IRMRC Research Report

MOTORCYCLE CRASHES INTO ROADSIDE BARRIERS
STAGE 3: SURVIVABILITY ANALYSIS

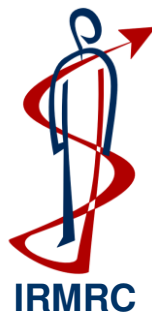Prepared by

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Executive Summary

This report presents the results of Stage 3 of the Motorcycle Crashes into Roadside Barriers research project. Stage 1 determined the human, vehicle and environmental crash characteristics and causal factors associated with fatal motorcycle-barrier collisions in Australia and New Zealand between 2001 and 2006. Stage 2 investigated the crash mechanics and biomechanical injury causation in these crashes. Stage 3 involves a survivability analysis of motorcyclists colliding with roadside barriers, and other types of fixed roadside objects. A short literature review of the effect of barrier modifications on motorcyclist injuries is also presented in an Appendix B.

It is important to note that the present research report involves only data from the United States. This is due to the fact that a survivability analysis is dependent on two factors: firstly, the data must involve all types of injury outcomes, from no injury to fatal injury; and secondly, the travel speed of the motorcyclist must be known for each data case. From these two data items, a relationship between the travel speed and the likelihood of fatality may be established, and fatality risk curves may be generated. This is the aim of the present research report, and unfortunately no data in Australia or New Zealand exists that contains these two pre-requisite items. The data was thus extracted from a database of crash data in the United States. Since the roadway, motorcycle and roadside barrier conditions are similar between the United States and Australia and New Zealand, the results are nominally valid for use in these countries (and indeed many other countries). Unfortunately, wire rope barriers are completely excluded from the database used, thus no conclusions regarding wire rope barriers may be drawn from this report.

It is also important to note that the statistical method used in the present report indicates the probability of fatality, *conditional upon* a motorcyclist being involved in a collision with a fixed object. That is, associations with a fatality are determined from a range of possible predictor variables (such as travel speed, roadway conditions, safety equipment used etc.), assuming that the motorcyclist is involved in a crash. This type of analysis does not represent in any way the *causal factors* that led up to the initiation of the crash (such as loss of control, excessive speed, impairment from alcohol etc.). For an assessment of crash causal factors the reader should refer to the Stage 1 Research Report.

Motorcyclists contribute significantly to road trauma around the world through the high incidence of serious injuries and fatalities. Around one quarter of motorcyclist fatalities may be attributed to collisions with fixed objects. A greater understanding of factors associated with fatalities occurring from fixed object collisions will enable safer roadway infrastructure design for motorcyclists. In this report, a multiple variable logistic regression model is developed to determine such factors, from a nationally representative weighted sample of around 30,000 single-vehicle fixed object motorcycle collisions which occurred in the United States over the ten year period between 2000 and 2009. Additionally, a single variable logistic regression model is developed for motorcyclist fatality risk

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from fixed object collisions as a function of travel speed. This model may be a useful predictive tool for implementing motorcyclist safety strategies.

Key findings in this report related to the survivability of motorcyclists colliding with a fixed object include:

- increased travel speed, older motorcyclists, speed related crashes, late model motorcycles, darkness, interchange locations, non-level roadway profiles and departures from the roadway on the same side as the travel lane, are all associated with an increase in the likelihood of motorcyclist fatality;

- departures from the roadway on the same side as the travel lane are nearly four times more likely to result in fatality, due to the reduced distance over which the motorcyclist may decelerate as a result of braking, skidding or sliding;

- fatality risk remains relatively low below a pre-crash travel speed of 100 km/h, however above this speed the risk rises sharply;

- the serious injury risk is significantly greater than the fatality risk, and is above 20% even for low speed crashes;

- motorcyclists with a pre-crash travel speed less than about 55 km/h, could be expected to survive a collision with a fixed object;

- trees and poles were found to be a greater fatality risk than roadside barriers, which indicates that the deployment of a barrier to protect road users from tress and poles reduces motorcyclists risk;

- concrete barriers were found to be a lower fatality risk to motorcyclists than steel W-beam barriers (wire rope barriers were not included in the data collection used);

- wearing a helmet was associated with a lower likelihood of a fatality at pre-crash travel speeds that are typically at or below Australia's maximum speed limits;

- work by other authors have shown that impact attenuators and modifications to steel guardrails provide positive benefits to reducing motorcyclist injuries, when impacts occur below 60km/hr.

Funding partners and researchers

During all three phases of this project, results were reported to and discussed by the Motorcycle into Roadside Barriers Scientific Advisory Committee (MRBSAC). The following people are or have served on the MRBSAC at one time or another:

> Dr. Soames Job – NSW Centre for Road Safety, Roads and Traffic Authority
> Mr Steve Levett – (formerly NSW Centre for Road Safety, Roads and Traffic Authority)
> Mr David Pratt – NSW Centre for Road Safety, Roads and Traffic Authority
> Mr. Wal Smart – NSW Centre for Road Safety, Roads and Traffic Authority
> Mr. Fabian Marsh – (formerly New Zealand Transport Agency)
> Mr. James Cameron – Australian Automobile Association
> Mr. Craig Newland – Australian Automobile Association
> Mr. John Metcalfe (formerly with Australian Automobile Association)
> Mr. Brian Kidd – Main Roads Western Australia
> Mr. Jan Karpinski – Main Roads Western Australia
> Ms Nadine King – NSW Motor Accidents Authority
> Ms Dimitra Vlahomitros – (formerly with NSW Motor Accidents Authority)
> Mrs Pam Albany – (formerly with NSW Motor Accidents Authority)
> Prof. Clay Gabler – Virginia Tech, USA
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> A/Prof. Mario Attard – Department of Civil and Environmental Engineering, UNSW
> Ms Rena Friswell – IRMRC, UNSW

Researchers who have worked on Stage 3 of the project to date are:

> Prof. Raphael Grzebieta – IRMRC, UNSW
> Dr. Mike Bambach – Research Fellow, IRMRC, UNSW
> Dr. Jake Olivier – Senior research Fellow, IRMRC, UNSW

1.   Project introduction

The Motorcycle Crashes into Roadside Barriers project seeks to investigate the crash characteristics, causal factors and injury mechanisms that motorcycle riders and pillions are subjected to when they impact a roadside barrier. It also seeks to determine the survivability envelop for motorcyclists crashing into each of the different barrier system types. This survivability envelop will be compared to the survivability envelope for occupants in other vehicles that impact the barriers. There is currently a reasonable amount of knowledge in regards to what is a survivable crash for occupants in cars, trucks and buses that crash into different barrier systems but little credible information concerning survivability of such crashes involving motorcyclists.

