SAFETY PERFORMANCE BASED DEPARTURES FROM GEOMETRIC DESIGN REQUIREMENTS

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ABSTRACT

Most of the geometric design requirements that are specified or recommended in New Zealand (and Australia) roadway design guidelines pre-date the development of models and factors that relate crashes to design elements. Given the uncertainty around safety performance, design guidelines do include margins of safety at varying levels on each design element. What most designers need to know is where design requirements can be relaxed and by how much, without having a major impact on road safety. The Austroads extended design domain (EDD) does provide a framework under which some design minimums can be relaxed. In some areas of design there is considerable scope to fall below minimums, while in other cases the safety impacts are likely to be significant. With the emergence of better crash prediction models and crash modifying factors, and associated crash prediction tools, it is now possible to challenge many design requirements using these models. This paper will discuss the various approaches to dealing with 'design exceptions' in different countries, and where design requirements can be challenged using crash models and factors. The paper also demonstrates how these new crash prediction tools could be used under the Austroads extended design domain (EDD) framework.

ACKNOWLEDGMENTS

The authors acknowledge the research undertaken by others in this area. This paper draws significantly from the research undertaken by other researchers, the main purpose of this paper being to raise the profile of this important area of research to a New Zealand audience. In particular, the work by Dr Owen Arndt and Ricky Cox in Queensland, Professor Tarek Sayed in British Columbia (Canada) and a large group of researchers in USA and specifically, Darren Torbic, Director Doug Harwood, John Milton and Jim Bonneson.

INTRODUCTION

Background

Road design guidelines and standards in Australia and New Zealand have originated largely from a simplistic and deterministic approach employing empirical data and practical experience over many years from around the western world; but the knowledge about design inputs and parameters, such as speed and driver perception and reaction time, is imperfect (Sayed, 2015). To account for this uncertainty, these guidelines and standards have inbuilt empirical factors of safety in the form of conservative values for design inputs and parameters, which aim to broadly account for site variables such as road conditions and human and vehicle factors. However, the safety margins of the current design guidelines are normally unknown, not consistent, and do not target explicit margins or risks.

Nevertheless, despite the lack of knowledge or understanding of the uncertainties surrounding the guidelines and standards, design engineers and road controlling authorities often resist departures and design exceptions due to the unknown implications of the departure on road safety and the risk of tort liability.

The purpose of this paper is to demonstrate some of the tools that are now available internationally to understand the impacts of design exceptions, especially in terms of road safety. There are considerable benefits that can be achieved to road controlling authorities, particularly in terms of reduced construction costs, from design exceptions. Such tools can assist in value engineering exercises, by estimating the likely crash consequences of lower costs upgrade options. Any cost savings can then be used to fund other road improvement projects that have better road safety benefits. The departure from design standards is a commonly accepted approach for the upgrading of brownfield sites where constraints (e.g. existing infrastructure, culturally/environmentally sensitive land etc.) make retrofitting projects cost prohibitive or impractical.

Design Departures / Exceptions

In New Zealand where a design involves a departure from accepted standards or normal design practice on road projects, endorsement of the decision must be sought from the road controlling authority. The level of justification required for approval/acceptance of design departures depends on the significance (e.g. safety, cost, traffic capacity etc.) of the subject item. In many instances, design exceptions can be based on only qualitative assessments of safety implications or using past precedents. Cases are considered on site-by-site basis and are undertaken generally in conjunction with a road safety audit.

In Australia the process for using design exceptions in road design can vary between states; however, the approach typically requires comprehensive documentation of the design decisions made, particularly when variation from the accepted design standards is adopted. The philosophy in most of the Australia State standards is that design exceptions should be a last resort when the design standards cannot be practicality achieved. In Australia, the overarching principle is that the design exception should be defendable in court as a protection against potential litigation.

A number of factors should be taken into account when determining whether a *design exception* parameter would be appropriate. These factors include the approach of a Context Sensitive Design (CSD) with the following key factors:

- safety,
- cost,

- environment and social impacts; and
- operational requirements.

The focus of this paper is on the safety implications of designs that depart from recommended standards. However, these other impacts of design exceptions are also important.

