasia.
- The Interactive Highway Safety Design Model (*14*) – is a software tool developed by FHWA that can assist designers with evaluating design alternatives for two-lane rural highways.
- The Highway Safety Manual (*15*) is a resource being developed by the Transportation Research Board of the National Academies.

As far as the authors are aware, the data on which such models are built have not specifically been based on studies analysing the effect of multiple geometric minima on accident rates. If this is true, these models will not be very accurate in predicting the effect of combining multiple geometric minima. Such geometry forms outliers in the data. Using the results from these models may under predict the effect. It is possible that accident rates may increase exponentially as more geometric minima are combined at the one location.

Unfortunately, identifying the effect of combining geometric minima on accident rates would be a very difficult task. Relationships between individual parameters and accident rates still have not been established for many parameters. Identifying relationships between combinations of various geometric minima and accident rates would be much more difficult, as has been noted in research findings mentioned earlier in this paper.

Road Design Accident Risk Model

Historically, human error has been identified as the major contributing factor in a high proportion of accidents. Research indicates that human error contributes to as much as 75% of all roadway crashes (*16*, *17*).

Salmon et al (*18*) reports on a number of approaches to modelling road user error including the 'Systems Perspective' model as proposed by Reason (*19*), which is the most influential and widely recognised of the error models. The model is more widely known as the Swiss Cheese Model (due to its resemblance to a series of layers of Swiss cheese) and considers the interaction between latent conditions and errors and their contribution to organisational accidents. According to the model, systems comprise various organisational levels that contribute to the production of system outputs (e.g. decision makers, line management, productive activities and defences).

Salmon et al (*18*) proposes that the Swiss cheese model can be applied in road transport and for this purpose produced a road transport systems perspective model. In the model, accidents are the result of a systems failure, rather than just the road users fault. It considers the combined role of latent or error causing conditions (e.g. poor policy and management decisions, poor staff training, poor road designs etc) as well as driver errors in accident causation.

Each of the levels (each piece of 'cheese') has various defences in place that are designed to prevent accidents and safety compromising incidents. Holes or weaknesses in the defences created by latent conditions and errors create 'windows of opportunity' for accident trajectories to breach the defences and cause an accident. Accidents occur when the holes line up in a way that allows the accident trajectory to breach each of the different defences that are in place. On most occasions, accident trajectories are halted by defences at the various levels in the system. However, on rare occasions, the holes or windows of opportunity line up to allow the accident trajectory to breach all of the defences, culminating in an accident or safety compromising incident.

Using the concept of the Swiss Cheese Model, the authors have represented various inputs/conditions including driver behaviour and road geometry that contribute to accident risk and severity. This representation is depicted in Figure 2. The inputs/conditions shown in Figure 2 are not intended to be a comprehensive list of all the possible contributing factors with respect to accident risk and severity.

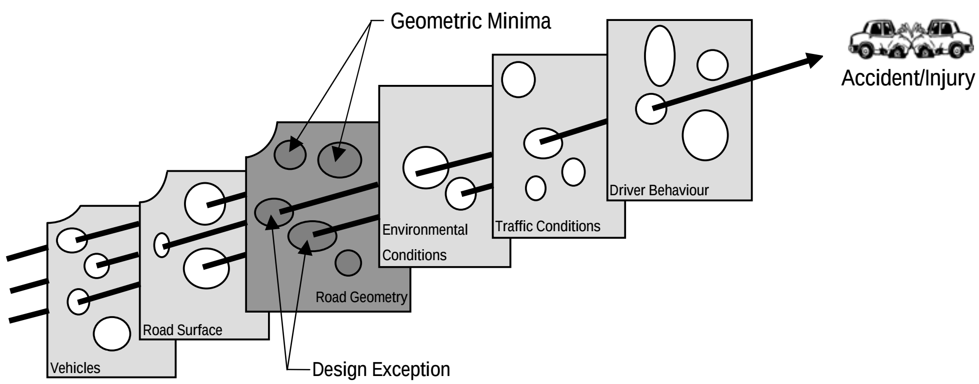

FIGURE 2 Road design accident risk model

Less conservative values of road geometric parameters can be compared to larger holes in the road geometry 'slice'. For example, a tight horizontal curve would represent a larger hole than a generous radius horizontal curve. A steep high fill slope would represent a larger hole than a flat, low fill slope.