Roadside barriers are typically concrete, guardrail and wire-rope. There has been a significant concern raised by motorcycle organisations in Australia and overseas regarding the use of wire rope barriers. This research project is intended to inform such public debate and policy, and propose scientifically validated solutions, in regards to the safety or otherwise of motorcycle riders and pillions impacting roadside barriers.

The project is also exploring how to reduce the injuries to motorcyclists impacting concrete, wire-rope barriers and guardrail systems. Innovative injury mitigating engineered solutions will be assessed as well as new solutions explored. In particular any solutions proposed will be assessed in regards to whether they effect a barrier's current crash and redirection characteristics for vehicles such as cars, trucks and buses. The project will also involve computer crash simulation and crash testing that, it is hoped, will demonstrate survivability outcomes for current and upgraded systems.

In summary, the project is providing the following outcomes:

a. A statistical overview of motorcycle rider/pillion passenger involvement in roadside and median barrier crashes employing NCIS data and fatality case files;

b. The causal human factors (speed, alcohol, fatigue, inexperience, bad cornering technique, etc) that lead to motorcycle/rider/pillion impacts into crash barriers and road side hazards;

c. A categorisation of typical crash scenarios that provides impact angle, speed, motorcycle and rider kinematics;

d. Reconstruction of a selected number of representative categorised cases;

e. The causal biomechanical mechanisms related to each barrier system that lead to the serious or fatal injury of the rider/pillion;

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f. Rider/pillion survivability impact analysis for each barrier system, i.e. determination of the survivability envelops for different impact scenarios for varying rider configuration, speed and angle of impact and barrier type;

g. Proposed engineering design modifications to road barriers that are effective in reducing injuries to riders and pillions involved in roadside barrier crashes but will not reduce current crash safety characteristics for occupants of vehicles in cars, trucks and busses. The effectiveness of the modifications will be proven using current computer simulation and crash test technology.

The Stage 1 Research Report provides information addressing parts 'a' and 'b' above. The Stage 2 Research Report addresses parts 'c' to 'e' above. The present Stage 3 Research Report addresses part 'f' above.

2.   Background information

In the United States, around 25% of the approximately 5,000 motorcyclist fatalities that occur annually result from a collision with a fixed object (NHTSA, 2008). Motorcyclists are 37 times more likely to be killed in a road crash than car occupants per distance travelled (NHTSA, 2008). A range of factors have been identified as contributing to motorcycle crashes, their severity and the severity of the motorcyclists' injury(s): speed, age, time of year, experience, alcohol, illicit drug use, time of day, conspicuity, risk taking behaviour, roadside infrastructure and helmet use (Clarke et al 2006, Colburn et al 1994, Elvik 1995, Harrison and Christie 2005, Jama et al 2010, Grzebieta et al 2009, Lin and Kraus 2009, Quddus et al 2002, Rutledge and Stutts 1993, Savolainen and Mannering 2007, Shankar et al 1992, Shankar and Mannering 1996).

Investigations of particular relevance to the present study include those of Shankar and Mannering (1996), Quddus et al (2002) and Savolainen and Mannering (2007), where statistical models were developed to determine associations with injury severity in motorcycle crashes. Shankar and Mannering (1996) found from a study of single-vehicle motorcycle crashes in Washington State that: helmeted riders had an increased likelihood of being fatally injured when colliding with fixed objects; motorcyclists that were both non-helmeted and alcohol-impaired had an increased likelihood of fatality; alcohol-impaired motorcyclists, speeding motorcyclists, increased travel speed, increased motorcycle displacement and increased motorcyclist age, all had an increased likelihood of fatality. Quddus et al (2002) found from a study of motorcycle crashes in Singapore that: crashes occurring at bends, cross-junctions, expressways (higher speed roadways), dry roadways, collisions with stationary objects and increased motorcycle engine capacity, all had an increased likelihood of fatality. Savolainen and Mannering (2007) found from a study of motorcycle crashes in Indiana, that for single-vehicle crashes: increased motorcyclist age and alcohol involvement were associated with an increased likelihood of injury; helmet use, wet pavements and

intersection crashes were associated with a decreased likelihood of injury; speeding motorcyclists, crashes occurring in the dark and collisions with roadside objects (particularly trees and poles) were associated with an increased likelihood of fatality.

In the present paper, associations with a fatality are determined for motorcyclists involved in single-vehicle crashes for which the most harmful event was an impact with a fixed object, while independently controlling for the characteristics of the roadway, the motorcyclist and motorcycle, and the environmental conditions at the time of the crash. The specific aims are: (1) determine the factors associated with fatality, and (2) determine predictive models for fatality risk as a function of travel speed. The latter aim arises from a growing concern amongst road safety advocates to protect vulnerable road users (pedestrians, motorcyclists and pedal cyclists). Fatality risk curves as a function of travel speed have been shown to be effective tools for road designers, in order to provide safety strategies for vulnerable road users. Currently such curves have only been developed for pedestrians (a recent example of which was developed by Rosen and Sander 2009). However, the present study aims to provide such curves for motorcyclists colliding with fixed roadway hazards and infrastructure.

3.   Methods

3.1 Data

The United States National Automotive Sampling System (NASS) General Estimates System (GES) began in 1988, and provides data about all types of crashes involving all types of vehicles. The GES obtains its data from 400 police jurisdictions in 60 areas that reflect the geography, roadway mileage, population, and traffic density in the US. Around 50,000 police accident reports (PARs) are sampled each year, from the estimated 5.8 million police-reported crashes which occur annually. These crashes include those that result in a fatality or injury, and those involving property damage only. The GES is a probability sample, stratified by geographic regions. Within each region a probability sample of police jurisdictions are selected, with the probability proportional to the number of crashes investigated by that jurisdiction. The PARs are then stratified by crash type, and sampled at different rates depending on the stratum to which they have been assigned. National estimates may be produced from GES data. However, the data may differ from the true values because they are based on a probability sample of crashes and not a census of all crashes. In order to calculate national crash estimates, a weighting is provided for each PAR.

The GES data were queried for the years 2000 – 2009 (inclusive) according to the following inclusions: the PAR involved a motorcyclist in a single-vehicle crash, the most harmful event was coded as a collision with a fixed object, and the different variables of interest were known.