Paper Outline

This paper first outlines the current practice specific in Austroads design guides for justifying design departures, the extended design domain requirements, and equivalent processes in the USA and Canada. It then presents how design exceptions are evaluated and approved in Queensland and New Zealand. It then presents two quantitative methods that are used to justify design exceptions. It acknowledges that some design exceptions are based mainly on expert opinion of designers (qualitative methods). Even in these cases decision makers do prefer some scientific evidence to help justify their decisions.

The paper also touches on the trend towards a probabilistic (stochastic rather than deterministic) risk-reliability theory where designer treats the variables in the design equations as probability distributions, not as absolute values, in support of the departure from standards and guidelines (Donnell, 2015). It includes a worked example of the effects of varying distributions of operating speed, driver perception and reaction time, driver eye height etc. on stopping sight distance and crest vertical curvature.

AUSTROADS EXTENDED DESIGN DOMAIN (EDD)

The Extended Design Domain (EDD) concept aims to provide more cost-effective minimal design values for restoration type works where the provision of the Normal Design Domain (NDD) standards are considered impractical/prohibitive for various reasons. The Austroads *Guide to Road Design Part 2: Design Considerations (2006)* describes EDD approach as being based on:

"through research and/or operating experience, (that) *particular road authorities have found to provide a suitable solution in constrained situations (typically at brownfield sites)."*

The Austroads Guide also states that for EDD;

"the lower regions of the Design Domain represent values that would generally be considered less safe or less efficient, but usually less expensive than those in the upper regions of the domain"

The location of the EDD approach in relation to typical design standards is illustrated in Figure 1:

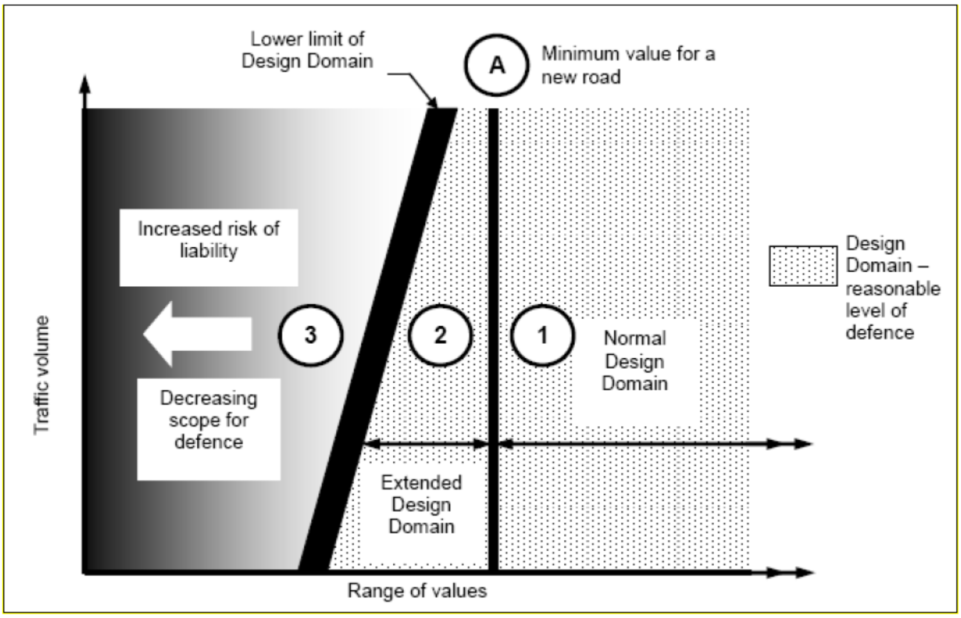

Figure 2.1: EDD Conceptual Design
(from AGRD Part 2, Commentary F)

Figure 1: EDD Conceptual Design

The EDD is classed different to a *design exception* as it is provided based on research/past experiences and is typically reserved for brownfield sites under set criteria. This is different from a design exception, which is a specific design parameter that falls outside the design domain (both EDD and NDD). Both design exceptions and EDD require approval from the relevant road authority and assessment of risks based on engineering grounds. EDD should not be used for project sites with an existing crash history or identified safety issue that relates to the parameter being considered for EDD.