The larger the holes and the greater the number of holes in the road geometry slice leads to less chance of this slice being able to defend an accident trajectory. Combination of geometric minima may be seen as several large holes in the slice. That will lead to much less area being available as a defence. In fact, the level of defence may rapidly diminish as the number of geometric minima is increased.

CASE STUDIES ASSESSING COMBINATIONS OF GEOMETRIC MINIMA

Detailed geometric investigations have been undertaken at some of the worst accident sites in Queensland, Australia. All of the sites recorded far more accidents than would normally be expected for the type of road/intersection, the speed limit and the traffic volume. Some of the geometric assessments were undertaken as part of accident investigations at sites with media and political attention. All of the sites assessed were found to comprise substantial combinations of geometric minima. The case studies in this section discuss the findings of some of these investigations.

The geometric minima and design exceptions identified in these case studies were determined by comparing the on-site values for a number of geometric parameters with the minimum values adopted in the **current** design guidelines (*20, 21*). The on-site values were not necessarily the geometric values selected in the design of the projects. Further, the on-site values were not necessarily minima or design exceptions at the time when the projects were designed and constructed.

In some cases, it was determined that factors other than geometry were also contributing to the accidents. Where this occurred, it has been discussed in the case studies.

Accident data used in the investigation was extracted from the Queensland Department of Transport and Main Roads' Road Crash 2 database. In some of the case studies, further interrogation of the accident data was required to ascertain a more accurate summary of the number and nature of the accidents reported at each location.

Case Study A – Overtaking Lanes on Bruce Highway at Federal

This case study recorded 25 crashes in 3 years up to the year 2005, after the installation of stone mastic asphalt to a 1.3km (0.813 mile) section of rural two-lane road on the Bruce Highway at Federal (located approximately 137 km (86 mile) north of Brisbane, Queensland). The section comprised two horizontal curves with an intervening straight. Overtaking lanes were present in each direction. The posted speed limit was 100km/h (62.5 mile/h) and the two-way traffic volume was 14,000 veh/d. At least 22 of the reported accidents involved vehicles losing control on the horizontal curves. Of these, 20 were casualty accidents.

Using data on the effect of horizontal curve radius from Turner et al (*22*), an average of 3.5 casualty accidents could be expected on a roadway with this horizontal geometry, traffic volume and time period. This figure assumes no influence from the overtaking lanes. The actual number of casualty crashes is 5.7 times higher than this.

Accidents at three adjacent overtaking lane sections on this roadway were analysed. The lengths of the overtaking lanes varied between 1.3 and 2.0 km (0.813 – 1.25 miles). Two of the adjacent overtaking lanes did not comprise geometric minima. The third overtaking lane did comprise geometric minima (including design exceptions), however, they were fewer in number than for the Federal site. These three overtaking lanes recorded an average of 5.7 accidents per ten million vehicles. The rate at the Federal site is 16.3 accidents per 10 million vehicles, which is 2.9 times higher than that at the adjacent overtaking lanes.

These basic accident statistics show that the number of accidents is considerably higher than what would normally be expected at such at site.

Several geometric minima were found at the Federal site as given in Table 1. The northbound overtaking lane was found to comprise a total of 7 geometric minima including 4 design exceptions. For the southbound overtaking lane, there were 5 geometric minima including 1 design exception.

This section of the Bruce Highway is quite busy for a two-lane, two-way highway. Drivers overtaking usually do so at quite high speeds (can typically be up to around 120km/h), due to the short length of the overtaking lanes and the number of vehicles on the road. The high speed on the relatively 'tight' horizontal curves requires the surfacing to produce a high degree of side friction. This high side friction demand in the area of early runoff of the superelevation on the R600m horizontal curve led to premature polishing of the road surface. On a wet road (when many of the single vehicle accidents occurred), it is difficult for the pavement to produce the required degree of side friction, especially considering the water flow depth through the superelevation transition.

Reflecting on the 'Swiss Cheese' model in Figure 3, this combination of geometric minima produces a large number of holes in the road geometry element. Consider then a driver of a motor vehicle with bald to near bald tyres in poor light conditions travelling at a speed too high for the conditions (creating large holes in the vehicles, environmental conditions and driver behaviour slices, respectively) further disabling the barriers/controls put in place to reduce risk. It is not difficult to then understand how each level of defence can be breached, resulting in a single vehicle accidents occurring at this location.

