INJURY RISK ASSESSMENT FROM REAL WORLD INJURY OUTCOMES IN EUROPEAN CRASHES AND THEIR RELATIONSHIP TO EURONCAP TEST SCORES.

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ABSTRACT

Assessment of vehicle occupant injury outcomes from the analysis of real crash data is important not only for measuring the safety performance of particular vehicle models but also for monitoring the design improvements in vehicles over time. This paper describes the development and application of methods to assess driver injury risk and injury severity outcomes from the analysis of large police reported crash databases from two major European countries: France and Great Britain. Analysis of injury risk and severity has utilised a new method of analysis based on the paired comparison approach that corrects for inherent bias in the established methods whilst adjusting the injury risk and severity ratings for the influence of non vehicle factors such as occupant and crash characteristics. Outputs from the initial analysis are example vehicle safety ratings that could be developed and used for consumer information on relative vehicle occupant protection performance throughout Europe. A final focus of the study is to examine the relationship between the injury risk and severity ratings derived from the police crash data sources and the relative vehicle safety performance ratings published by EuroNCAP. Comparison is made both at the overall level and between real crash ratings based on specific crash configurations similar to those used in the EuroNCAP test protocol.

INTRODUCTION

This paper describes the analysis in sub-tasks 2.1 and 2.2 of the second phase of the project *Quality Criteria for the Safety Assessment of Cars based on Real-World Crashes* being carried out by the Safety Rating Advisory Committee (SARAC) for the European Commission who fund the project.

Assessment of vehicle occupant injury outcomes from the analysis of real crash data is important not only for measuring the safety performance of particular vehicle models but also for monitoring the design improvements in vehicles over time. To this end, a number of systems to rate relative vehicle safety from the analysis of injury outcomes recorded in police reported crash data. A review of all these systems can be found in Cameron et al (2001a). A number of these systems regularly produce vehicle safety ratings that are published for consumer information in the countries where the ratings systems were developed. Three ratings systems have been developed by the following European organisations:

- Road and Transport Laboratory, University of Oulu, Finland (Huttula, Pirtala and Ernvall 1997)
- Department of the Environment, Transport and Regions (DETR), U.K. (Transport Statistics Report 1995)
- Folksam Insurance, Sweden (Hägg et al 1992; Kullgren 1999)

Each of these vehicle safety ratings systems has developed different measures of vehicle crashworthiness, each attempting to measure the risk of injury or serious injury to a vehicle driver involved in a two-car collision.

This paper reviews the three identified European crashworthiness measures. It then proposes a new crashworthiness measure which overcomes one of the key deficiencies noted in each of three existing measures considered. Application of the new measure is then demonstrated on police reported crash data from both France and Great Britain. Finally the vehicle safety ratings resulting from the application of the method are compared to the outcomes of EuroNCAP barrier testing to assess the relationship between these two measures of driver injury risk in a crash.

A REVIEW OF THE EXISTING EUROPEAN SAFETY RATING SYSTEMS

The rating criteria for each of the three existing methods considered are measures of the risk of injury or severe injury to drivers of specific car models when involved in a crash. In the first two systems, the criterion stops at the risk of injury. In the Folksam method, the criterion goes beyond injury to measure the risk of severe injury in two steps: (1) the risk of injury in a crash, multiplied by (2) the risk of severe injury, given that the driver is injured. For the moment, only the component which measures the risk of injury in a crash is considered. Each of the three rating systems is based on the injury outcomes of two-car crashes involving specific car models. In each system, only two-car crashes in which at least one driver was injured are analysed. Although the University of Oulu has also developed a rating system based on all two car crashes, including those not involving injury, only the system based on injury crashes is considered here.

In reviewing the vehicle crashworthiness measures, it seems apparent that each of the three considered has been developed to overcome limitations when only crashes involving injury to at least one of the drivers involved in the crash are reported. In each of these systems, measures of driver injury risk have been derived that compensate for the lack of availability of non-injury crash data. Whilst each measure is computationally and conceptually different, each has inadequacies in the way it uses the data to form an estimator of driver injury risk in a crash.

To illustrate these inadequacies, consider a conceptual framework similar to that derived by Folksam in the derivation of their injury risk measure based on the two-car crash matched-pair concept. This framework is also suitable for comparing all other vehicle safety estimators considered under the SARAC project. The Folksam framework is defined as follows.

Consider *N* observed two car crashes involving vehicle model *k*. Let p_{1k} be the average injury probability to the driver of the focus vehicle model, *k*, and p_{2k} be the average injury probability to the drivers of all vehicles colliding with vehicle model *k*. Categorising the *N* observed crashes into a 2x2 table defined by injury or no injury to the focus and other vehicle drivers, the following table of expected crash frequencies arises, assuming p_{1k} and p_{2k} to be independent (Table 1).

Let the observed categorised crash frequencies corresponding to the expected values under the conceptual framework in Table 1 for vehicle model *k* be as shown in Table 2.

For data systems not reporting non-injury crashes, n_{nnk} will be unknown in Table 2.

Table 1.
Expected Number of Two-car Crashes between Vehicle Model (k) and Other Vehicles

Drivers of vehicle model *k*	**Drivers of other vehicles**		
	INJURED	NOT INJURED	
INJURED	$N p_{1k} p_{2k}$	$N p_{1k} (1-p_{2k})$	$N p_{1k}$
NOT INJURED	$N(1-p_{1k})p_{2k}$	$N(1-p_{1k})(1-p_{2k})$	$N(1-p_{1k})$
	$N p_{2k}$	$N(1-p_{2k})$	N

Table 2.
Observed Number of Two-car Crashes between Vehicle Model (k) and Other Vehicles

Drivers of vehicle model *k*	**Drivers of other vehicles**		
	INJURED	NOT INJURED	
INJURED	n_{iik}	n_{ink}	$n_{iik}+n_{ink}$
NOT INJURED	n_{nik}	n_{nnk}	$n_{nik}+n_{nnk}$
	$n_{iik}+n_{nik}$	$n_{ink}+n_{nnk}$	N

When the total number of two-car crashes where both drivers are uninjured (n_{nnk}) is known, and hence *N* is known, the margins of Table 2 can be used to derive an unbiased estimator of injury risk to the focus car driver. Such an estimator has been used in crashworthiness systems in Australia (Newstead et al, 2002) and Finland (Huttula et al, 1997) and is defined as follows

$$R_{Ck} = \frac{n_{iik} + n_{ink}}{N}$$

Based on the conceptual framework given in Table 1, the expected value of R_{Ck} is given by

$$E(R_{Ck}) = p_{1k}$$

That is, R_{Ck} is an unbiased estimator of the risk of injury to the driver in the focus vehicle model, *k*.