3.2 Statistical methods

A standard multiple variable logistic regression model was used, whereby the conditional probability that the outcome is present is denoted:

$$P(Y = 1|x) = \pi(x) = \frac{e^{g(x)}}{1 + e^{g(x)}} \qquad (1)$$

and the logit *g(x)* is a linear combination of *p* independent variables:

$$g(x) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_p x_p \qquad (2)$$

The commercial software SAS v9.1.3 was used for statistical analyses. Model parameters were included based on their significance levels, and parameter estimates were determined from the method of maximum likelihood. Model selection was based on Wald chi-square statistics, Akaike's information criterion (AIC) and likelihood ratio tests. The best model was selected as the model with the maximum Wald and log-likelihood values, with corresponding minimal AIC value. The GES weightings were included in the logistic regression models, such that the data are nationally representative. An unweighted model is developed to assess the effect of weighting in Appendix A. The Hosmer and Lemeshow goodness-of-fit test was employed in SAS to assess the fit of the selected model (Hosmer and Lemeshow, 1989).

The dispersion parameter is defined as the deviance (likelihood ratio chi-square test statistic) divided by the model degrees of freedom. A value for the dispersion significantly greater than 1.0 indicates that a model suffers from overdispersion. While not affecting the parameter estimates, overdispersion may result in an over-representation of the significance of the covariates in the model. The deviance correction (covariance matrix multiplied by the dispersion parameter) was implemented in SAS to correct for overdispersion where required.

The area under the receiver operating characteristic curve (AUC) may be interpreted as the probability that the model will predict a greater probability of fatality for a randomly selected fatal case, than a randomly selected non-fatal case. It is therefore a measure of the predictive power of the model, where a value of 0.5 is equivalent to random chance. A value of 0.8 to 0.9 may be considered as moderate predictive power, whereas a value of 0.9 to 1.0 may be considered as high (Shapiro, 1999). The AUC value was output from SAS, to assess the predictive power of the model.

In the present study the aim is to assess associations with fatality, for which a multiple variable logistic regression model was developed with all possible predictor variables. Associations between variables and fatality were established with this model. Subsequently, single variable logistic regression models were developed for fatality risk as a function of travel speed. These models provide predictive equations for fatality risk as a function of travel speed that may be useful for road safety practitioners. The conditional probability of a fatality as a function of travel speed (*v*) for the single variable models is given by:

$$P(v) = \frac{1}{1 + \exp(-a - bv)} \qquad (3)$$

The confidence band of the single variable models may be determined from (Kutner et al, 2004):

$$a + bv \pm 1.96\sqrt{\sigma_a{}^2 + 2\sigma_{ab}v + \sigma_b{}^2 v^2} \tag{4}$$

where σ_a and σ_b are the variance of the constants *a* and *b*, and σ_{ab} is the covariance between *a* and *b*.

3.3 Dependant variable - outcome

Injury severity is coded in the GES as one of five levels: no injury, possible injury, non-incapacitating injury, incapacitating injury or fatal injury. To assess associations with a fatality using the multiple variable logistic regression model, the outcome of the collision of the motorcyclist with the fixed object was coded as a binary variable that took the value of one for a fatal outcome, or zero otherwise. Additionally, the probability of serious injury (termed *KSI* – killed or seriously injured) as a function of velocity was sought, using the single variable logistic regression model. In this case the outcome was coded as a binary dependant variable that took the value of one when the GES coded the injury outcome as either incapacitating injury or fatal injury. This model provides a predictive equation for serious injury risk as a function of travel speed that may be useful for road safety practitioners.

3.4 Independent variables – possible predictors

In the GES, some 90 data elements are coded from the PARs, and of these the following were extracted for the present study: number of vehicles involved, most harmful event, first harmful event, type of fixed object, travel speed, speeding related, alcohol involvement, direction of roadway departure, roadway horizontal alignment, roadway vertical profile, lighting condition, interstate highway, interchange area, divided roadway, surface condition, motorcycle model year, motorcycle defect, motorcyclist age, gender and motorcycle helmet use.

In the GES, there are sixteen different types of fixed objects coded. Four fixed object categories were formed from these, where geometric specificity was used as the distinguishing feature. That is, fixed objects with well defined geometric properties such as *trees*, *poles* and *barriers* were categorised individually. Fixed objects with not well defined geometric properties were categorised as *other*, and include buildings, bridge structures, curbs, culverts, ditches, embankments, fences, walls and hydrants. Trees, poles and roadside barriers are quite specific structures that are fairly representative across different countries, whereas buildings or bridge structures, for example, could define a very wide range of material and geometric conditions. The *pole* category includes sign posts, utility posts and support poles. *Barriers* could be further subdivided into *guardrail* (steel W-beam roadside barrier) and *concrete* traffic barriers. Steel wire-rope barriers are not coded in the GES, thus while such crashes do exist, they would not be sampled.

In the GES, travel speed is the police estimate of the speed the motorcyclist was travelling prior to the crash. The travel speed was coded in miles per hour, and was converted to kilometres per hour for this study. It should be noted that travel speed is not the impact speed with which the motorcyclist struck the fixed object. In inertia induced trauma, it is well understood that the injury outcome is associated with the impact kinetic energy of the subject. Thus one would expect that the loss of velocity resulting from braking and sliding manoeuvres that the motorcyclist may have undergone prior to the impact with the fixed object might be associated with a fatality. This includes velocity reductions from braking and skidding while the motorcyclist remained on the motorcycle, and reductions from sliding if the motorcyclist was ejected from the motorcycle and slid along the roadway prior to the impact. Unfortunately, the GES does not provide such information.

The following variables were used to establish and verify the dataset: number of vehicles involved, most harmful event and first harmful event. All other variables were considered as factors that, based on consideration of the laws of physics, physiological factors or human factors, may possibly be associated with the outcome of a fatality. All covariates, and all possible linear and higher order combinations of covariates, were investigated for significance at the $\alpha = 0.05$ level. Travel speed was treated as a continuous covariate. Motorcyclist age and motorcycle model year were treated as continuous covariates, but were additionally investigated for significance as dichotomous covariates, where threshold values were determined from the method of maximum likelihood. The type of fixed object variable was treated as polytomous. Reference cell coding was used, where *barrier* was used as the reference group. All other covariates were treated as dichotomous.