TABLE 1 Geometric Minima for Case Study A

Direction	**Design Parameter**	**Bound of the Design Domain in Current Guidelines [(1)]**	**On-Site Value**	**Design Exception (To current Guidelines)**
Northbound	Horizontal curve radii	R530m (min) for 6% superelevation	600m with 8% superelevation 560m with 5% superelevation	No
	Crest vertical curve	K83.6 (min) for 2s reaction time and coefficient of deceleration of 0.36	K25 crest vertical curve on tangent near end of R600m horizontal curve	Yes
	Merge sight distance to the end of the overtaking lane	183m (min)	125m, limited by crest vertical curve	Yes
	Location of superelevation runoff	50% of the superelevation runoff on the tangent	95% of superelevation runoff on the R600m horizontal curve.	Yes
	Run-out area at the end of the overtaking lane	A 2m wide shoulder over the full length of the merge taper and extended for a further 30m	No run out area provided	Yes
	Overtaking lane length	620m (min)	800m	No
	Water depth for a rainfall intensity of 50mm/hr	4mm (max)	3.9mm on the R600m horizontal curve.	No
Southbound	Run-out area at the end of the overtaking lane	A 2m wide shoulder over the full length of the merge taper and extended for a further 30m	No run out area provided	Yes
	Overtaking lane length	620m (min)	950m	No
	Location of start taper for overtaking lane	Intersections along or in close proximity to overtaking lanes should be avoided	Commences immediately after an intersection	No
	Location of merge taper at end of overtaking lane	Termination of the merge on a left-hand curve should be avoided	Southbound merge taper located on left hand curve	No
	Water depth for a rainfall intensity of 50mm/hr	4mm (max)	3.9mm on the R600m horizontal curve.	No

1. *Geometric values based on a design speed of 110 km/h (68.9 mile/h) determined in accordance with the operating speed model.*
2. *For Crest Vertical Curves, K is defined as Length per 1% change in grade.*

FIGURE 3 Bruce Highway at Federal: End of northbound overtaking lane

Case Study Number B – Logan Motorway On-ramp

This case study investigates the westbound on-ramp exiting from the Logan Motorway and merging with the Ipswich Motorway (located on the western boundary of Brisbane City), prior to 2007.

The speed limit on the Ipswich Motorway has varied between 90 and 100km/h (56.3 and 62.5 mile/h respectively) in past years. The traffic volume on the westbound carriageway of the Ipswich Motorway was 28,400veh/d with 9,400veh/d using the Logan Motorway on-ramp.

Based on the accident data available for the 10 year period up to year 2006, 30 accidents resulted from problems with traffic merging. Furthermore, there is anecdotal evidence that many more accidents occurred at this location in addition to those reported.

Dividing the number of reported accidents by the cross product of the on-ramp traffic volume and the through road traffic volume gives a rate of 8.4 accidents per 10^{15} veh^2. The traffic volumes used in this calculation are the total number of vehicles using the roadways within the 10 year period. An analysis of three other on-ramps on the Ipswich Motorway with similar traffic volumes gave an average rate of 2.7 accidents per 10^{15} veh^2. The accident rate at the Logan Motorway on-ramp is 3.1 times the average rate of accidents of the other on-ramps, indicating that the number of accidents is considerably higher than what would normally be expected at such at site. In addition, the other on-ramps along the Ipswich Motorway also contained geometric minima (and design exceptions), although significantly fewer in number than for the Logan Motorway on-ramp.

Figure 4 depicts vehicles braking on the approach to the merge area at the system interchange in typical traffic conditions along this section of road. The on-ramp and adjacent through road was found to comprise 7 geometric minima, all design exceptions, as shown in Table 2.

FIGURE 4 Logan Motorway On-ramp

TABLE 2 Geometric Minima for Case Study B

Parameter	**Bound of the Design Domain in Current Guidelines (1)**	**On-site Value**	**Design Exception (To Current Guidelines)**
Sight distance to nose along the on-ramp	100m (min)	65m, limited by a K12.5 crest vertical curve	Yes
Sight distance to nose along the Ipswich Motorway	102m (min) for an operating speed of 92km/h (on the R300m horizontal curves)	93m, limited by a K29.3 crest vertical curve	Yes
Horizontal curve radii on the Ipswich Motorway at merge	R415m (min) for 3% superelevation	R300m	Yes
Acceleration distance	220m (min) for acceleration from 60km/h to 90km/h	140m	Yes
Length of parallel entry lane	102m (min) for an operating speed of 92km/h (on the R300m horizontal curves)	30m	Yes
Require a run-out are at the end of the merge	A 2m wide shoulder over the full length of the merge taper & extended for a further 30m	No run area provided	Yes
Merge on right side of the major road	Not allowed	Existing right-hand merge onto High-speed Major Roads	Yes