More recently, attention in vehicle safety ratings systems has turned to estimating the relative risk of injury various vehicle models pose to the drivers of other vehicles with which they collide, a concept labelled aggressivity. Using the same conceptual framework defined in Table 1, an aggressivity metric has been developed in Australia based on injury and non-injury two car crashes (Cameron et al, 1998). The aggressivity injury risk measure is defined as follows

$$R_{Ak} = \frac{n_{iik} + n_{nik}}{N} \text{ with } E(R_{Ak}) = p_{2k}$$

Like the crashworthiness injury risk measure, R_{Ak} is an unbiased measure of the risk of injury to drivers of other vehicles colliding with vehicle model *k*. Until the concept of aggressivity was considered, it was often assumed that p_{2k} would be the same for all vehicle models. In estimating the aggressivity metric on real crash data, however, Cameron et al (1998) show large differences in the aggressivity of different vehicle models. This is important when considering the European crashworthiness measures based on injury only data.

Consider firstly the Folksam estimator of relative injury risk for their vehicle safety ratings system. The Folksam relative injury risk estimator for vehicle model *k* is defined as follows:

$$R_{Fk} = \frac{n_{iik} + n_{ink}}{n_{iik} + n_{nik}}$$

Descriptively, this measure is the ratio of the number of crashes with injured drivers in vehicle model *k* to the number of crashes with injured drivers in all vehicles colliding with vehicle model *k*. This has been described by Folksam as the risk of injury to drivers of vehicle model k relative to the average injury risk of driver injury across the whole vehicle fleet. Based on the conceptual framework given in Table 1, the expected value of R_{Fk} is given by

$$E(R_{Fk}) = \frac{Np_{1k}}{Np_{2k}} = \frac{p_{1k}}{p_{2k}}$$

If R_{Fk} is to be a relative risk comparable across all vehicle models rated, it must be assumed that p_{2k}, the aggressivity injury risk measure, is equal for each vehicle model rated. Folksam argue that this is the case because each vehicle model collides with a similar population of 'other' vehicles. This assumption, however, ignores the possibility that different vehicle models pose different risk of injury to drivers of other vehicles with which they collide, an assumption challenged by the results of Cameron et al (1998). That is, it assumes each vehicle has identical aggressivity which, by definition, is measured by p_{2k} for vehicle model *k*. Consequently, if the Folksam relative injury risk measure is adopted, there can be no corresponding independent measure of vehicle aggressivity derived from the Folksam framework. This point is demonstrated clearly by Broughton (1996).

In practice, the Folksam relative injury risk measure is a function of not only the crashworthiness of the focus vehicle model *k*, p_{1k} , but also its aggressivity, p_{2k}. Further, if there are two vehicles with equal risk of driver injury but differing aggressivity, the vehicle with the higher aggressivity will rate better in the Folksam system.

Consider next the DETR measure of injury risk used in Great Britain defined as follows:

$$R_{Dk} = \frac{n_{iik} + n_{ink}}{n_{iik} + n_{nik} + n_{nik}}$$

Correspondingly, the expected value of R_{Dk} derived from Table 1 is given by

$$E(R_{Dk}) = \frac{p_{1k}}{p_{1k} + p_{2k} - p_{1k}p_{2k}}$$

Conceptually, R_{Dk} measures the risk of injury in the focus vehicle, *k*, given its involvement in a crash where at least one driver is injured. As evident from the expected value of R_{Dk}, the measure, like the Folksam measure, is also a confounded function of the focus vehicle passive safety, p_{1k} , as well as its aggressivity, p_{2k}.

Broughton (1996) considered a partner aggressivity measure similar to the DETR injury risk measure which may also be defined under the conceptual framework being used here as follows:

$$A_{Dk} = \frac{n_{iik} + n_{nik}}{n_{iik} + n_{nik} + n_{ink}}$$

The corresponding expected value is given by

$$E(A_{Dk}) = \frac{p_{2k}}{p_{1k} + p_{2k} - p_{1k}p_{2k}}$$

Whilst A_{Dk} is not the reciprocal of R_{Dk}, as would be the case with a Folksam aggressivity measure derived in the same spirit, A_{Dk} and R_{Dk} are far from independent, as also noted by Broughton (1996).

Turning to the Oulu measure of injury risk derived from injury crash data, defined as follows:

$$R_{Ok} = \frac{n_{iik} + n_{ink}}{2n_{iik} + n_{nik} + n_{ink}}$$

with the corresponding expected value given by

$$E(R_{Ok}) = \frac{p_{1k}}{p_{1k} + p_{2k}}$$

Conceptually, the Oulu injury risk measure is the proportion of all injured drivers in two car crashes involving vehicle model *k* who were drivers of vehicle model *k*. As with the DETR and Folksam measures, crashworthiness and aggressivity of vehicle model *k* are confounded in the Oulu crashworthiness injury risk measure.

AN ALTERNATIVE SAFETY RATING SYSTEM BASED ON INJURY CRASH DATA

To overcome the problem of crashworthiness and aggressivity being confounded in all the existing crashworthiness measures based on the analysis of two-car injury crashes, a new measure is proposed. Again, based on the conceptual framework shown in Table 1, the new measure of driver injury risk in vehicle model *k* is defined as follows:

$$\mathrm{R_{Nk}} = \frac{\mathrm{n_{iik}}}{\mathrm{n_{iik}} + \mathrm{n_{nik}}}$$

The corresponding expected value given by

$$E(R_{Nk}) = p_{1k}$$

R_{Nk} is an unbiased estimator of p_{1k} and as such is not confounded with the aggressivity parameter for vehicle model k, p_{2k}.

Because the new measure is an estimator of absolute injury probabilities, it can be estimated using logistic regression techniques. This allows simultaneous adjustment of concomitant factors affecting injury risk other than the vehicle model, such as driver age and sex and accident circumstances, in a way identical to that used in both the existing Australian and British crashworthiness rating systems. In practice, to estimate the new injury risk measure via logistic regression, two car crashes involving the focus vehicle where the driver of the other vehicle is injured are identified in the crash data. A dichotomous injury outcome for the driver of the focus vehicle is then defined (injured/not-injured) which becomes the dependent variable in the logistic regression model.

If desired, the new injury risk measure can be combined with an injury severity measure in the same way as the existing Australian and Swedish rating systems (Newstead et al, 2002; Haag et al, 1992) to produce a measure of serious injury risk. For the purposes of this paper, the injury severity measure (S_{Nk}) is defined in the same was as that used in the Australian crashworthiness ratings system of Newstead et al (2002). It is the risk of death or hospitalisation to the driver of the focus vehicle given some level of injury is sustained. It can also be estimated by logistic regression techniques incorporating adjustment for the effects of non-vehicle factors in injury severity outcome. The final crashworthiness measure estimates the risk of death or serious injury to the focus driver given crash involvement and is simply the product of the risk and severity components as follows.

$$\mathrm{CWR_{Nk}} = \mathrm{R_{Nk}} \times \mathrm{S_{Nk}}$$

Figure 1 shows the relationship between injury risk to the focus vehicle driver estimated using the new metric and that estimated using full data from both injury and non injury crashes (R_{Ck} above) using an assembled set of both injury and non-injury crash data from 3 States of the USA (see Cameron et al, 2001a). It shows a high degree of correlation between the two rating measures confirming that the new injury risk rating metric can provide ratings consistent with the unbiased measure derived from injury and non-injury data but using only injury data.