Available EDD parameters include:

- warrants for turn treatments on the major road at unsignalised intersections;
- cross-sections for rural two lane, two-way roads;
- stopping sight distances (SSD);
- safe intersection sight distance (SISD);
- approach sight Distance (ASD);
- minimum gap sight distance (MGSD);
- crest vertical curves to the extent that they affect sight distance;
- sag vertical curves to the extent that they affect sight distance; and
- median widths at intersections.

One example where an EDD parameter has been adopted without significantly affecting traffic safety of a project is the development of "*Expanded Warrants for Unsignalised Intersection turning treatments"* in Queensland, Australia (Sullivan and Arndt, 2014). The key purpose of the new warrants was to improve value engineering of turn treatments particularly at brownfield sites.

'PRACTICAL DESIGN' APPROACH USED IN USA AND CANADA

The equivalent approach to EDD dealing with design exceptions (or design departures and departure from standards) in the USA and Canada is called 'practical design'. Like New

Zealand and Australia, this approach is particularly well suited, but not exclusive, to brownfield developments where there are considerable design constraints and costs implications of acquiring additional land.

In the USA, the move towards 'practical design' by different States is often motivated by reducing costs and being able to achieve more within budgets. Beagle et al. (2015) equates practical design with performance-based design. Performance-based design requires a shift from a standard-based design to process-based design. Stamatiadis and Kirk (2015) explain practical design as an 'attempt to develop projects that are "right-sized" to meet the project purpose and need, avoiding the desire to arbitrarily bring the facility up to a maximum level for all design elements.'

For 'practical design' at brown-field sites Stamatiadis and Kirk (2015) talk about designers employing a 'design-up' philosophy to a project design rather than starting with the 'desirable' condition approach. The existing condition of the facility is considered the baseline design. The design-up then builds on that condition to meet the purpose and need of the project.

On larger projects, often the 'standard' design (that meets all of the road design guidelines) is compared with one or more practical design options. Beagle et al. (2015) and Stamatiadis and Kirk (2015) present various scientific methods for evaluating the safety and capacity of both standard and practical design options, in order to understand any adverse effects of the practical design options. The scientific methods draw on both the Highway Safety Manual (HSM) and Highway Capacity Manual (HCM) for safety and capacity respectively. Stamatiadis and Kirk (2015) provide an example of how these two manuals can be used to examine the safety and operational performance of various road cross section alternatives. More on the scientific approach latter on.

QUEENSLAND AND NEW ZEALAND APPROACHES TO EDD

Arndt et al. (2015) provides an overview of the progress that has been made in Queensland in the greater use of Extended Design Domain (EDD), especially for brown-field sites. A focus on making better use of existing road assets and space in Queensland has driven the greater use of EDD. The following examples show some of the challenges that face the State road controlling authority regularly. Most of the solutions put forward required design compromises (design exceptions) that include:

- introduction of narrower shoulder or no shoulder on motorways to add additional lanes;
- adding additional through or turning lanes at highly constrained urban intersections; and
- widening existing two-lane/two-way roads with minimum widening of earthworks.

The Queensland Department of Transport and Main Roads (DTMR) has developed a guideline document for brown-field sites (DTMR, 2013). This guideline outlines the EDD process, including what is required in terms of justification of various design exceptions. Information is provided in the guide on justifying design exceptions on 14 parameters, including 'urban road cross-section widths' and 'sight distance on horizontal curves around barriers and structures.'

In Queensland it is generally accepted that road design must adopt a risk management approach, regardless of whether design values used meet design standards or not. The importance of understanding and addressing crash risk is evident in safety audit outcomes, which often identify safety concerns with designs even when they meet current standards.

In assessing any design, whether it has design exceptions or not, Arndt et al. (2015) recommends quantitative methods such as 'substantive safety'. According to Hauer (2000), 'substantive safety' considers whether the measure of expected crash frequency of an option is within tolerable limits. With the availability of tools like the IHSDM, ARRB Road Safety Risk Manager, Highway Safety Manual crash analysis tools and ISAT, and the availability of crash prediction models and reduction factors in New Zealand and Australia, it is possible to estimate the crash risk of various road designs. Where tools are available, crash estimates can and should be used to support design exceptions.