4. Results

4.1 Multiple variable logistic regression model

The total number of cases for which there were no unknowns amongst the independent variables was 751, which corresponds to 29,305 weighted cases. The weighted empirical data is summarised in Table 1, and is nationally representative. The multiple variable logistic regression model for fatality risk, including the statistically significant covariates, model parameters, 95% confidence intervals and significance values, are presented in Table 2. The dispersion parameter was 16.7, indicating overdispersion in the weighted model (however, this was not the case for the unweighted model, as discussed in Appendix A). Significance values reported in Table 2 are those for which the deviance correction was applied. The initial log-likelihood (LL_i) was -443, and the final log-likelihood (LL_f) was -306. This results in a ρ^2 value of 0.31 ($\rho^2 = 1 - LL_f / LL_i$), which indicates that the model has good overall convergence. The Hosmer and Lemeshow goodness-of-fit test resulted in a chi-square value of 8.31 for 8 degrees of freedom. The corresponding value for a 0.05 significance level is 15.51, which indicates that the model is a good fit ($p = 0.403$). Comparison of

	Proportion of cases		Proportion of cases
alcohol involved	18%	motorcyclist was male	83%
speed related	46%	motorcyclist was more than 57 years old	7%
occurred on a bend	69%	motorcyclist was wearing a helmet	61%
occurred in daylight	73%	motorcycle had a defect	4%
occurred on a dry road surface	95%	motorcycle was manufactured after 2000	53%
occurred on an interstate highway	5%	fixed object cases that were fatal	7.0%
occurred on a divided roadway	17%	barrier cases that were fatal	6.6%
occurred at an interchange area	2%	pole cases that were fatal	11.9%
occurred on a level roadway	53%	tree cases that were fatal	14.7%
departed the road to the right side	68%	other fixed object cases that were fatal	4.4%

Table 1: Weighted empirical results for dichotomous variables and fatality rates, for single-vehicle motorcycle fixed object collisions ($n_{weighted}$ = 29,305)

observed and expected frequencies indicates that the model fits well within each of the 10 deciles of risk. The AUC was 0.84, indicating that overall the model has moderately good predictive power.

The following explanatory variables were found not to be significantly associated with a fatal outcome and were removed from the model (odds ratio, 95% confidence interval, *p* value): gender (1.766, 0.794-3.931, 0.164), roadway alignment (1.147, 0.642-2.049, 0.644), alcohol involvement (0.821, 0.44-1.531, 0.535), divided road location (1.810, 0.917-3.570, 0.087), surface condition (2.057, 0.671-6.303, 0.207), interstate highway location (0.461, 0.163-1.308, 0.146) and motorcycle defect (1.602, 0.735-3.492, 0.236). Motorcyclist age and the motorcycle model year were found to be more significant as dichotomous variables, than continuous variables.

Significant associations were found for the interactions between travel speed and the following: helmet use, motorcyclist age and lighting condition (Table 2). This indicates that the association of these variables with a fatality varies with travel speed. Helmet use is associated with a decrease in fatality risk (odds ratio of less than 1.0); however, this association diminishes with increasing travel speed. The odds ratio for helmet use becomes 1.0 at a travel speed of 124 km/h, and increases above 1.0 with increasing travel speed above 124 km/h. This is not unexpected mainly because of the bio-mechanical protective limits a helmet can offer in reducing head injury at high speed impacts. It should be noted that Australian highest speed limit for all States and the Australian Capital Territory are 110 km/h for the Northern Territory it is 130 km/h. Hence for Australian roads wearing a helmet will always be associated with a reduced fatality risk. Similarly, motorcyclist age and lighting condition have positive associations with fatality risk; however, these associations diminish with increasing travel speed.

For the outcome of a fatality, conditional upon a motorcyclist being involved in a collision with a fixed object, and assuming all other variables remain the same, the variable odds ratios and 95% confidence intervals are presented in Table 3.

Variable	Variable description	Probability of fatality			
		Estimate	Std. error	95% CI	p
Outcome	Dependant variable (1 fatal, 0 non-fatal)	--	--	--	--
Intercept	Constant	-8.7657	0.8379	-10.408, -7.1234	<.0001
travel speed	Police estimate of pre-crash travel speed (km/h)	0.0495	0.0075	0.0348, 0.0642	<.0001
type of fixed object	Relative to a barrier (0, 0, 0) Pole (1,0,0) Tree (0,1,0) Other (0,0,1)	0.6356 1.2774 -0.1590	0.3678 0.3404 0.2895	-0.0852, 1.3564 0.6103, 1.9445 -0.7264, 0.4083	0.0839 0.0002 0.5828
helmet use	Motorcycle helmet worn (1) or not (0)	-2.7616	0.6930	-4.1198, -1.4034	<.0001
motorcyclist age > 57	Motorcyclist was aged above 57 yr (1) or not (0)	5.5574	0.9644	3.6672, 7.4476	<.0001
speed related	Crash was speed related (1) or not (0)	0.5297	0.2604	0.0194, 1.0400	0.0419
motorcycle model > 2000	Motorcycle model later than 2000 (1) or not (0)	0.5228	0.2309	0.0703, 0.9752	0.0236
lighting	Crash occurred in daylight (0) or not (1)	3.2916	0.6573	2.0033, 4.5799	<.0001
interchange location	Crash occurred at an interchange (1) or not (0)	1.2209	0.5271	0.1878, 2.2541	0.0205
roadway profile	Crash occurred on level roadway (0) or not (1)	0.6693	0.2372	0.2045, 1.1341	0.0048
roadside departure direction	Departure was to the right (1) or left (0)	1.3456	0.2982	0.7611, 1.9301	<.0001
travel speed x helmet use	Interaction of variables previously defined	0.0225	0.0075	0.0078, 0.0373	0.0028
travel speed x age > 57	Interaction of variables previously defined	-0.0670	0.0156	-0.0976, -0.0364	<.0001
travel speed x lighting	Interaction of variables previously defined	-0.0312	0.0069	-0.0448, -0.0177	<.0001

Table 2: Parameter estimates, standard errors, 95% confidence intervals and significance values for the probability of fatality multiple variable logistic regression model ($n_{weighted}$ = 29,305)