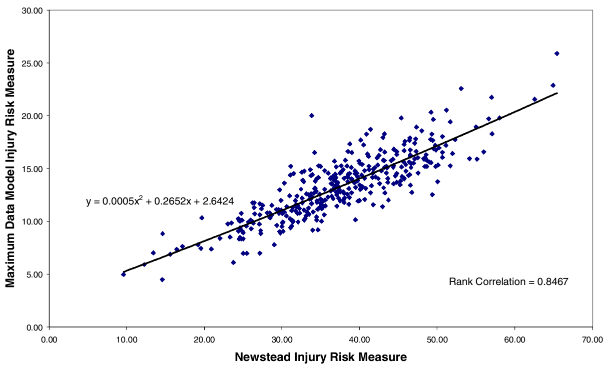

Figure 1: Relationship Between Injury Risk Estimated from Injury and Non-Injury Data and Estimated From Injury Data Only Using the New Metric.

An Associated Aggressivity Measure

It is straight forward to extend the logic by which the new crashworthiness injury risk metric was derived to derive an unbiased measure of aggressivity injury risk from injury only crash data. The corresponding new estimator of aggressivity injury risk in crashes with vehicle make/model *k*, is given by:

$$\mathrm{AR_{Nk}} = \frac{\mathrm{n_{iik}}}{\mathrm{n_{iik}} + \mathrm{n_{ink}}} \quad \text{with } \mathrm{E(AR_{Nk}) = p_{2k}}$$

AR_{Nk} is an unbiased estimator of p_{2k} and as such is not confounded with the crashworthiness parameter for vehicle model k, p_{1k}. Like the crashworthiness risk measure, it can be estimated using logistic regression techniques to adjust for the influence of non-vehicle factors on injury outcome. Like the Australian aggressivity measure based on injury and non-injury crash data (Cameron et al, 1998), the new aggressivity measure can also be extended to measure serious injury risk to the other driver by multiplying the injury risk component by a measure of injury severity.

Figure 2 shows the relationship between aggressivity injury risk to the focus vehicle driver estimated using the new metric and that estimated using full data from both injury and non injury crashes again using the data from 3 States of the USA (see Cameron et al, 2001b). As for the crashworthiness metric, it shows a high degree of correlation between the two aggressivity rating measures confirming that the new metric can provide ratings consistent with the unbiased measure derived from injury and non-injury data but using only injury data.

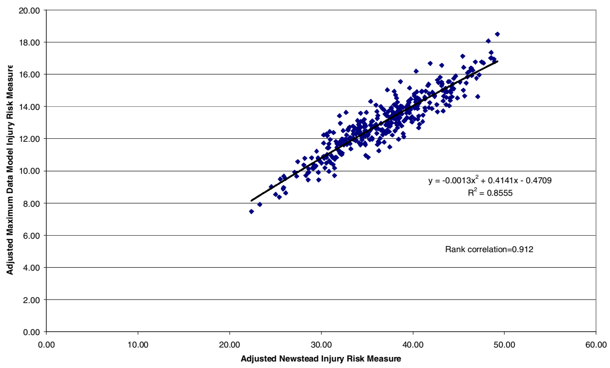

Figure 2. Relationship between aggressivity injury risk estimated from injury and non-injury data and estimated from injury data only using the new metric.

Figure 3 shows the relationship between the new risk measures of crashworthiness and aggressivity for the set of vehicle models rated from the USA data. It demonstrates the desirable property of a high degree of independence between the two measured dimensions of vehicle safety. As noted by Broughton (1996), none of the existing measures of vehicle safety derived from injury only crash data have been able to achieve this level of independence between measures in the two dimensions.

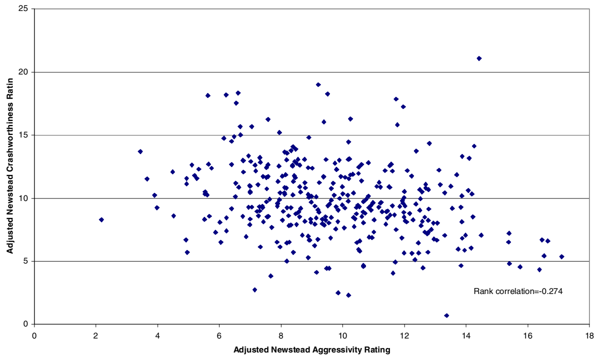

Figure 3. Relationship between the new measures of crashworthiness and aggressivity

APPLICATION OF THE RATING SYSTEM TO POLICE REPORTED CRASH DATA FROM FRANCE AND GREAT BRITAIN

To demonstrate the application of the new crashworthiness measure based on injury only police data, the methods have been applied to estimate crashworthiness ratings for specific vehicles using police reported crash data from two European countries, France and Great Britain. In both countries, only crashes involving injury are reported to police.

Crash Data Sources

<u>**Real Crash Data from Great Britain**</u>

In Great Britain, all road accidents involving human death or personal injury occurring on the highway ('road' in Scotland) and in which one or more vehicles are involved, are required to be reported to the police within 30 days of occurrence. In addition, all fatal or injury accidents on public roads involving at least one mechanically propelled vehicle should be reported to police unless insurance documents, driver details and ownership and registration information are exchanged between drivers. These data are then recorded in the STATS19 database. Crashes not involving human injury do not appear in the data. Crash data for the period 1993 to 2001 were supplied for use in this study by the UK Department for Transport (DfT).

Driver injury level is coded in the British data using a three level scale. These levels are:

1. Fatal: includes cases where death occurs in less than 30 days as a result of the accident
2. Serious injury: includes fractures, internal injury, severe cuts, crushing, burns, concussion, severe shock requiring hospital treatment, detention in hospital as

an in-patient immediately or at a later date, injuries from the crash resulting in death 30 days or more after the crash

3. Slight injury: including sprains or whiplash not necessarily requiring medical treatment, bruises, slight cuts, slight shock requiring roadside attention.

After selecting passenger vehicles only, complete information for the required variables was available for 1,635,296 crashes. Information on the non-vehicle factors driver age, driver sex, junction, point of impact and speed limit of the crash site was also available in the data. Estimation of injury risk for all crash types using the new method considered 546,984 two-car crashes. Estimation of injury severity for all crash types using the Australian severity measure considered a total of 775,972 injured drivers involved in either single vehicle (159,306) or two-vehicle crashes (616,666). For the purposes of comparison with EuroNCAP results, sub-sets of these data were also used to estimate injury risk and injury severity for front impact and side impact crashes after selecting for the point of impact on the focus vehicle.