Arndt also refers to pilot projects for design innovations in Queensland, such as the Dutch turbo roundabout. Such pilot projects are treated as 'design exceptions' and therefore undergo a more rigorous level of assessments before being approved, including post implementation monitoring.

In New Zealand, innovations such as signalised roundabouts and displaced right turn signalised intersections, have been analysed using New Zealand crash prediction models and overseas crash reduction factors. Turner and Brown (2013) outline an assessment of alternative intersections designs at the intersections of Takitimu Drive/ Elizabeth Street and Te Muanga (SH29)/Tauranga Eastern Link in Tauranga. The application of the ISAT (interchange crash assessment) tool (from USA), referred to early on, is also applied.

Hughes (2015) outlines how the Extended Design Domain (EDD) approach is implemented in New Zealand. In New Zealand, the philosophy around EDD is about achieving the most appropriate value for each design parameter and understanding the risks associated with any that are deficient from the desirable value. Hughes provides examples of the type of information that needs to be provided to support a design exception.

One example considers the sight distance over crest vertical values, which can lead to excessive cut volumes through some terrains. In a specific example the designer was looking to increase the object height of the hazard in the calculation of the curvature from 0.2 m to 0.8 m (the latter being height of the taillights on a car). The rationale was that on a dual carriageway road a driver has the ability to avoid a low or small sized hazard on the road by weaving into the other traffic lane. The same approach can also be taken when looking at horizontal curve safe stopping distance on motorways. The worked example in the following section of this paper describes a practical way of taking such an approach to design.

In the current approval process, 'design exceptions' are identified in the development of business case at various levels in the project development process (business cases detail the transport problem being addressed, the consequence of the problem and then the proposed solution options/project). Supporting information, prepared by technical specialists is provided in business case documentation for 'design exceptions'. Technical specialists in the NZ Transport Agency (NZTA) national office then review the overall business case and the design exceptions. The project team, rather than the technical experts, have the final sign-off in terms of the design adopted, including any design exceptions.

QUANTITATIVE APPROACHES TO JUSTIFYING DESIGN EXCEPTIONS

There are two key quantitative approaches presented in the literature, 1) risk-reliability theory and 2) substantive safety, for assessing design exceptions or developing alternative design parameter values.

Risk-reliability Theory

Several researchers have developed and used a reliability-based framework (that uses risk-reliability theory) to quantify suitable 'design exceptions' for individual and multiple design parameters. Papers by Ismail and Sayed (2009 and 2010) and Essa et al. (2015) provide the theory behind this approach and some case study examples. The risk-reliability theory approach can be used to challenge the 'traditional' deterministic approach to design. The traditional approach does not consider the variability that is present in a number of the design parameters. In support of their risk based (risk-reliability theory) approach Ismael and Sayed (2009) specified the following:

"Highway geometric design is essentially a study of a stochastic (random) system since the multitude of human factor, vehicle properties and road conditions that control the safety performance of a highway system are variable and do not take on the same values"

To allow for this variability most values of design parameters are set high (conservative percentile values e.g. 80 % to 90 %) and often incorporate additional factors of safety. *The selection of the percentile values is not based on definitive safety measures but rather an attempt to compensate for insufficient knowledge by conservative design* (Ismael and Sayed 2009). A major limitation of this deterministic approach is that the safety consequences of a series of minimum design values cannot be assessed directly. For example, safety engineers are well aware of the dangers of applying several minimum dimensions in a road cross-section. Road safety experts understand that cycle safety is likely to be compromised if a 1.2 m wide cycle lane is placed between a 3 m wide traffic lane and a 1.8 m wide parking lane. At the other extreme, motorways can be overdesigned due to the levels of safety built into parameters, if all are set to desirable levels i.e. not compensating for the covariance phenomenon. In this case, funding that could be better utilised elsewhere is being spent on what may be a marginal improvement in road safety. Most would agree that what is important is designing a road so that it meets a minimum safety level, irrespective of the value of the design parameters, and understanding what risk is associated with not meeting a specified or recommended minimum. In this respect, there is still a strong belief among some designers and road-controlling authorities that 'substandard' necessarily implies 'unsafe,' and therefore exposes them to the risk of tort liability. There is a misconception that safety is an absolute value below which it instantly fails to be safe and above which it can be assumed safe under most conditions. In reality, safety is a continuum, and departures from the recommended minimums or standards may have a negligible effect on the risk of a crash or the reliability of the system.