	Odds ratio	95% CI
pole vs barrier	1.888	0.918, 3.882
tree vs barrier	3.587	1.841, 6.990
other vs barrier	0.853	0.484, 1.504
speed related	1.698	1.020, 2.829
motorcycle model > 2000	1.687	1.073, 2.652
interchange location	3.390	1.207, 9.526
roadway profile not level	1.953	1.227, 3.108
right side departure vs left side	3.840	2.141, 6.890
travel speed[a]	1.075	--
helmet use[b]	0.285	0.163, 0.498
motorcyclist age > 57[b]	2.911	1.204, 7.038
not in daylight[b]	3.324	1.923, 5.746

[a] For a motorcyclist wearing a helmet, less than 57 years old, crashing in daylight
[b] Using the mean value for the associated interaction variable of travel speed (67 km/hr)

Table 3: Odds ratios and 95% confidence intervals for the probability of fatality, conditional upon a motorcyclist being involved in a collision with a fixed object, and assuming all other variables remain the same ($n_{weighted}$ = 29,305)

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4.2 Multiple variable logistic regression model diagnostics

The residuals and influence diagnostics (confidence interval displacements) for the multiple variable logistic regression model were examined. Specific cases which resulted in large residuals and/or large influence on the model include: 35 year old travelling at 40 km/h, 52 year old travelling at 40 km/h, 29 year old travelling at 56 km/h, 47 year old travelling at 63 km/h, 56 year old travelling at 56 km/h. All these cases resulted in fatalities, and all except the last case were wearing a motorcycle helmet. These results indicate that the model does not predict fatalities that occur at low speeds well, and may be a result of missing covariate(s), or simply a result of unusual events. It is possible that additional injuries occurred before or after the impact with the fixed object. The motorcyclist may have had a pre-existing medical condition, or may have received a concentrated impact to the head, neck or chest on part of the fixed object, for example. In all these specific cases the results are biologically plausible, thus there is no justification for removing them from the dataset. Exclusion of the two most influential cases from the model resulted in very small changes in parameter estimates, which were well within the parameter standard errors. Overall, while some low speed fatalities were not well predicted, they do not significantly affect the parameters in the general model and the conclusions reached from it.

4.3 Single variable logistic regression models

The total number of cases for which there were no unknowns for the independent variable of travel speed was 920, which corresponds to 34,746 weighted cases. Single variable models were developed for the following groups of cases: all cases, barrier-only, guardrail-only, concrete barrier-only, pole-only, tree-only, other-only, helmeted motorcyclists-only, non-helmeted motorcyclists-only, right side departure-only and left side departure-only. The parameter estimates for statistically significant models at the $\alpha = 0.05$ level are tabulated in Table 4, as are the significance levels (after employing a deviance correction for overdispersion). The models are plotted in Figures 1 and 2, to the maximum travel speed recorded amongst all cases of 242 km/h. The models for pole-only and concrete-only cases were not found to be significant, due to a combination of small case numbers and confounding results (low speed fatalities and high speed non-fatalities). The model of the risk of *KSI* as a function of travel speed is also plotted in Figure 1, and the coefficients tabulated in Table 4.

It is of general interest to road safety practitioners to define a speed threshold, below which one might say with some certainty that the occupant will survive. Considering the importance of minimising the number of events (fatal) that are predicted as non-events (survival), the required sensitivity level was set at 90%. Using the receiver operating characteristic curve for the single variable model of fatality as a function of travel speed, a sensitivity of 92% results from setting a threshold travel speed of 56 km/h. Thus we predict that in about 9 cases out of 10, a motorcyclist travelling less than about 55 km/h will survive a collision with a fixed object.

Group (weighted no. of cases)	Intercept a (standard error)	b (standard error)	p value
All (34,746)	-5.0686 (0.4987)	0.0318 (0.0054)	<0.0001
Barrier (8433)	-5.1187 (0.9197)	0.0300 (0.0092)	0.0011
Guardrail (6509)	-6.0946 (1.2609)	0.0414 (0.0128)	0.0013
Tree (4340)	-8.0787 (1.5418)	0.0751 (0.0170)	<0.0001
Other (18,621)	-5.8042 (0.6467)	0.0367 (0.0069)	<0.0001
Helmet (21,204)	-5.7237 (0.6234)	0.0366 (0.0062)	<0.0001
No helmet (13,542)	-4.3887 (0.7854)	0.0271 (0.0097)	0.0051
Right side departure (21,531)	-4.9593 (0.6134)	0.0342 (0.0068)	<0.0001
Left side departure (13,215)	-5.4962 (0.6826)	0.0285 (0.0072)	<0.0001
KSI (34,746)	-1.6764 (0.2315)	0.0205 (0.0032)	<0.0001

Table 4: Single variable logistic regression model coefficients (Equation 3), for the probability of fatality as a function of travel speed
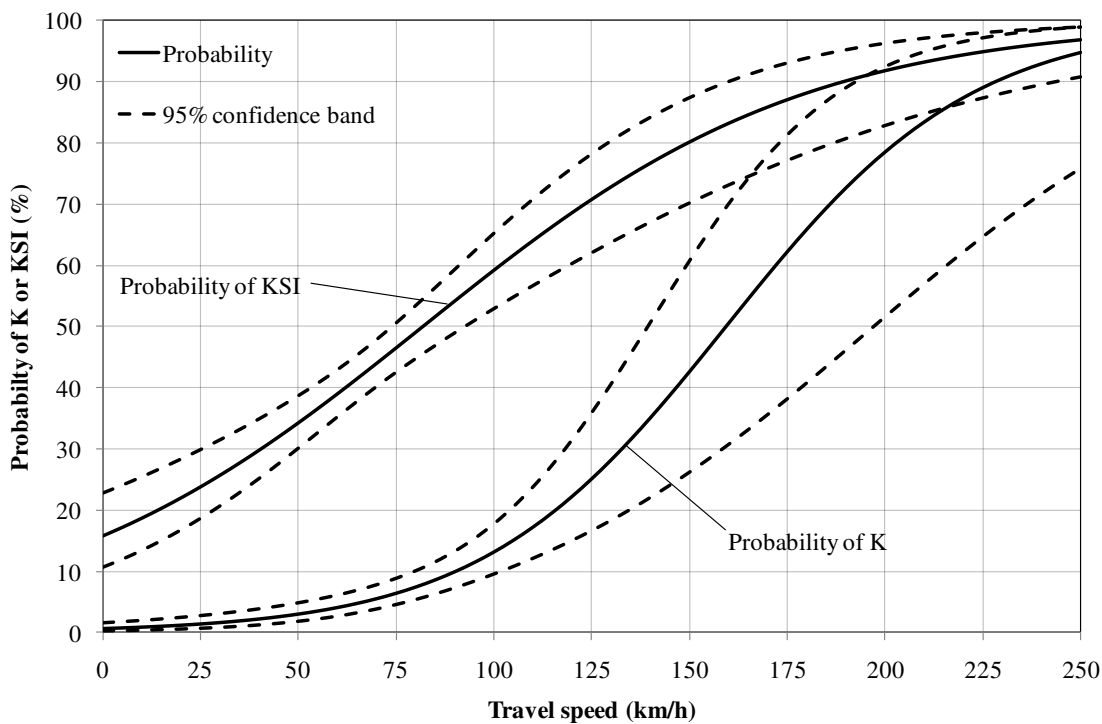