Real Crash Data from France

In France, every road accident in which at least one road user received medical treatment is investigated by the police and included in a national database managed by the Ministry of Transportation. An extract this database for the years 1993 to 2001 was supplied by the Laboratory of Accidentology, Biomechanics and Human Behaviour (LAB) in France for use in this study. Only those cases meeting the following criteria were provided:

- No two wheelers involved;
- Only drivers or right front passengers of private cars whose injury severity is known;
- All types of collisions and obstacles.

Driver injury level is coded in the French data using a four level scale. These levels are:

1. Uninjured: no medical treatment
2. Fatal: death within seven days of the crash
3. Serious injury: more than 6 days in hospital
4. Slight injury: less than seven days in hospital

Of the records provided, a total of 610,118 contained complete information for the required variables. Variables on the non-vehicle factors driver age, driver sex, road junction type, point of impact and speed limit of the crash site were also available in the data. Estimation of injury risk using the new method considered 280,603 two-car crashes. Estimation of injury severity using the Australian severity measure considered a total of 379,557 injured drivers involved in either single vehicle (98,249) or two-vehicle crashes (281,308). Sub-sets of these data were used to estimate injury risk and injury severity for front impact and side impact crashes after selecting for the point of impact on the focus vehicle.

Because of fundamental differences in injury level coding of the French and UK data, they could not be combined for analysis and were analysed separately.

Identification of Vehicle Models

Because the secondary focus of this study was to compare the new crashworthiness metric with results from EuroNCAP testing, only EuroNCAP tested vehicle models were chosen from the real crash data for analysis. EuroNCAP tested vehicles were selected for inclusion in the analysis where at least 80 drivers were involved in two-car crashes and at least 20 drivers were injured in single and two-car crashes combined. Of the 138 EuroNCAP vehicle models tested to the middle of 2003, there were 70, 52 and 23 vehicle models with sufficient real crash data from all crash types, front impact crashes and side impact crashes respectively, to be included in the British analysis. The French data was sufficient to estimate 36, 31 and 5 vehicle models in all crash types, front impact crashes and side impact crashes respectively.

Information on the vehicle identification number (VIN) was available in neither the British nor the French database. Therefore, selection of vehicle models from the crash data for comparison with EuroNCAP test result had to be carried out on the basis of the make and model coding descriptions available in the data along with year of manufacture in comparison with the model specifications reported for the EuroNCAP tested vehicles.

Vehicle safety ratings estimated from real crash data

Adjustment for Non-Vehicle Factors

Logistic models of injury risk and injury severity as a function of the non-vehicle factors available in the data were fitted separately for each component using the logistic procedure of the software package SAS. At this stage the vehicle model was not included as a factor in the model. In addition to fitting main effects of the non-vehicle factors, interactions of first and higher order were included. To avoid an overly complex final model or one that might become unstable in the estimation procedure, a stepwise approach was used to fit the model, with the restriction that an interaction could only be considered if the main effect terms of the interaction were significant predictors of injury risk/injury severity. This approach has been used successfully in estimating the Australian crashworthiness ratings (Newstead et al, 2002) and gives a greater chance that the fit of the final model to the data will be acceptable.

Table 3.
Significant factors in the logistic regression models of injury risk and injury severity derived from the British data

Significant Model Factors	Injury Risk	Injury Severity
Main Effects	driver age (age) driver sex (sex) junction type (jun) point of impact (poi) speed limit (sl)	driver age (age) driver sex (sex) junction type (jun) no. of vehicles (nov) point of impact (poi) speed limit (sl)
1st Order Interactions	jun×poi, jun×sl, age×poi, sex×jun, poi×sl, age×sex, sex×poi, age×sl, age×jun	nov×sl, nov×poi, jun×poi, jun×nov, sex×nov, age×sex, sex×sl, poi×sl, jun×sl, age×jun, sex×jun, age×sl, sex×poi, age×poi, age×nov
2nd Order Interactions	jun×poi×sl sex×jun×poi age×sex×poi age×poi×sl age×jun×poi	jun×poi×sl, jun×nov×poi, age×nov×poi, age×jun×poi, jun×nov×sl, sex×jun×sl, sex×jun×nov, age×sex×sl, nov×poi×sl, sex×poi×sl, sex×jun×poi, age×sex×nov
3rd Order Interactions		jun×nov×poi×sl

Tables 3 and 4 detail the main effects and interactions that were judged to be significant predictors of injury risk and injury severity for all crash types through the stepwise logistic modelling approach. As a final step, the model was re-fitted including the significant non-vehicle factors and their interactions along with a variable indicating vehicle model as a main effect in each of the models. In each case, vehicle model was a significant predictor of injury outcome. No interaction between the "vehicle model" and other covariates in the model was included, as this would cause difficulty in interpretation of the vehicle model main effect.

Table 4.
Significant factors in the logistic regression models of injury risk and injury severity derived from the French data

Significant Model Factors	Injury risk	Injury Severity
Main Effects	driver age (age) driver sex (sex) Intersection type (int) urbanisation (urb)	driver age (age) driver sex (sex) number of vehicles involved (nbv) Intersection type (int) urbanisation (urb) year of crash (yea)
First Order Interactions	age × sex sex × int age × urb int × urb age × int	age × sex age × nbv sex × nbv age × int sex × int nbv × int age × urb sex × urb nbv × urb int × urb
Second Order Interactions	age × sex × int age × int × urb	age × nbv × int sex × nbv × urb age × int × urb sex × int × urb age × sex × nbv Age × nbv × urb

An identical approach was adopted to determine the significant predictors of injury risk and injury severity for front impact and side impact crashes. Due to space constraints these results are not presented here.

Estimated Ratings

Crashworthiness ratings for each EuroNCAP tested vehicle included in the analysis were calculated by taking the product of the estimated injury risk and severity components. Tables 5 and 6 show the resulting British and French crashworthiness ratings for all crash types, front impact crashes and side impact crashes. Upper and lower confidence limits for the all crash type crashworthiness rating are also provided and were calculated using the method detailed in the Newstead et al (2002).