1. *Geometric values based on 100 km/h (62.5 mile/h) desired driver speed for the Ipswich Motorway and Logan Motorway ramp design speed of 90km/h (56.3 mile/h)*
2. *For Crest Vertical Curves, K is defined as Length per 1% change in grade.*

The combination of minima at this location results in drivers on the Logan motorway on-ramp having insufficient distance to accelerate up to the Ipswich Motorway speed; limited visibility to the nose in order to detect the presence of the merge; followed by a more difficult right to left merge (equivalent to left to right merge for most of Europe and the USA); with limited parallel lane and no run-out area. All this meant that drivers on the on-ramp had very little time to detect the presence of the merge, observe vehicles on the major road on the left side of the vehicle, choose a gap and then merge, all in a very short distance at a speed much lower than that of the through road vehicles.

This often caused drivers on the on-ramp to stop on the ramp, increasing the chances of a rear-end accident with other drivers on the on-ramp. It also caused some drivers on the major road to brake heavily resulting in the potential for rear-end accidents on the major road and caused other major road drivers to change lanes quickly increasing the potential for sideswipe accidents with another major road vehicle.

Case Study C – Horizontal Curve on Wivenhoe–Somerset Road

This case study involves a radius 150m (492 feet) horizontal curve on the Wivenhoe – Somerset Road about 80km (50 mile) west of Brisbane. This road is in a rural environment with a 100km/h (62.5 mile/h) posted speed limit and the two-way traffic volume at this location was approximately 500veh/d. The road is a motorcycle route on weekends.

After a thorough analysis of the crash data in the Queensland Department of Transport and Main Roads' Road Crash 2 database, it was found that at least 14 single vehicle out-of-control accidents occurred on the curve in the 10 years up to mid 2006. Of these, 13 were casualty accidents. The following compare the number of reported accidents over the 10 year period with the number of accidents that could normally be expected at such a site (a radius 150m horizontal curve on a rural road) for the given traffic volumes, the length of curve and the time period:

- Using data on the effect of horizontal curve radius from Turner et al (*22*), an average of 0.24 casualty accidents could be expected. The actual number of casualty accidents (of 13) is 54 times higher than this. If all of the motorcycle crashes were removed from the sample, the actual number of accidents would still be 17 times higher than expected.
- Using the regression equation for single vehicle out-of-control accidents on the through road from Arndt (*23*), an average of 0.16 accidents could be expected. The actual number of accidents (of 14) is 88 times higher than this. If all of the motorcycle crashes were removed from the sample, the actual number of accidents would still be 31 times higher than expected.

The above figures indicate that the actual accident rate is much higher than what would normally be expected on a radius 150m horizontal curve in a rural area.

In the northbound direction, 5 geometric minima including 3 design exceptions were identified, and in the southbound direction, 7 geometric minima including 3 design exceptions were found (see Table 3).

TABLE 3 Geometric Minima for Case Study C

Direction	Parameter	Bound of the Design Domain in Current Guidelines [(1)]	On-site Value	Design Exception (To Current Guidelines)
Northbound	Degree of side friction	0.25 (max)	0.32	Yes
	Decrease in speed between geometric elements	15 km/hr (max)	14 km/hr	No
	Angle of horizontal curve	No value given within the design domain	124 degrees	No
	Shoulder Width	1.5m (min)	1.4m	Yes
	Location of superelevation runoff	On transition curve	On circular curve before transition curve	Yes
Southbound	Degree of side friction	0.25 (max)	0.29	Yes
	Decrease in speed between geometric elements	15 km/hr (max)	12 km/hr	No
	Angle of horizontal curve	No value given within the design domain	124 degrees	No
	Length of transition curve	46m for 5% superelevation, 92m for 10% superelevation	80m with 5% superelevation	Yes
	Coordination of R150m horizontal curve and K150 vertical crest curve	Horizontal curve to precede vertical curve or be at the same location	Vertical curve preceded the horizontal curve	No – only an advisory criterion
	Sight distance on the inside of the horizontal curve	92m for cars (min) 100m for trucks (min)	Down to 72m at cut face	Yes
	Superelevation at curve-spiral point on opposing lane	3% (min), 10%+ required by Point Mass Formula for design speed.	0%	No – not generally a design criterion

1. Geometric values based on a design speed of 82 km/hr determined in accordance with the operating speed model.

In the southern direction the parameters listed in the last four parameters of Table 3 all produced inadequate perception of the horizontal curve as portrayed in Figure 5. This was compounded by the fact that the southbound approach to the curve was in a cutting that formed a vista to Wivenhoe Dam and that there was no backdrop around the outside of the curve.