Figure 1: Probability as a function of travel speed for fixed object collisions - probability of being killed (K) and probability of being killed or seriously injured (KSI) ($n_{weighted}$ = 34,746)
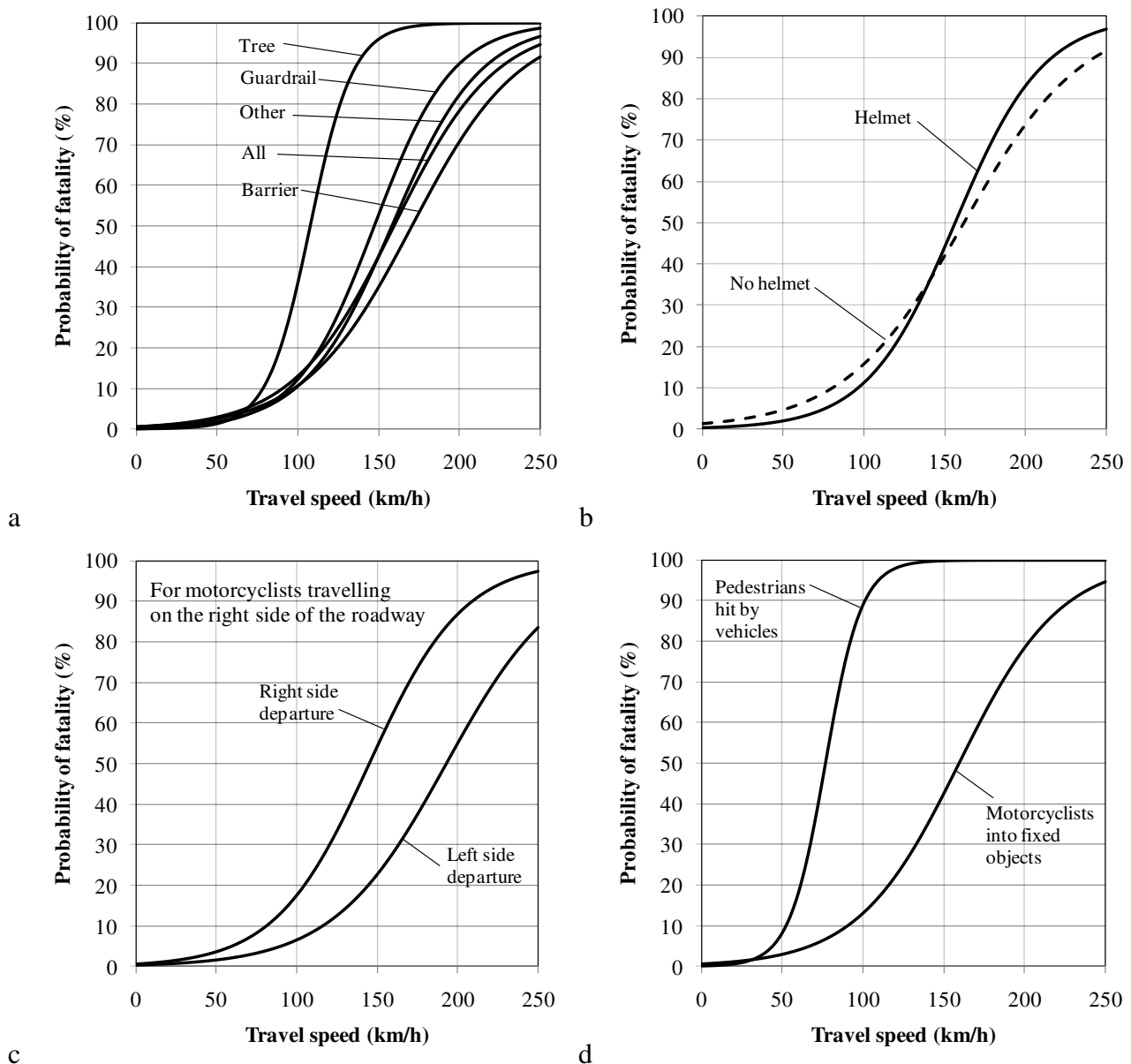
Figure 2: Probability of fatality as a function of travel speed (Table 4), comparing: a) type of fixed object, b) helmet use, c) roadside departure direction and d) motorcyclists and pedestrians

In the interest of comparing the fatality risk for vulnerable road users, a model of fatality risk as a function of vehicle speed for pedestrians impacted by a passenger vehicle (Rosen and Sander, 2009), is compared with the present motorcyclist result in Figure 2d. The model parameters *a* and *b* for the pedestrian model (Equation 3), were determined as -6.9 and 0.09 respectively in Rosen and Sander (2009). It should be noted that the pedestrian fatality risk was developed as a function of impact speed rather than pre-crash travel speed, which explains the large difference in fatality risk versus speed between these two vulnerable road users. The motorcyclist had an opportunity to reduce impact speed through braking and sliding. Unfortunately information was not available to determine the speed at which the motorcyclist struck the object.

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5.   Discussion

The coefficients of the multiple variable logistic regression model in Table 2 indicate that: increased travel speed, older motorcyclists, speed related crashes, late model motorcycles, darkness, interchange locations, non-level roadway profiles and roadside departure to the right-side, are all associated with an increase in the likelihood of fatality. The associations with motorcyclist age and darkness diminish as the travel speed increases. These associations are generally in agreement with those of Quddus et al (2002), Savolainen and Mannering (2007) and Shankar and Mannering (1996), discussed in the introduction. However, the variables that were found not to be significantly associated with a fatality in the present study, in some cases were found to have associations with injury severity in these previous studies.