Table 5.
Crashworthiness ratings estimated from British crash data

Vehicle Make/Model	Crash-worthiness Rating	Estimated Injury Risk	Estimated Injury Severity	Lower 95% CI CWR	Upper 95% CI CWR	Front Impact CWR	Side Impact CWR
All Model Average	**3.72**	**34.74**	**10.72**			**4.61**	**4.87**
Fiat Punto 94-97	4.28	39.73	10.77	3.59	5.10	4.80	3.93
Ford Fiesta 95-99	4.27	39.25	10.87	3.85	4.73	5.02	5.36
Nissan Micra 93-98	5.76	40.42	14.26	4.94	6.73	6.82	6.97
Renault Clio 91-98	4.97	42.22	11.78	3.42	7.23	5.82	
Rover 100 95-98	5.42	40.18	13.48	4.67	6.28	6.20	7.90
Vauxhall Corsa 93-98	4.05	36.27	11.16	2.70	6.07	6.01	
V'wagen Polo 94-99	4.26	38.98	10.92	3.57	5.07	4.92	5.98
Audi A4 95-00	3.54	31.67	11.18	2.41	5.20	2.83	
BMW 3 Series 91-98	3.10	27.93	11.10	2.64	3.64	3.39	4.04
Citroen Xantia 93-00	3.04	30.08	10.11	2.43	3.80	3.47	3.26
Ford Mondeo 96-00	3.57	33.78	10.57	3.08	4.14	4.01	5.84
Mercedes C180 93-00	1.69	31.29	5.40	0.99	2.90	1.48	
Nissan Primera 96-99	3.64	31.05	11.71	2.71	4.89	4.37	
Peugeot 406 96-99	2.95	27.92	10.57	2.42	3.60	3.65	3.59
Renault Laguna 94-98	3.12	34.35	9.07	2.36	4.12	4.23	
Rover 620 93-99	3.31	32.26	10.27	2.58	4.25	3.27	7.04
Saab 900 93-98	3.02	24.32	12.43	1.64	5.57		
Vauxhall Vectra 95-99	3.92	33.13	11.82	3.42	4.48	4.42	5.47
V'wagen Passat 97-00	4.95	32.40	15.27	3.16	7.75	6.79	
Audi A3 96-02	3.22	33.46	9.62	1.83	5.67	4.43	
Citroen Xsara 97-02	3.82	38.18	10.00	2.42	6.02	4.45	
Daewoo Lanos 97-02	4.06	35.00	11.59	2.68	6.14	4.54	
Fiat Brava 95-02	3.66	35.27	10.38	2.93	4.58	4.62	3.42
Honda Civic 95-00	5.26	37.92	13.87	4.47	6.19	5.79	6.25
Hyundai Accent 94-99	5.20	42.23	12.30	3.48	7.76	4.39	
Peugeot 306 97-01	4.74	38.06	12.47	4.09	5.50	5.24	5.72
Renault Megane 96-99	3.52	34.87	10.09	2.84	4.37	3.97	3.55
Suzuki Baleno 95-01	4.03	35.13	11.46	2.36	6.86	4.41	
Toyota Corolla 97-01	4.22	33.45	12.62	3.04	5.87	3.98	
V'wagen Golf 97-02	3.46	27.65	12.53	1.79	6.69		
Audi A6 97-02	1.92	29.44	6.53	0.84	4.38		
BMW 520i 96-02	3.24	25.25	12.84	2.12	4.95	3.89	
Mercedes E200 95-99	3.36	28.95	11.59	1.87	6.03		
Saab 9-5 97-01	2.05	25.07	8.18	0.74	5.68		
Vauxhall Omega 94-99	2.93	31.94	9.17	2.21	3.88	3.09	2.99
Volvo S70 96-99	4.04	35.63	11.34	1.77	9.21		
Ford Focus 98-02	3.43	33.69	10.17	2.78	4.23	3.86	3.93
Mercedes A140 98-02	5.51	40.42	13.63	3.23	9.39	7.03	
Vauxhall Astra 98-02	4.53	40.21	11.27	3.89	5.28	4.90	6.27
Ford Escort 91-00	4.18	37.79	11.05	3.80	4.59	4.62	5.52
Nissan Almera 95-00	4.01	40.90	9.80	2.66	6.05	5.76	
Nissan Serena 93-00	4.33	32.08	13.49	2.07	9.05		
V'wagen Sharan 95-00	2.69	26.94	10.00	1.25	5.79		
Vauxhall Corsa 98-00	4.02	37.83	10.64	3.30	4.90	4.68	4.76
Honda Accord 98-99	1.01	33.79	2.99	0.25	4.06		
Saab 9-3 98-02	2.22	20.55	10.79	1.00	4.91		

Vehicle Make/Model	Crash-worthiness Rating	Estimated Injury Risk	Estimated Injury Severity	Lower 95% CI CWR	Upper 95% CI CWR	Front Impact CWR	Side Impact CWR
Ford Ka 96-02	4.44	39.12	11.34	3.70	5.32	5.46	4.78
Volvo S40 96-02	2.38	33.69	7.06	1.36	4.15	3.54	
Toyota Avensis 97-00	3.37	36.68	9.18	2.35	4.83	3.25	
Citroen Saxo 96-02	4.80	45.16	10.63	4.17	5.52	5.26	5.97
Daewoo Matiz 98-00	8.69	49.54	17.54	6.05	12.48	9.05	
Fiat Seicento 98-02	5.66	48.13	11.77	3.53	9.10	7.92	
Ford Fiesta 99-02	4.67	41.23	11.32	3.73	5.84	5.74	
Nissan Micra 98-02	6.82	44.22	15.41	4.15	11.19	8.23	
Peugeot 206 98-02	4.15	38.32	10.83	3.14	5.49	4.47	
Renault Clio 98-01	3.08	36.05	8.53	2.22	4.26	3.58	
Rover 25 99-02	4.76	45.19	10.53	3.04	7.44	5.43	
Toyota Yaris 99-02	4.69	42.01	11.16	2.85	7.70	6.20	
V'wagen Polo 00-02	4.08	37.23	10.95	2.54	6.53	4.04	
Nissan Almera 99-02	3.17	35.48	8.93	1.61	6.23		
BMW 3 Series 98-00	3.04	30.11	10.11	2.12	4.36	3.13	
Peugeot 406 99-02	3.46	30.22	11.46	2.41	4.98	4.17	
Rover 75 99-02	1.60	19.96	8.02	0.63	4.08		
Vauxhall Vectra 99-02	4.23	32.41	13.05	3.30	5.43	4.25	4.00
V'wagen Passat 00-02	3.21	33.22	9.66	2.14	4.81	4.06	
Citroen Picasso 00-02	3.93	36.34	10.82	1.62	9.55		
Renault Scenic 99-02	3.25	36.20	8.98	1.77	5.98	3.84	
Mazda MX-5 98-02	5.44	38.70	14.05	3.45	8.58		
Jeep Cherokee 96-02	2.22	22.03	10.09	1.06	4.64		
Vauxhall Corsa 00-02	3.99	39.96	9.99	2.03	7.85		