The advantage of the reliability-based frameworks as presented by Ismail and Sayed (2009 and 2010) is that they consider the 'probability of non-compliance (P_{nc})' (being the equivalence of probability of failure in the highway design) of a combination of parameter values as shown in Table 1. While it may be possible to consider the consequence of a single 'design exception' (as undertaken by Hughes, 2015 for the effect of higher object height on curve K value) it is a lot more complicated to do this for all the stochastic factors that might influence a design parameter (like safe stopping sight distance).[1]

Table 1 - Stochastic and deterministic parameters (from Ismail and Sayed 2009)

Parameter	Mean	Standard Deviation	Distribution	Design Values	Percentile value
Perception and brake-reaction time (PRT)	1.5 s	0.4 s	Log normal	2.5 s	98.1

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[1] The stopping sight distance worked example in this paper describes one approach that designers might consider.

Driver eye height	1.14 m	0.055 m	Normal	1.08 m	10.4
Driver deceleration	4.2 m/s^2	0.62 m/s^2	Normal	3.4 m/s^2	9.1
Object height	-	-	Deterministic	-	-

The safety level that is represented by P_{nc} is termed the "design safety". This is different from objective safety, which is based on observed or predicted collisions. Design safety is an alternative measure that reflects the safety margin of a design against unfavourable design outputs. Ismail and Sayed (2009) provide the detail on how to calculate whether the combination of parameter values is above or below $P_{nc.}$ The main question is 'what does the probability P_{nc} actually represent in a particular situation?' P_{nc} can be regarded as an index of the quality associated with a designed road feature. Other researchers like Faghri and Demesky (1988) have found at railway crossings that there is a positive correlation between P_{nc} and crash frequency.

For each 'design exception' or combination of 'design exceptions' the reliability frame-work approach will indicate whether the 'design safety' probability will be significantly reduced and if so road safety is likely to be impacted.

Worked example

This worked example illustrates one way in which designers might implement the probabilistic approach in practice. The authors point out that there are other approaches as well.

Consider designing for stopping sight distance (SSD) on a crest vertical curve in a motorway

$$SSD = \frac{R_T V}{3.6} + \frac{V^2}{254(d + 0.01a)}$$

Austroads (2009) p.104

driving environment.

SSD = stopping sight distance (m)
R_T = driver perception and reaction time (s)
V = vehicle speed (km/h)
d = deceleration coefficient
a = longitudinal gradient (%)

$$K = \frac{S^2}{200\left(\sqrt{h_1} + \sqrt{h_2}\right)^2}$$

Austroads (2009) p.179

K = vertical curvature (m/1%)
S = distance (m)
h_1 = driver eye height (m)
h_2 = observed object height (m)

Using the above formulae, the deterministic approach prescribes the following. Generally, designers would adopt a deceleration of 0.36g m/s^2, with an SSD of 209 m.

Table 2 – Example of deterministic design parameters for a motorway

Design speed	Perception & reaction time	Deceleration coefficient	SSD	Driver eye height	Object height	Crest curvature
V	R_T	d		h_1	h_2	K
km/h	s		m	m	m	m/1%
110	2.5	0.26	260	1.1	0.2	151
110	2.5	0.36	209	1.1	0.2	97
110	2.5	0.46	180	1.1	0.2	72

However, this approach does not readily take the difference between a rural free flow motorway driving environment and a managed urban congested motorway under constant surveillance into consideration. In the former, the drivers' choice of speed may be determined only by a regulatory speed limit, e.g. 100 km/h, and drivers would expect to drive in an undemanding relaxed frame of mind. Drivers on a high traffic volume urban motorway would be acutely aware of other drivers, especially those ahead of the vehicle, and would expect to have to come to a standstill from 80 km/h many times over and with little advance warning. The behavioural probability distributions of vehicle speed, driver reaction time, and deceleration would be quite different in the two scenarios. Moreover, the recognition criteria for a hazard for which the driver may have to stop would be different in the two scenarios. On a rural motorway, it may be flooding or debris. On an urban motorway, it is more likely to be the brake lights of vehicles ahead of the driver; and, being a managed motorway, is less likely to be unforeseen debris or flooding.