Numerous worldwide studies have shown that ‘tight’ horizontal curves on average record higher single vehicle accident rates than on larger radii horizontal curves (*24, 25, 26, 27, 28, 29, 30)*. In this case study, other geometric minima such as the long length of the curve, minimal superelevation, minimal clear zones, and little driver perception were added to problems already associated with having a ‘tight’ horizontal curve. This meant that some drivers misread the curve then travel too quickly into it. Minimal superelevation and the long length of the curve then make it even more difficult for these drivers to negotiate.

As with Case Study A, it is not difficult to understand how a driver of a motor vehicle can breach all levels of defence in the Swiss Cheese Model, resulting in a single vehicle accident at this location with any one or more of the following conditions/factors:

- Bald to near bald tyres;
- In poor light conditions;
- Misperception of the approaching road alignment due to the lack of cues for the curve; and
- Distraction by the vista.

FIGURE 5 Wivenhoe–Somerset Rd: approach to R150 horizontal curve in southbound direction

Case Study D – Boat Harbour Drive / Bideford Street Intersection

This case study considers a previous unsignalised intersection at the intersection of Boat Harbour Drive and Bideford Street in Hervey Bay located approximately 250km (156 mile) north of Brisbane. This intersection is now signalised. The intersection was in an urban environment with 60km/h (37.5 mile/h) posted speed limits on all legs. Traffic volumes on the major and minor roads were 9,200veh/d and 3,200veh/d respectively. The intersection comprised 4 legs with the minor legs aligned via horizontal and vertical straights as depicted in Figure 6.

FIGURE 6 Boat Harbour Dr/Bideford St Intersection – Southern (Minor) Approach

The intersection recorded 16 accidents in 5 years up to the year 1999. These were mainly the result of drivers on the minor legs failing to give way and colliding with drivers on the major road. Using the regression equations from Arndt (*23*), about 8 accidents over 5 years could be expected at a 4-way intersection with good visibility, protected turn lanes, unaligned single-lane minor legs and the same traffic volumes and approach speeds as the intersection in the case study. These values show that the actual accident rate is about double that expected at a 4-way intersection comprising few geometric minima.

The Boat Harbour Drive / Bideford Street intersection was found to comprise 5 geometric minima including 2 design exceptions (see Table 4).

TABLE 4 Geometric Minima for Case Study D

Parameter	**Bound of the Design Domain in Current Guidelines** [(1)]	**On-site Value**	**Design Exception (To Current Guidelines)**
Number of legs	4 (max)	4	No
Alignment of the minor legs	No value given in design domain	Aligned horizontally and vertically	No
Observation angle	110 degrees (max)	110 degrees	No
Right turn type	A dedicated right turn lane (equivalent to a left turn lane in most of Europe and the USA)	A short length of passing lane on the left of the through road.	Yes
Number of lanes on the minor road	1 (max)	2	Yes
Safe Intersection Sight Distance to the West	141m (min)	150m northern approach 250m southern approach	No

1. Geometric Values based on a 70 km/h (43.8 mile/h) operating speed on the major road.

Numerous studies show that unsignalised crossroads are usually associated with increased accident rates over T-intersections [such as Arndt (*23*)]. This case study is an unsignalised crossroad with the minor legs aligned horizontally and vertically. This, combined with the width of the roadway (because of the 2 stand-up lanes at the intersection) does not provide good perception of the intersection. Arndt (*23*) found that the accident rate at this type of intersection for drivers failing to give way on the minor road approach and striking a vehicle on the major road was almost double that if the minor legs were not aligned.

The unsignalised crossroad, which is already a geometric minima, combined with other minima such as the skew angle between the major and minor roads and the limited sight distance to the west is likely to have made the situation worse. Also, the two stand-up lanes make it difficult for drivers behind the giveway (yield) line to view around/through other vehicles in the adjacent lane.