NB: Blank cells indicate insufficient data was available to obtain an estimate

Table 6.
Crashworthiness ratings estimated from French crash data

Vehicle Make/Model	Crash-worthiness Rating	Estimated Injury Risk	Estimated Injury Severity	Lower 95 CI CWR	Upper 95 CI CWR	Front Impact CWR	Side Impact CWR
All Model Average	**11.45**	**48.88**	**23.42**			**11.76**	**17.35**
Fiat Punto 94-97	13.45	57.06	23.57	11.54	15.67	13.28	15.33
Ford Fiesta 95-99	14.20	56.36	25.20	11.79	17.11	14.88	
Nissan Micra 93-98	16.09	57.51	27.98	8.96	28.88		
Renault Clio 91-98	17.10	59.31	28.84	15.41	18.98	16.59	17.75
Opel Corsa 93-98	15.06	56.52	26.64	12.51	18.11	15.72	
Volkswagen Polo 94-99	15.54	56.29	27.61	12.97	18.63	13.73	
BMW 3 Series 91-98	14.29	46.29	30.87	9.73	20.99	16.00	
Citroen Xantia 93-00	11.52	45.24	25.47	9.87	13.46	10.63	16.52
Ford Mondeo 96-00	4.54	40.57	11.18	2.11	9.75	5.18	
Mercedes C180 93-00	7.89	36.64	21.52	3.15	19.72		
Nissan Primera 96-99	1.97	39.20	5.04	0.30	12.90		
Peugeot 406 96-99	9.28	40.32	23.01	7.39	11.65	9.57	
Renault Laguna 94-98	11.36	45.96	24.71	8.90	14.50	11.61	
Opel Vectra 95-99	8.82	41.89	21.06	5.50	14.15	7.57	
Audi A3 96-02	8.48	45.50	18.63	3.82	18.81	6.08	
Citroen Xsara 97-02	13.60	53.83	25.26	10.19	18.15	15.06	
Fiat Brava 95-02	15.78	52.88	29.85	12.04	20.69	13.58	
Honda Civic 95-00	10.67	42.05	25.38	6.51	17.49	10.90	
Peugeot 306 97-01	12.03	49.16	24.47	10.16	14.25	11.12	16.75
Renault Megane 96-99	15.29	52.00	29.40	12.84	18.20	15.25	
Ford Focus 98-02	10.18	50.51	20.16	5.78	17.93	10.23	
Opel Astra 98-02	9.30	48.89	19.03	5.72	15.13	9.39	
Ford Escort 91-00	14.01	52.08	26.89	11.72	16.73	14.98	
Renault Espace 97-02	5.32	29.83	17.85	2.68	10.59	6.32	
Peugeot 806 95-98	17.02	43.41	39.20	9.60	30.18		
Opel Corsa 98-00	12.67	53.52	23.67	8.76	18.32	14.47	
Ford Ka 96-00	10.30	48.50	21.24	6.40	16.58	12.42	
Citroen Saxo 96-02	17.69	59.90	29.53	15.21	20.56	16.78	16.79
Ford Fiesta 99-02	12.34	62.04	19.89	6.66	22.87	15.20	
Peugeot 206 98-02	13.79	58.01	23.77	10.08	18.86	12.55	
Renault Clio 98-01	10.11	50.34	20.08	7.51	13.61	10.80	
Volkswagen Polo 00-02	14.97	57.42	26.08	8.99	24.93	15.02	
BMW 3 Series 98-00	12.44	39.21	31.72	6.42	24.11		
Peugeot 406 99-02	8.57	40.65	21.09	5.68	12.95	8.65	
V'wagon Passat 97-00	16.22	44.04	36.84	10.38	25.36	12.74	
Renault Scenic 99-02	6.18	43.64	14.17	3.33	11.47	5.81	

NB: Blank cells indicate insufficient data was available to obtain an estimate

COMPARISON OF REAL CRASH RATINGS WITH EURONCAP RATINGS

Having successfully estimated vehicle safety ratings from the French and British police reported crash data using the new crashworthiness metric, of interest was to compare the consistency of these ratings to those derived through the EuroNCAP barrier test program.

In comparing EuroNCAP crash test results with real crash outcomes in Sweden, Lie and Tingvall (2000) computed the average real crash injury rates for vehicles grouped within each overall star rating. It was hypothesised that occupants of EuroNCAP tested vehicles with a particular rating should have a lower average risk of serious injury in real crashes than those with a lesser star rating. If so, the overall barrier crash performance star rating given to each vehicle from EuroNCAP testing would be broadly representative of relative real crash outcomes. Based on the Swedish data analysed, Lie and Tingvall (2000) indeed found that EuroNCAP tested vehicles rated four stars had a lower average risk serious injury risk in real crashes than those rated three stars. The three star vehicles had a correspondingly lower average risk than vehicles rated two stars. The analysis that follows also considers the relationship between real crash safety ratings and overall EuroNCAP star ratings.

An overall EuroNCAP star rating scale of five categories is used to classify vehicle safety performance based on crash test results. The four star categories are derived from the results of both the offset frontal and side impact EuroNCAP test components. In this study the overall EuroNCAP score and corresponding star rating are calculated based only on the driver dummy measurements in the EuroNCAP test to ensure compatibility with the real crash ratings that relate to driver injury outcome only. In contrast, the official scores published by EuroNCAP consider both the driver and front passenger dummy scores in the offset frontal barrier test. Also, the EuroNCAP overall scores used here do not include the pole test result. Analysis conducted using EuroNCAP overall scores including the pole test for those few vehicle models for which it was available produced similar results.

Figures 4 and 5 show overall EuroNCAP scores plotted against crashworthiness estimated from the British and French data respectively. Individual EuroNCAP scores are grouped according to the corresponding star rating and 95 per cent confidence limits are placed on the estimates of the real crash measures.

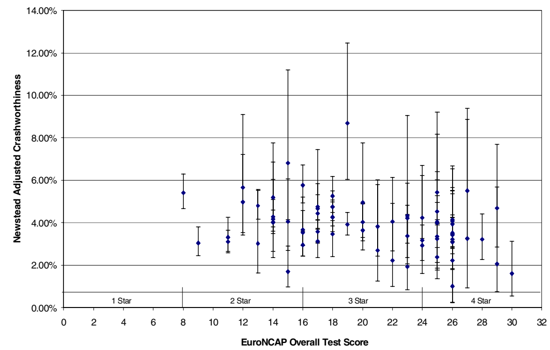

Figure 4. Overall EuroNCAP test score vs. estimated crashworthiness (Great Britain).

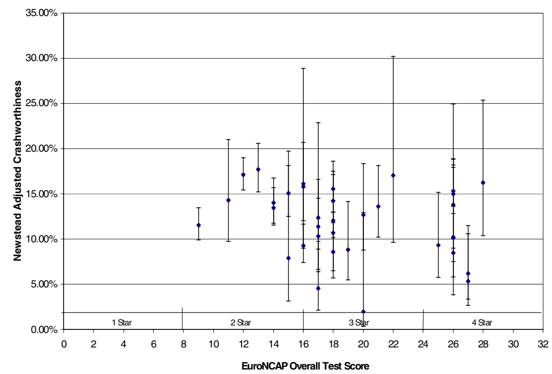

Figure 5. Overall EuroNCAP test score vs. estimated crashworthiness (France).