Table 3 and Table 4 show the results of a Monte Carlo simulation applied to arbitrary probability distributions for each of the variables in the two illustrative motorway scenarios described above. The simulations produced the resultant SSD and crest curvature distributions in the tables below.

Table 3 - Example of stochastic design parameters for a rural motorway

Distri-bution	Driver speed	Perception & reaction time	Deceleration coefficient	SSD	Driver eye height	Object height	Crest curvature
percentile	V	R_T	d		h_1	h_2	K
%	km/h	s		m	m	m	m/1%
1	89	0.8	0.28	94	1.01	0.16	19
5	92	0.9	0.32	105	1.05	0.17	24
10	94	1.0	0.35	111	1.07	0.17	27
50	101	1.4	0.43	137	1.14	0.20	41
90	109	2.0	0.51	169	1.21	0.23	63
95	110	2.2	0.53	180	1.23	0.23	71
99	113	2.7	0.58	203	1.27	0.24	90
99.5	113	2.8	0.59	211	1.28	0.24	99
99.9	114	3.2	0.62	235	1.31	0.25	119

These values are arbitrary and illustrative only, and must not be used for design purposes.

Comparing the results of Table 3 with the deterministic input values in Table 2 shows how variable the values can be, and how it is not possible to know with any certainty what safety margins are embodied in the values in Table 2.

Table 4 - Example of stochastic design parameters for a managed urban motorway

Distri-bution	Driver speed	Perception & reaction time	Deceleration coefficient	SSD	Driver eye height	Object height	Crest curvature
percentile	V	R_T	d		h_1	h_2	K
%	km/h	s		m	m	m	m/1%
1	82	0.8	0.28	80	1.01	0.42	10
5	84	1.0	0.32	88	1.05	0.44	12
10	85	1.0	0.35	92	1.07	0.45	13
50	90	1.4	0.43	109	1.14	0.50	19
90	95	1.8	0.51	132	1.21	0.55	28
95	96	1.9	0.53	140	1.23	0.56	31
99	98	2.2	0.58	157	1.27	0.58	39
99.5	98	2.4	0.59	165	1.28	0.58	44
99.9	99	2.6	0.62	187	1.31	0.59	55

These values are arbitrary and illustrative only, and must not be used for design purposes.

Comparing the results of Table 3 and Table 4 shows how variable the results can be for different driving environments and different driver behaviours. In the case of the rural motorway in Table 3, the assumed distributions reflect higher speeds, longer reaction times due to the easy ride expectation of drivers, and lower object heights than the urban motorway example in Table 4, where drivers might be more alert to the greatest hazard being stopped vehicles due to flow breakdown.

Choosing the most appropriate design input values from the array of possibilities illustrated in Table 3 or Table 4 could be a daunting prospect. Instead, if designers were to accept that there can be no correct deterministic input values, and were to concentrate on selecting the most appropriate driver behaviour and driving environment distributions, then, for any given circumstance, the proportion of drivers who would be able to stop within a given distance could be determined.

For instance, assuming that the various distributions in Table 3 were valid for the specific circumstances in the examples above, the 99.5th percentile value suggests that 99.5 % of drivers would be able to stop within 211 m, and on a crest vertical curve with a K-value of 99 for a rural motorway.

Therefore, rather than choosing specific input values for speed, driver reaction time, etc. designers could choose an appropriate percentile value within which distance drivers should be expected to stop. The specific percentile value could be derived from a comparison between known safety and known geometry of existing roads for various sets of roads. It is conceivable that a designer might then choose only the percentile value for SSD (and not the distance itself) to be reasonably certain of achieving a certain safety outcome commensurate with considerations such as traffic volume, collective and personal risk, and budget.