DISCUSSION

Based on the anecdotal evidence given in the case studies and other experience gained by the authors, sites with very high crash rates (crashes per number of vehicles) tend to comprise multiple geometric minima. Conclusive results cannot be drawn from the case studies because many more sites would be needed for investigation. The sample would need to include sites with many geometric minima through to sites with no geometric minima. Some of the sites with combinations of geometric minima would also need to include combinations of significant design exceptions. This ensures a wide range of the values of each variable is obtained, which seeks to optimise the data collected by avoiding the collection of many similar data (*31*).

The effects of individual geometric elements on safety would need to be first established. This has been completed for some geometric elements (*13,14,15*) but for others further work is still required. The effect of other parameters such as lighting and signing would also need to be considered. Then the effects of combining geometric minima would then need to be analysed. The number of parameters and combinations of parameters to be analysed is extraordinary. The authors consider that the scope and budgeting to undertake such a study may well be beyond the reach of most road authorities.

In the absence of such an extensive study, the findings of case studies such as those in this paper give some insight as to the likely effect of combining geometric minima. The Road Transport Accident Risk Model supports this result by indicating that the holes in each 'slice of cheese' must be minimised to minimise accidents. In road design, this means that the holes in the road geometry slice must be minimised. One way of achieving this is to avoid combining geometric minima, especially design exceptions.

Further, many road design guides from throughout the world have for a long time highlighted the potential safety problems of combining geometric minima.

It is therefore recommended that, in general, geometric minima should not be combined. This is considered to be one of the most important principles of road design. Where a geometric minima is adopted for one design parameter, it is good practice to use a better than lower order value for the other design parameters to compensate.

Based on the authors' experiences, many road designers tend to adhere to values within the design domain. After all, it is relatively easy given that many of the bounds of the design domain are given in tables that are easy to read. But a concept such as avoiding the combination of geometric minima is a principle that does not contain values. Such principles tend to get overlooked much more readily than parameters with numerical values. In reality, however, adherence to such principles is probably much more important than strict adherence to numerical values alone.

COMBINATION OF GEOMETRIC MINIMA TO BE AVOIDED

Although the quantitative effect on safety of combining multiple geometric minima would be difficult to determine, research has shown that particular design parameters influence safety to a greater degree than others (at least within the bounds of the design domain). For this reason, it is especially important to avoid combining geometric minima where one of the parameters has been shown to have a strong link with safety. For example 'tight' horizontal curves (*24, 25, 26, 27, 28, 29, 30*), long steep downgrades (*32*), the presence of intersections (*23*) have been shown to have strong links with safety. Examples of some of these have been shown in the case studies. It is most important that such parameters are not combined with other geometric minima.

Avoiding the combination of multiple geometric minima is also more important if one or more of the geometric minima are design exceptions. This is because design exceptions are likely to have a more adverse affect on safety than geometric minima, as design exceptions are outside the design domain.

When reviewing the geometry of existing roads in Australia, it is not uncommon to find combinations of geometric minima, including design exceptions. It is suspected that Australia would not be alone in this regard. Whilst combinations of geometric minima can still find their way into new road designs in Australia, the authors believe that this practice is becoming less common as the awareness of the potential safety problems caused become evident.

Most new designs record lower accident rates than equivalent sites on existing roads. One of the reasons for this is that older roads are often based on a design speed significantly lower than the speed drivers currently use. What may be a geometric minima now (for the current operating speed) may not have been a geometric minima in the past due to the slower speeds at which drivers of early model vehicles travelled at and/or because of an increase in speed limit.

It is recommended that when undertaking works to existing roads, including safety remedial works, shoulder sealing projects, widening and overlay projects, locations where there are combinations of geometric minima should be identified. The number of geometric minima at these locations should be reduced, especially if the following apply:

- There already is an accident history
- One or more of the parameters is known to have a strong link with safety
- One or more of the geometric minima are design exceptions

Where it is impractical to remove all of the geometric minima, mitigating measures should be incorporated into the design.

Combinations of geometric minima to generally be avoided are given in Table 5, based on the results of the case studies, the findings of research on the effect of geometry on accident rates, and the authors' own experiences. Such combinations have been reported at sites with high accident rates.