Figures 4 and 5 show a general trend of improvement in the new crashworthiness measure with increasing EuroNCAP star rating, in line with the findings of Lie and Tingvall (2000). However, within each overall star rating category, there is significant variation in the estimated new crashworthiness measure between vehicles. This variation is partly a product of the estimation error in the crashworthiness measure, particularly for vehicle models with relatively few records in the crash data, as shown by the 95% confidence limits. However, there are significant differences in the real crash measures between vehicle models within the same EuroNCAP star rating, and even between vehicle models with almost the same overall EuroNCAP rating score from which the star ratings are derived. This is demonstrated by the non-overlapping confidence limits on the real crash measures between pairs of vehicles within the same overall star rating category.

These results suggest that there are other vehicle factors, apart from those summarised in the overall EuroNCAP score that are determining real crash outcomes. These other factors are also different from the non-vehicle factors that have already been compensated for in the estimation of the real crash based ratings, such as driver age and sex and speed limit at the crash location.

A comparison of real crash safety ratings and EuroNCAP scores for front and side impact crashes has also been conducted using both the British and French data. In this analysis the driver dummy measurements recorded in the offset frontal and side impact EuroNCAP test components respectively are segregated into four categories to develop a pseudo star rating for comparison with real crash outcomes. Figures 6 and 7 show overall EuroNCAP scores plotted against crashworthiness estimated from the British data for front and side impact crashes respectively. Similar analysis was conducted using the French data producing similar results that are not shown here.

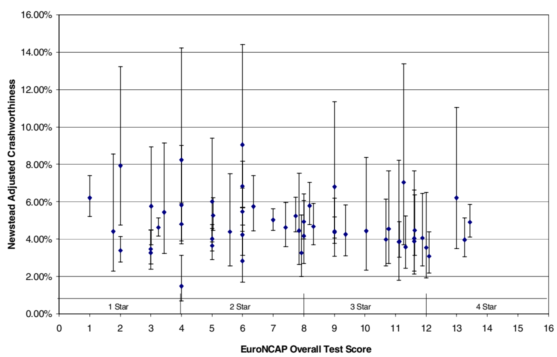

Figure 6. Front impact EuroNCAP test score vs. estimated crashworthiness (front impact crashes: Great Britain).

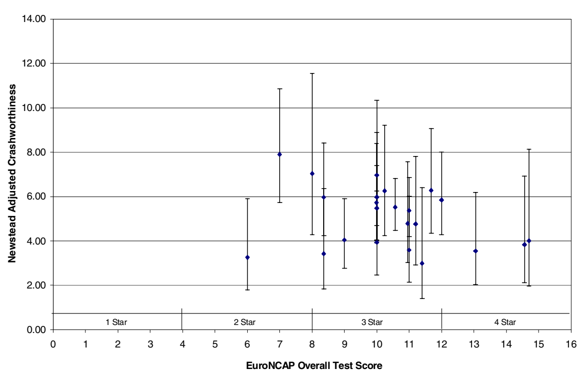

Figure 7. Side impact EuroNCAP test score vs. estimated crashworthiness (side impact crashes: Great Britain).

The comparison of EuroNCAP front and side impact test scores and estimated crashworthiness for front and side impact crashes showed even weaker association between the two measures. Similar to the results found in the analysis of all crash types, analysis by impact type showed significant variation in the estimated crashworthiness of vehicles within each EuroNCAP score range. However, the relatively wide confidence limits on the crashworthiness estimates by impact type make it difficult to draw conclusions from these comparisons.

Logistic regression comparison of real crash ratings and overall EuroNCAP star ratings

The above analysis has studied the general relationships between the real crash based and EuroNCAP based secondary safety ratings using graphical techniques. In order to make more definitive statements about the relationships between the two safety measures a logistic regression analysis framework has been used. Vehicle safety rating measures derived from real crash data have been modelled as a function of the EuroNCAP overall star rating to assess the statistical significance of differences in average serious injury risk in real crashes between EuroNCAP star ratings.

The new crashworthiness measure for each vehicle model i (CWR_i) has been modelled as a function of the overall EuroNCAP star rating in a logistic model of the following form.

$$\begin{aligned} &\operatorname{logit}(\mathrm{CWR}_i) = \\ &\alpha + \beta(\text{EuroNCAP overall star rating}_i) \end{aligned}$$

In the equation, i is the vehicle model index and α and β are parameters of the logistic model. The EuroNCAP star rating is one of 1, 2 ,3 or 4. It may be expected that a higher star rating would be associated with improved crashworthiness in real crashes, or that there will be some monotonic relationship between the barrier test and real crash measure. However, to maintain objectivity, no restriction has been placed on the form of the relationship between the star rating categories and the dependent injury outcome variable.

Previous work has highlighted the relationship between vehicle mass and real crash outcome with vehicles of higher mass generally having better real crash ratings for injury risk, injury severity and crashworthiness. To test this relationship on the current data, a logistic regression, estimating the effect of mass on real crash outcome, has been conducted using the British and French data. Figure 8 demonstrates a strong relationship between the crashworthiness measure and vehicle mass, with vehicles of higher mass generally associated with a lower (better) crashworthiness rating.

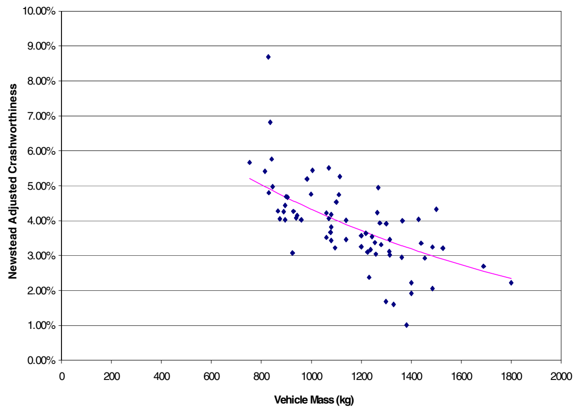

Figure 8. Newstead adjusted crashworthiness for all crash types (Great Britain) vs Vehicle mass.

Analysis of crashworthiness estimates derived front and side impact real crash data produces similar results, as does an analysis of the French data.

In contrast to real crash outcomes, the EuroNCAP score is purported to be independent of vehicle mass. Therefore, in exploring the relationship between the real crash safety measures and EuroNCAP test scores, the apparent contrasting influence of vehicle mass on the two safety measures must be accounted for. To achieve this, vehicle mass is included as an extra predictive term in the logistic regression form given above and operates to remove the effect of mass from the analysis.

The key output from the logistic model is the average crashworthiness across vehicles within each EuroNCAP star rating. Analysis of the point estimates and associated confidence limits of parameters in the logistic regression analysis provides information on the statistical significance of the relationship between each of the real crash safety measures and EuroNCAP star ratings. Non-overlapping confidence limits across EuroNCAP star rating classes indicate that there is a statistically significant relationship between EuroNCAP star ratings and the real crash safety measure. That is, the EuroNCAP star ratings are able to differentiate between levels of real crash outcome. In contrast, overlapping confidence limits across EuroNCAP star rating classes indicate that the EuroNCAP star rating is unable to statistically significantly differentiate between real crash injury outcomes as measured by the new crashworthiness metric.