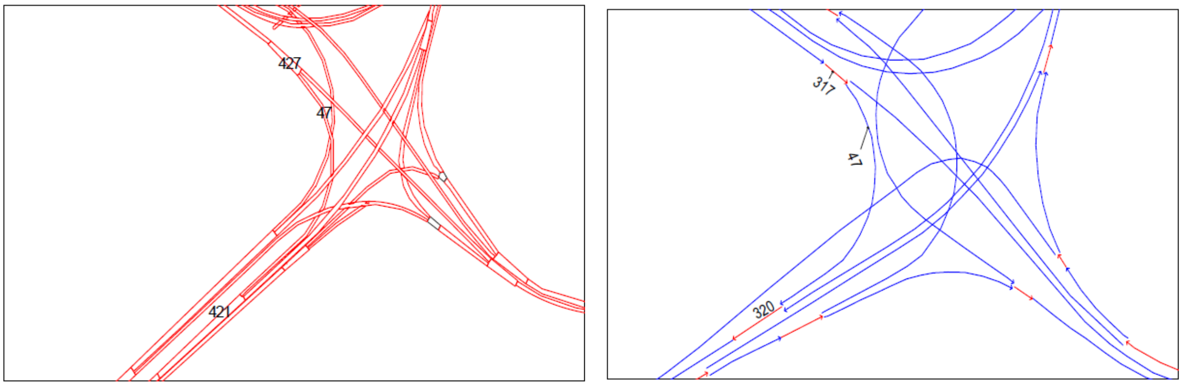
Assuming that a designer chose, or were prescribed, a particular percentile value, but found that the resulting SSD was physically or economically impractical to achieve, there needs to be a mechanism for departing from, or compensating for, or mitigating that risk. With the probabilistic approach, the designer would have the tools with which to assess the safety consequences of that departure.

For example, if the desired SSD for the 99th percentile were 203 m, but only 180 m could be achieved, that may correlate with the 95th percentile value, which could be correlated with a known expected increase in crashes due to insufficient SSD. If the expected increase in crash rate were unacceptable, then the designer could consider employing measures to change driver behaviour and could therefore legitimately use different distributions for speed and perception time In doing so, the revised 99th percentile value for SSD may well fall within the bounds of practicality. The designer could then meet the originally desired level of safety of the road with a measurable or defendable degree of certainty.

Substantive Safety (Measurement of Expected Crash Frequency)

As discussed earlier 'substantive safety' considers whether the measure of expected crash frequency of an option is within tolerable limits Hauer (2000). There are a number of crash prediction tools that are now available that can be used to understand the likely crash rate for a series of brownfield improvement options. These options may include those that are undertaken using a normal design domain (i.e. do not have any design exceptions) and those that have one or more design exceptions and fall under the extended design domain (or practical design). It is important that the crash analysis tools are detailed enough to predict the impact of the design exceptions. The worked example above describes one approach that designers might consider.

To demonstrate the use of crash analysis tools, a summary of the assessment methods used by Zarei et al. (2009) for various improvements to the Tarcot interchange in Montreal Canada is presented in Figure 2. This interchange has a complex layout and the upgrade options consisted mainly of changing the ramp locations and connections. Figure 2 (a and b) shows the existing and proposed design of the interchange. In the existing situation 'direct ramp' (link 47) with its 'start painted gore' (link 427) and 'end painted gore' (link 421 are one entity. In the proposed upgrade design 'direct ramp' (link 47) and its 'start painted gore' (link 317) and 'end painted gore' (link 320) are one entity.



a) Existing condition – Direct ramp (link 47) along with its

b) Proposed design - Direct ramp (link 47) along with its “start

Figure 2 - Turcot Interchange showing ramps connections for existing and proposed

To predict crashes for each combination of interchange elements within the existing and proposed designs the interchange assessment tool ISAT has been used. ISAT can look at a variety of different ramp types and link connections. ISAT consists of safety performance functions (SPFs- in New Zealand called crash prediction models) that have been developed and presented in Torbic et al. (2007 and 2009). Multiple SPFs are used for each of the following interchange elements:

1. ramps (different types),
2. mainline freeway segments,
3. painted gore areas,
4. acceleration and deceleration lanes,

5. crossing road segments, and
6. ramp terminal intersections.

Mainline sections are further divided into; area type (urban/rural), number of lanes (2, 3, 4 or more) and inside and outside interchange area (between ramps).