TABLE 5 Examples of Combination of Geometric Minima that should be Avoided

GEOMETRIC MINIMA especially if a Design Exception	**Combined with other Geometric Minima** **TO GENERALLY BE AVOIDED**
A tight horizontal curve radius or tight compound horizontal curve	× A tight crest curve, especially if the horizontal curve/ compound curve starts after the crest curve × Inadequate perception of/sight distance to the horizontal curve / compound curve × A hazardous roadside (eg larger trees, deep v-drains, steep fills close to the roadside) × Little superelevation × Long drainage paths on the road surface × A floodway × A narrow carriageway (eg due to narrow bridge/culvert/ grid) × A steep downgrade × An intersection
A small radius vertical crest curve size	× A small radius horizontal curve or compound curve × A narrow carriageway × A hazardous roadside × A floodway just after the crest curve × A likelihood of hazards on roadway (eg stock, fallen rocks) × An intersection
A narrow bridge or culvert (one-lane or two-lane of substandard width) or floodway	× Limited visibility × Steep downgrades leading to it × A small radius horizontal curve or compound curve × Being located just after a small radius crest curve
Limited sight distance	× A small radius horizontal curve or compound curve × A narrow carriageway × A floodway × A minor leg of an unsignalised intersection

CONCLUSION

The case studies in this paper give anecdotal evidence that sites with very high crash rates (crashes per number of vehicles) tend to comprise multiple geometric minima. For this reason, it is recommended that the combination of geometric minima should generally be avoided. Expanding the systems perspective model of human error by Reason (*19*) also gives weight for why geometric minima should not be combined.

In many road design guidelines throughout the world, the practice of not combining geometric minima is preferred. However, it is generally overlooked by designers as it is a principle written as text and can tend to get lost. This is unlike tables of design values which designers tend to adhere to. In reality, however, adherence to not combining geometric minima may well be more important than strict adherence to numerical values alone. In the latter case, combinations of design minima can occur.

Guidance on combinations of geometric minima that should generally be avoided is given in this paper. It is recommended that when undertaking works to existing roads, locations where there are combinations of geometric minima should be identified. The number of geometric minima at these locations should be reduced, especially if the following apply:

- There already is an accident history;
- One or more of the parameters is known to have a strong link with safety; or
- One or more of the geometric minima are design exceptions.

Where it is impractical to remove all of the geometric minima, mitigating measures should be incorporated into the design.

Extensive research would be required to determine robust relationships between combinations of geometric minima and accident rates. The authors consider that the scope and budget to undertake such a study may well be beyond the reach of most road authorities. Until such research is undertaken, findings such as those given in this paper give more support for the preferred practice of avoiding combinations of geometric minima.