The result for the single variable model of fatality risk as a function of travel speed in Figure 1, indicates that the risk remains relatively low below 100 km/h, however above this speed the risk rises sharply. As one would expect, the risk of *KSI* is significantly greater than the risk of fatality; however, the increasing risk with travel speed is more gradual. It is interesting to note that the risk of *KSI* does not reduce to zero, and that the risk is above about 20% even for low speed crashes. It should be noted again that travel speed is not the impact speed with which the motorcyclist struck the fixed object. Therefore, one cannot directly compare the present results with those typically used by road authorities such as Austroads (2005), for example, where risk of fatality is typically expressed as a function of impact speed. The impact speeds in the present study would be less than the travel speeds, due to braking, skidding and sliding that may have occurred prior to the collision with the fixed object.

The variable for the type of fixed object impacted by the motorcyclist was significant ($p < 0.0001$); however, not all comparisons with the *barrier* reference group were significant in Tables 2 and 3. Trees are significantly associated with a greater fatality risk than barriers, where collisions with trees are around 3.5 times more likely to result in a fatality than striking a barrier. Poles are *likely* to be associated with a greater fatality risk than barriers (95% confidence interval for the odds ratio of 0.918 – 3.882). Other types of fixed objects were not found to be significantly associated with a greater or lesser fatality risk than barriers. In Figure 2a, trees clearly have the highest fatality risk of the fixed objects considered. Savolainen and Mannering (2007) also found trees and poles to be particularly hazardous to motorcyclists involved in single-vehicle crashes, where the probability of a fatality was increased 525% and 344% with such collisions, respectively. Amongst the two barrier types of guardrail and concrete, Table 4 shows that guardrail is associated with a greater fatality risk than barriers in general, inferring that concrete barriers are a lesser risk (noting that a significant single variable regression model for concrete barriers could not be established). This is a similar result to that of Gabler (2007), who found that the percentage of motorcycle-barrier crashes that were fatal was 12% for guardrail and 8% for concrete. These results suggest that protecting trees or poles with barriers will reduce motorcyclist fatality risk, and that employing a concrete barrier is more beneficial than guardrail. However, the latter conclusion has obvious economic implications.

It should be noted that the conclusions related to concrete barriers apply to the types typically used in these data, being long sections of barrier along which motorcyclists may slide or be redirected, rather than short sections protecting a tree or pole in isolation.

The interaction of helmet use and travel speed indicates that wearing a helmet is associated with a lesser likelihood of a fatality at speeds below 124 km/h (i.e. travelling at or below Australia's highest speed limits); however, a greater likelihood above this speed. This relationship is represented graphically in Figure 2b. Shankar and Mannering (1996) found that helmeted riders have an increased likelihood of being fatally injured, when colliding with fixed objects. They attributed this finding to the possibilities that: non-helmeted motorcyclists may be a self-selected group of safer riders that have riding habits and skills that make them less susceptible to fatal injuries; risk compensation in helmeted riders; some unknown physiological factors associated with fixed object crashes. They also found that, amongst all single-vehicle crashes that occurred at lower speeds (less than 72 km/h), non-helmeted motorcyclists were less likely to be involved in a non-injury crash. The result of a threshold speed value, at which the association of helmet use with fatality changes, may indicate that the functional range of helmets may be exceeded in crashes at higher speeds. This is further supported in a recent study by the authors (Bambach et al), in which 44% of fatally injured motorcyclists received serious (AIS3+) head injury, and 36% received the most severe injury in the head region, while 97% wore helmets. That is, many helmeted motorcyclists received serious or fatal head injuries. The study consisted of 78 motorcyclists fatally injured as a result of a single-vehicle collision with a roadside barrier in Australasia, and the mean travel speed was 101 km/hr. Additionally, in 50% of these barrier cases a thorax injury was the most severe injury received, thus the wearing of a helmet may have had little influence on the fatal injury. While these issues may help to explain why helmet use may not always be associated with a lower likelihood of fatality, they do little to explain why one may find an increased likelihood of fatality with helmet use at much higher speeds (in excess of Australia's highest speed limits). In their discussion of helmet effectiveness, Lin and Kraus (2009) point to a number of studies where authors have speculated that helmet use may increase the likelihood of cervical spinal injuries (as a result of the increased inertial mass of the helmet). However, there are many more authors who have found the converse to be true, thus this issue remains unresolved. Unfortunately, physiological factors could not be further investigated in the present study, since injury outcome was only coded in the GES according to overall severity, with no further detail of the occurrence or severity of particular injuries.

It should be noted that the benefits of helmet use to motorcyclists in all crash modes (single- and multi-vehicle) have been well documented. Statistical studies have found that non-helmeted riders are 2.4 times more likely to receive brain injuries or skull fractures (Gabella 1995), and 3.1 times more likely to receive head injuries (Rowland 1996). A large number of studies have analysed hospital/trauma/emergency room data, and shown that the percentage of motorcyclists that suffer head injuries are significantly greater for non-helmeted riders. For example, the percentage of head injury for non-helmeted riders compared to helmeted riders were; 1.6, 2.8, 3.0, 4.1, 2.8, 2.3, 1.7,

1.9, 1.9, 2.7, 1.7, 2.7 and 3.0 times, respectively, in the studies by; Carr (1981), Luna (1981), Bried (1987), May (1989), Kelly (1991), Murdock (1991), Offner (1992), Shankar (1992), Rutledge (1993), Karlson (1994), Orsay (1995), Rowland (1996) and Goslar (2008).

It is interesting to note the large odds ratio for right-side roadway departure in Table 3. Departures from the roadway on the same side as the travel lane are nearly four times more likely to result in a fatality. This relationship is shown graphically in Figure 2c. This may be a result of the reduced distance over which the motorcyclist may decelerate, as a result of braking, skidding or sliding. Thus while mentioned previously that an important covariate that was missing from the analysis was this magnitude of velocity reduction, the inclusion of the variable for roadway departure direction may partially account for this value.

The odds ratio for motorcycle age in Table 3 indicates that motorcyclists riding a motorcycle of model later than 2000, have 1.687 times the fatality risk. There would likely be many issues involved in how motorcycle age affects crashes: motorcycle power increases over time; braking, suspension and stability improve over time, allowing motorcyclists to respond to situations better; some motorcycles have introduced new safety features such as ABS braking; and motorcyclist protective equipment has improved over time. With the data available, it is presently not possible to determine exactly which issue(s) have resulted in an increase in fatality risk for late model motorcycles.