Given site constraints in a brownfield area, some of the interchange elements had reduced lane width and shoulder width. These are the 'design exceptions' that might be considered in an Extended Domain Design (EDD) or 'practical design' assessment. To assess the implications of these departures from design requirements crash predictions on each road element can be modified using crash modifying factors (CMFs). A crash modifying factor is 'unity less crash reduction factor.' CMFs are set to 1.0 for the standard design value and can range from greater than one to less than one depending on the design value. For example, a standard road width for ramps might be 3.5 m, with a CMF of 1.0. If the ramp is 3.0 m wide then the ramp is likely to be less safe and the CMF value would be greater than 1.0. If ramp were say 4.0 m wide then the CMF would be below 1.0 as the ramp is likely to be safer. For this analysis, Zarei et al. (2009) have used the CMFs produced by Bonneson et al. (2005), as follows (many of the CMFs are functions):

1. lane width,
2. inside shoulder width,
3. outside shoulder width,
4. horizontal alignment, and
5. vertical alignment.

The crash prediction for each interchange element is calculated using the following formula.

$$predicted\,crashes\,(element) = SPF\ \ (element) \times CMF1 \times CMF2 \ldots CMFn$$

The total safety performance of the interchange can be calculated by adding up the predicted crashes of all design elements. However, in addition to using the SPFs and CMFs Zarei et al. (2009) have also included the crash history for each ramp where this is available and applicable. This approach is called the empirical Bayes method. In the empirical Bayes method both the crash prediction (from SPF and CMFs) and the 'historical' crash rate (from crash history) are combined to produce an estimate of the interchange element crash rate. The following equation is used.

$$Expected\ Crashes(element) = w \times predicted\,crashes + (w-1) \times historical\,crashes$$

The 'w' values depends on the variability that has been measured for the SPF. For good fitting crash models (SPFs) 'w' is high. For poor fitting crash models, the 'w' is low. The empirical Bayes method is already used in New Zealand for safety analysis (in the Economic Evaluation Manual, NZTA, 2012). This method can be used only for existing ramps, or where a new ramp has a very similar layout to an existing ramp (and the crash history is considered valid). For new ramp types, the crash prediction is estimated purely from the SPF and CMFs.

The paper shows that the interchange crashes per year (all types from non-injury to fatal) will increase from 369 in the existing situation to 476 in the proposed option. This is an increase of almost 30%. This indicates quite a big increase in crashes if the proposed option goes ahead.

Refer to Turner and Brown (2013) for New Zealand examples of this type of analysis. What is important, in terms of 'design exceptions' under the extended design domain (EDD), is that both these methods, but particularly the second one that gives and estimated number of crashes, can be used to support or otherwise these exceptions.

DISCUSSION/SUMMARY

Under the extended design domain (EDD) framework, decisions on whether to accept 'design exceptions' are normally made using both qualitative and quantitative methods. This paper demonstrates some of the tools that are now available to quantify the safety impacts of 'design exceptions'. This information can assist decision makers who will often also consider each situation based on their design experience and expertise (a qualitative approach).

A review of papers from the recent (2015) '5th International Symposium on Highway Geometric Design' held in Vancouver, Canada, shows approaches similar to EDD are being used in a number of US States. In these states the process is referred to as 'practical design.' The objective of the 'practical design' process, which varies across the USA, is to achieve better 'value for money' from projects and to maximise what can be done within each State's highway budget. There are some key learnings that can be taken from the 'practical design' approach and used in EDD in New Zealand and Australia.

As specified in Arndt et al (2015), there are a number of crash prediction modelling tools, such as ISAT (recent update is ISATe), IHSDM, the Highway Safety Manual (HSM) crash analysis tools and a considerable body of research (including New Zealand models and factors in the EEM, 2012) that can be used to understand the crash impacts of various 'design exceptions'. Where applicable, these tools and models need be used more often in the EDD process. The literature also presents other tools like risk-reliability theory that can be used to assess the consequences of design exceptions.

In the future, as the crash analysis tools become more sophisticated (this is an active field of research overseas), it should be possible to assess the safety implications of the majority of key design parameters and combinations of different design parameter values. This may in turn lead to a rethinking of some design minimums and desirable values with respect to road safety outcomes. There may be the need to increase some minimum values where safety appears to be compromised and relaxing some requirements where safety is not unduly affected. There are considerable benefits to Government in terms of reduced construction costs that are likely to be achieved from a better understanding of the linkage between design parameter values and crash risk.

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