REFERENCES

1. *Guide to Road Design – Part 2: Design Considerations.* AGRD02/06, Austroads, Sydney, Australia. 2006.
2. *Geometric Design Guide for Canadian Roads*. Transportation Association of Canada, Ottawa, Ontario, 1999.
3. Robinson, J., and G. S. Smith. The 1999 Canadian Geometric Design Guide: Road Safety Initiatives. In *Proceedings of the 2nd International Symposium on Highway Geometric Design*. Transportation Research Board, FGSV. Mainz, Germany, 2000, pp.49-56.
4. Arndt, O. K., and R. L. Cox. *Using an Extended Design Domain Concept for Road Restoration Projects*. CD-ROM. 3rd International Symposium on Highway Geometric Design, Chicago, Illinois, 2005.
5. *Mitigation Strategies for Design Exceptions*. U.S. Department of Transportation, Federal Highway Administration, Washington D.C., 2007.
6. Hauer, E. Safety in Geometric Design Standards I and II. In *Conference Proceedings of 2nd International Symposium on Highway Geometric Design*, Mainz, Germany, 2000.
7. Stamatiadis, N., K.R. Agent, and J.G. Pigman. *Safety Implications from Design Exceptions*. Kentucky Transportation Center, University of Kentucky, 2002.
8. Pellegrino, O. A method to manage design solutions outside the road standard criteria. In *Road and Transport Research Journal, Vol: 18, No.1*, 2009, pp.39-52.
9. Malyshkina, N.V., and F.L. Mannering. Empirical assessment of the impact of highway design exceptions on the frequency and severity of vehicle accidents. In *Accident Analysis and Prevention 42 (2010)*, pp.131-139.
10. *Road Safety Risk Reporter No. 4*. ARRB Group Ltd, Victoria, Australia, 2006.
11. Turner, B. Road Safety Engineering Risk Assessment – Findings from a Program of Research. In *Proceedings of the 23rd ARRB Conference – Research Partnering with Practitioners*, Adelaide Australia, 2008.
12. Zimmermann, M. and R. Ross. Increased Safety Resulting from Quantitative Evaluation of Sight Distances and Visibility Conditions of Two-Lane Rural Roads. In *3rd International Symposium on Highway Geometric Design*, Chicago, Illinois, 2005.
13. ARRB Group and Austroads. *Road Safety Risk Manager*. ARRB Transport Research Ltd, Victoria, Australia. www.arrb.com.au/index.php. Accessed Oct. 14, 2009.
14. Interactive Highway Safety Design Model (IHSDM). U.S. Department of Transportation, Federal Highway Administration. www.tfhrc.gov/safety/ihsdm/ihsdm.htm. Accessed Oct.14, 2009.
15. Highway Safety Manual. Transportation Research Board of the National Academies. Washington D.C. www.highwaysafetymanual.org/. Accessed Oct. 14, 2009.
16. Hankey, J.M., W.W. Wierwille, W.J. Cannell, C.A. Kieliszewski, A. Medina, T.A. Dingus, and L.M. Cooper. *Identification and evaluation of driver errors: Task C report, driver error taxonomy development* (Draft Technical Report), Project No. DTFH-61-97-C-00051. Blacksburg, VA: Virginia Tech Transportation Institute, 1999.
17. Medina, A.L., S.E. Lee, W.W. Wierwille, and R.J. Hanowski. Relationship between infrastructure, driver error, and critical incidents. In *Proceedings of the Human Factors and Ergonomics Society, 48th annual meeting*, Santa Monica, CA, 2004.
18. Salmon, P.M., M. Regan, and I. Johnston. *Human Error and Road Transport: Phase One – A framework for an error tolerant road transport system*: Report No. 256. Monash University Accident Research Centre, Australia, 2005.
19. Reason, J. *Human Error.* Cambridge University Press, Cambridge, UK. 1990.
20. *Guide to Road Design (Parts 1-4C).* Austroads, Sydney, Australia, 2009.
21. *Guide to Traffic Management Part 6 – Intersections, Interchanges and Crossings.* Austroads, Sydney, Australia, 2007.
22. Turner, B., C. Jurewicz, B. Frith, P. Cairney, J. Affum, and P. Roper. *Road Safety Engineering Risk Assessment – Stage 6 – Overview of Research*. Publication No. IR-168/09, Austroads, Sydney, Australia, 2009.
23. Arndt, O.K. *Relationship Between Unsignalised Intersection Geometry and Accident Rates*. Queensland University of Technology, Australia, 2004.

24. Choueiri, E.M., R. Lamm, J.H. Kloeckner, and T. Mailender. Safety aspects of individual design elements and their intersections on two-lane highways: international perspective. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1445*, Transportation Research Board of the National Academies, Washington, D.C., 1994, pp. 34-46.
25. Elvik, R., and T. Vaa. *The Handbook of Road Safety Measures*. Elsevier, Oxford. 2004.
26. Fambro, D., K. Fitzpatrick, and R. Koppa. *NCHRP Report 400: Determination of Stopping Sight Distances*. TRB, National Research Council, Washington, D.C., 1997.
27. Glennon, J. Effect of alignment on highway safety. In *State of the Art Report 6: Relationship between safety and key highway features: a synthesis of prior research*, Transportation Research Board of the National Academies, Washington, D.C., 1987, pp. 48-63.
28. Iyinam, A.F., S. Iyinam, and M. Ergun. *Analysis of relationship between highway safety and road geometric design elements: Turkish Case*. Traffic Forum, Technical University of Dresden. vwisb7.vkw.tu-dresden.de/TrafficForum/vwt_2003/beitraege/VWT19proceedings_contribution_91.1-91.8.pdf#search='geometric%20design%20and%20accidents.
29. Los, T. Relationship between free speed and sight distance on two-lane roads. Bachelor of Engineering Thesis, University of Queensland, Australia, 1974.
30. Olson, P.L., D.E. Cleveland, P.S. Fancher, L.P. Kostyniuk, and L.W. Schneider. *NCHRP Report 270: Parameters affecting Stopping Sight Distance*. TRB, National Research Council, Washington, D.C., 1984.
31. Arndt, O.K. and R.J. Troutbeck. *Techniques for Analysing the Effect of Road Geometry on Accident Rates Using Multi-factor Studies*. 22nd ARRB Conference, Canberra, Australia, 2006.
32. Arndt, O.K. and P.M. Shelton. *Development of Design Standards for Steep Downgrades*. Design and Survey Branch, Transport Technology, Queensland Department of Transport, Australia, 1992.