The comparison of the fatality risk for pedestrians and motorcyclists in Figure 2d, indicates that the associations between speed and fatality are very different for these two groups of vulnerable road users. The pedestrian fatality risk was developed as a function of impact speed rather than pre-crash travel speed. Clearly, a passenger vehicle impacting a pedestrian is physiologically very different to a motorcyclist losing control at a particular travel speed and then impacting a fixed object. The motorcyclist had an opportunity to reduce impact speed through braking and sliding. Unfortunately information was not available to determine the speed at which the motorcyclist struck the object. Additionally, motorcyclists often wear protective clothing and helmets. This could have had a further effect on survivability compared to pedestrians who typically do not wear helmets or protective clothing. Future work points to the development of such curves for motorcycle-passenger vehicle collisions, and pedal cycle-passenger vehicle collisions, in order to assist road safety practitioners to address the safety of vulnerable road users in roadway design.

The limitations of the study should be noted. The GES data is a probability sample, not a census. There are errors involved in the weighting values used in the statistical analysis; however, comparison with the unweighted results indicated the conclusions were not significantly affected (Appendix A). The GES sample was taken from police reported crashes; however, not all crashes that occur are reported to police. Travel speeds were determined by the police investigators, and involve inherent inaccuracies. There may be discrepancies between the manner in which different police jurisdictions record different particulars of a crash. There may be additional variables that are

associated with a fatality, that were not available in the GES data. The statistical method used determines associations with a fatality; however, this does not conclusively imply causality.

6.   Conclusions

Associations with a fatality, conditional upon a motorcyclist being involved in a single-vehicle collision with a fixed object, have been determined from a nationally representative weighted sample of nearly 30,000 crashes that occurred in the United States. Trees and poles were found to be particularly hazardous, and more so than barriers. Fatality risk increased sharply above a travel speed of about 100 km/h, while serious injury risk was greater than 20% even at the lowest travel speeds. Fatality risk as a function of travel speed has been determined, and may provide a useful tool for roadway infrastructure design. It predicts that motorcyclists travelling less than about 55 km/h, could be expected to survive a collision with a fixed object. The effectiveness of motorcycle helmets has been shown to diminish at higher travel speeds; however, motorcyclists travelling at or less than Australia's maximum speed limits, lower their fatality risk by wearing a helmet.

7.   References

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8.   Appendix A – Effect of weighting

The GES weightings for each PAR were set to 1.0, and the multiple variable logistic regression model was generated using SAS in the same manner as that for the weighted model. Unlike the weighted model, the unweighted model did not suffer from overdispersion, as indicated by a dispersion parameter of 1.062. The values of the 16 parameter estimates for the unweighted model, which may be directly compared with those for the weighted model, are (in order from top to bottom of column "Estimate" in Table 2): -7.3473, 0.0353, 0.5430, 0.8340, -0.3494, -3.0081, 4.0983, 0.5848, 0.2294, 2.5738, 0.9813, 0.9036, 1.0670, 0.0283, -0.0407, -0.0212 ($n_{unweighted}$ = 751). Comparison with Table 2 shows that all parameters are within the 95% confidence limits of the weighted model, which indicates that the effect of weighting is small and does not significantly affect the model or the conclusions reached from it.

9.   Appendix B – Literature review of the effects of barrier modifications on injuries

This Appendix presents a literature review of barrier modifications, specifically of modifications for which test or numerical simulations have been performed in order to assess their affect in reducing motorcyclist injures.

The only full scale motorcycle with dummy barrier collision tests that tested original and modified barriers, and are published in the open literature, are those of Berg et al [1]. The test series included concrete barriers, steel guardrail barriers and the steel guardrail barriers modified with an underrun protection board. Tests were performed in both the sliding and upright crash postures. The test results are summarised in Table B1. It is clear that the modified steel barriers generally reduced the measured dummy injury indicators of HIC, accelerations and loads. The paper also noted that in the sliding crash posture, when the dummy impacts the concrete barrier, the HIC, head and chest accelerations and femur loads all exceed the corresponding values for the steel guardrail. In the upright crash posture, only the chest and pelvis accelerations in the concrete barrier collision exceeded those for the steel guardrail.

In [2], tests are described that consisted of dummies launched into IPE 100 barrier posts, including the original post and a post fitted with a polystyrene protector. The tests indicated that impact decelerations were halved with the protector fitted, halving the impact force and approximately doubling the impact time. The deceleration for a chest impact was $860 m/s^2$ for the unprotected post, and $472 m/s^2$ for the protected post. Considering a biomechanical tolerance of around 600-800 m/s^2, the attenuator reduced a fatal crash to a survivable crash.

Additionally in [2], tests are described that consisted of cadavers sliding on their back at 33 km/hr, impacting feet first at 15° into IPE 100 barrier posts, including the original post and a post fitted with a polystyrene protector. The tests indicated that the resulting injuries were AIS 3 against the original post, reducing to AIS 1 for the protected post.

Dummy load	Sliding original	Sliding modified	Upright original	Upright modified	Biomechanical limit
Head HIC	1074	510	277	103	1000
Head acceleration (g)	125	96	74	36	80
Chest acceleration (g)	39	31	13	17	60
Pelvis acceleration (g)	57	19	10	11	60
Femur load (kN)	3.4	3.7	4.1	9.3	10

Table B1: Maximum dummy loads for tests in the sliding and upright postures, colliding with steel guardrail (original) and steel guardrail with underrun protection board (modified)

In [3], numerical simulations using MADYMO were developed for motorcyclists colliding with W-beam guardrails. A number of simple modifications to the guardrails were introduced, including extending the face of the guardrail further towards the ground. Such modifications were simulated to reduce head accelerations and HIC values by 91% and 96%, respectively.

From these studies, it is clear that both impact attenuators and modifications to steel guardrails provide positive benefits to reducing motorcyclist injuries, in the event of a collision below 60km/hr. The studies on steel guardrails suggest that the modifications should include a barrier that extends below the W-beam towards the ground level. This reduces motorcyclist injuries by tending to deflect the motorcyclist along the barrier, rather than impacting directly with a barrier post. However, care needs to be taken in regards to changing the characteristics of the barrier if such changes are made. It is important that the crashworthiness characteristics that result in safe redirection of the vehicles such as small cars, sedans, 4 wheel drives and SUV's are not altered. To this end the 'motorcycle friendly' barrier must be tested for the full range of road users using world's best practice testing and certification regimes.

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10.   Acknowledgements

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