Tables 7 and 8 present the results of the logistic regression analysis for all crash types based on the British and French data respectively. The tables present the average of the new crashworthiness measure for vehicles within each overall EuroNCAP star class along with 95% confidence limits. To assess which pairs of the star rating classes have significantly different average crashworthiness, the confidence limits on the parameter point estimates generated from the logistic modelling procedure must be compared to see if they overlap.

Table 7.
Mass adjusted Crashworthiness estimates and 95% confidence limits by EuroNCAP star rating categories: all crash types (Great Britain)

	All Crash Types (with mass adjustment)			
	Overall Star Rating			
	1	2	3	4
Estimate	**4.48%**	**3.99%**	**4.14%**	**3.86%**
LCL	4.01%	3.78%	3.93%	3.60%
UCL	4.99%	4.20%	4.36%	4.14%

Table 8.
Mass Adjusted Crashworthiness estimates and 95% confidence limits by EuroNCAP star rating categories: all crash types (France)

	All Crash Types (with mass adjustment)			
	Overall Star Rating			
	1	2	3	4
Estimate		**14.72%**	**13.31%**	**13.00%**
LCL		14.08%	12.66%	12.20%
UCL		15.38%	14.00%	13.83%

Table 7 shows a general trend to improving average crashworthiness with increasing EuroNCAP star rating in the British data, although there is little difference between the average crashworthiness in star categories 2 and 3. Furthermore, because the confidence limits on the average crashworthiness ratings for each star category overall, it is not possible to conclude that the average injury outcomes are statistically significantly different between star rating categories.

Analysis of the French data ratings in Table 8 show a more consistent trend to improving crashworthiness with increasing EuroNCAP star rating from 2 to 4. There were no 1 star rated cars with sufficient French police crash data to assess this category. The French analysis results found that 2 star rated vehicles had an average crashworthiness significantly worse than higher star rated vehicles, indicated by the non-overlapping confidence limits. However, 3 star rated vehicles did not have an estimated crashworthiness rating statistically different to 4 star rated vehicles.

Analysis of the relationship between the EuroNCAP pseudo star ratings developed for front and side impact crashes and the real crash measures for these crash types derived from the British data is presented in Tables 9 and 10. These results do no indicate any statistically significant relationship between the EuroNCAP star ratings and the crashworthiness estimates derived from the British data for either front or side impact crashes. However, the side impact analysis pointed to a trend of improving side impact injury risk in real crashes with increasing EuroNCAP side impact star rating, with 4 star rated vehicles being on average significantly better than 2 star rated vehicles.

Table 9.
Mass adjusted crashworthiness estimates and 95% confidence limits by EuroNCAP star rating categories: front impact crashes (Great Britain)

	All Crash Types (with mass adjustment)			
	Overall Star Rating			
	1	2	3	4
Estimate	**4.58%**	**4.75%**	**4.83%**	**4.70%**
LCL	4.31%	4.48%	4.50%	4.25%
UCL	4.87%	5.03%	5.18%	5.20%

Table 10.
Mass adjusted crashworthiness estimates and 95% confidence limits by EuroNCAP star rating categories: side impact crashes (Great Britain)

	All Crash Types (with mass adjustment)			
	Overall Star Rating			
	1	2	3	4
Estimate		**6.71%**	**5.56%**	**4.04%**
LCL		5.45%	4.75%	3.10%
UCL		8.24%	6.51%	5.24%

DISCUSSION AND CONCLUSIONS

This paper has detailed the development of a new measure of vehicle secondary safety estimated from police reported crash data covering only crashes where an occupant injury has occurred. The new crashworthiness measure estimates the risk if injury to drivers of vehicles given involvement in a crash. It can be multiplied by existing measures of injury severity outcome, typically the risk of death or serious injury given an injury was sustained, to give a resulting measure of serious injury risk to drivers in a crash.

The key feature of the new crashworthiness injury risk measure is that it is not confounded by the aggressivity of the vehicle model of which the secondary safety performance is being assessed. Aggressivity in this context is defined as the risk of injury to the driver of a vehicle colliding with the focus vehicle. Because aggressivity is not confounded with the crashworthiness injury risk measure, a corresponding new independent measure of vehicle aggressivity has also been defined. None of the vehicle secondary safety measures estimated from injury-only crash data currently in use in Europe can claim this property.

Another key advantage of the new measure is that it is an estimator of absolute injury risk in a crash. This allows logistic regression techniques to be used to estimate the measure whilst simultaneously controlling for the effects of non-vehicle factors associated with the occupant and crash that effect injury outcome. Only one of the three currently used European measures has this property, the DETR method. Controlling for non-vehicle factors in the other two methods is achieved through post-hoc normalisation techniques requiring assumptions to be made about the likely asymptotic statistical distribution of the resulting measures to be able to calculate standard errors and confidence limits on the adjusted estimates. No such assumptions need to be made when using logistic regression for the adjustment process.

Successful application of the new measures of secondary safety on police reported crash data from both Great Britain and France has been demonstrated. The resulting ratings by vehicle model only cover those vehicles tested under EuroNCAP to suit the goals of the study. There is no reason why the technique could not be applied to estimate ratings for the full range of vehicle models represented in each data set with sufficient data to produce meaningfully accurate results.

Estimation of the aggressivity measure on the European data sets considered in this study was not demonstrated in this paper. However, prior experience in applying the new measures to sample crash data from the USA confirms the process of estimating aggressivity ratings is also viable producing meaningful estimates that are empirically independent of the corresponding crashworthiness estimates. Given this experience, in tandem, the new measure of crashworthiness and aggressivity presented in this study could together provide a means of ongoing assessment of vehicle secondary safety performance in both dimensions in many European countries where only injury crash data are recorded by police. Currently ratings of vehicle aggressivity are only published in Finland.

On average, there appears to be an association between the new measure of vehicle crashworthiness presented in this paper and EuroNCAP ratings. In both the British and French data, there was a trend towards reduced severe injury risk in police reported crashes with increased EuroNCAP star rating. This relationship was stronger in the French data which uses a somewhat different measure of severe injury outcome to the British data. The French measure might be more compatible with aim of the EuroNCAP protocol in assessing injury outcome. Whilst this general association could also be seen between the side impact EuroNCAP results and police reported side impact crashes, it did not extend to frontal impact comparisons in the data examined.

When examined on an individual vehicle model level the relationship between the new injury outcome measure and EuroNCAP results is not as strong with significant variation in estimates of the new measure for vehicles within the same EuroNCAP star class. This is however not a fatal indictment on either system considering the fundamental differences between the two measures and their clearly different objectives in measuring relative vehicle secondary safety; one prospectively and one retrospectively.

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