# Evaluation of Seat Performance Criteria for Rear-End Impact Testing BioRID II and Insurance Data

Johan Davidsson and Anders Kullgren

***Abstract*** The BioRID is recommended for legislative rear-end impact seat tests. Recommended injury criteria are, however, lacking; biomechanical data are limited and confines any evaluation of proposed criteria.

This study aimed at addressing these limitations by comparing BioRID II data from sled tests with real-life accident data. Results will evaluate injury predictability of the complete sled test method, which includes performance criteria, the use of a generic acceleration pulse, and the BioRID, etc.

Real-life injury risk was calculated for 17 groups of similar seat designs from data provided by Folksam. The number of insurance cases range from 150 to 1136 per group. Regression coefficients were calculated. Two types of injury risks were used: those leading to documented symptoms of more than one month's duration and those classified as leading to permanent medical impairment as a consequence of a rear-end impact. These risks were compared to parameter values from sled tests performed with a BioRID II at 16 km/h pulses.

NIC, the maximum rearward Occipital Condyle relative T1 x-displacements and L1 x-acceleration best predicted the risk of developing permanent medical impairment and symptoms of more than one month, given the occupant had initial symptoms following a rear-end impact.

***Keywords*** BioRID, injury criteria, real life data, rear-end, WAD

## I. INTRODUCTION

Several studies have compared BioRID rear-end crash test results to real-life performance with the main goal of recommending seat evaluation methods.

Linder et al. [1] reconstructed 25 rear-end impacts with a known one month duration of neck injury symptoms. In the reconstructions, the BioRID II was placed in the same type of seat as in the struck vehicle, and vehicle accelerations were reproduced. They found that the following criteria and parameters should be further studied: the neck injury criterion NIC [2] and Nkm [3]; maximum upper neck loads and T1 x-acceleration.

Cappon et al. [4] correlated crash test parameters by using the RID3D and the BioRID II with German accident statistics (acute injuries). The injury risk of each vehicle model was estimated using insurance claims combined with the number of vehicles registered in the data collection region for the particular model. This approach gave a rough estimate of real-life risk. The study found a reasonable correlation between the NIC as measured in the BioRID II and real-life risk.

Boström and Kullgren [5] compared the real-life performance of car seats with BioRID II test results for Saab, Volvo and Toyota seats, before and after introduction of the anti-whiplash systems. The

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authors presented data indicating that the NIC and upper neck shear loads were reduced more than other parameters when seats were fitted with anti-whiplash systems. The reduction of these two parameters may have contributed largely to the reduced injury risk observed in the seats with anti-whiplash systems.

Farmer et al. [6] investigated the relationship between the seat rating schemes used by the Insurance Institute for Highway Safety and the rating schemes used by the Swedish Road Administration (SRA) to real-world neck injury rates due to rear-end impacts. The main finding was that the better performing seat systems in dynamic sled tests had a lower risk of neck injury than seats that rated poorly. This was especially clear for long term injuries (> 3 month injury claim). However, the study also concluded that further research is needed in the fields of injury criteria, injury thresholds and test design to improve the predictability of real-world neck injuries by mechanical tests of seat systems.

Zuby and Farmer [7] studied the correlation between 26 BioRID II test parameters and seat design injury rates. Fifty-five seat designs were included in the analysis for which more than 30 claims had been filed. The study found that none of the 26 studied parameters were highly correlated with neck injury rates. It was mentioned that variables other than sled test variables, such as the insurance system used in the States from which data were collected, crash damage or vehicle price, could have reduced the expected correlations.

Ono et al. [8] used mathematical modeling to reconstruct real-life, rear-end impact accidents with known initial, short and long-term risks for neck injury symptoms, as well as known crash pulse and seat characteristics, to recommend criteria for the BioRID II. In all, 20 cases were reconstructed; velocity change ranged from 9 km/h to 28 km/h. Results revealed that displacements between the cervical vertebrae may have been responsible for the persistent neck symptoms. The study also suggested adopting the NIC and neck loads (Upper My, Lower Fx and Fz) to assess the risk of these injuries.

Davidsson and Kullgren [9-10] correlated insurance claims data following rear-end impacts with BioRID II measurements. They used a limited number of seat models. This paper is an update of those two earlier works; the differences between the studies are presented in the discussion section.

The objective of this study was to assess the applicability of BioRID II seat performance criteria, i.e. crash test dummy parameter values and injury criteria values, for rear-end impact seat-system testing. This was done by finding a correlation between the risk for whiplash-associated disorders (WAD), as calculated from real-life insurance data, and BioRID II values. An analysis of groups of seats of the same seat design, e.g. all cars from Volvo in which WHIPS seats were installed, will be presented.

## II. METHODS

### *Insurance data*

Whiplash injury claims from crashes that occurred between 1998 and 2012, at +/-30 degrees from straight rear-end impacts and in the driver position only, as reported to the Folksam Insurance Company were used in this study. 7 893 drivers reporting initial neck and spine injuries were included. Insurance claims were used to verify whether reported WAD led to long-term symptoms. Three combinations were studied; merged male and female data, and female and male data separately.

Medical expertise in Sweden has gradually been classifying WAD more restrictively. A reduction factor for compensating for this change in classification can be calculated by studying the injury claim outcome for vehicles with an identical introduction year over the sampling period. The risk of long term symptoms, given reported initial symptoms, should not change over the sampling period. The reduction in the likelihood of classifying an injury as a permanent medical impairment (PMI) appears to be linear over the sampling period, from 1998 to 2012, and was found to be 11% yearly for a large number of

vehicle models, and for a representative distribution of males and females. In the same way, the reduction in classification of those with symptoms lasting longer than one month was found to be 6.5% per year. Adjustments were made by weighting the number of occupants with long-term symptoms according to the year of impact. In order to retain the total number of occupants with long-term symptoms, weighting was made based on the accident year 2005, the middle accident year in the accident sample. All occupants with long-term symptoms in crashes occurring before 2005 were weighted lower, and all those after 2005 were weighted higher (Equations 1 and 2). By making an adjustment for the accident year for each occupant, outcomes from all groups of cars under study could be compared.

$$X_{PMI,\ \text{adjusted}} = \frac{X_{PMI}}{1{,}110^{(2005-year\ of\ accident)}};\ X_{PMI} = occupant\ with\ PMI \quad (1)$$

$$X_{1\ month,\ \text{adjusted}} = \frac{X_{1\ month}}{1{,}065^{(2005-year\ of\ accident)}};\ X_{1\ month} = occupant\ with\ symptoms > 1\ month \quad (2)$$

Risk measures used:

- Symptoms >1 month were defined as: occupants who had medical records of symptoms lasting longer than one month and claiming compensation for symptoms, divided by all those reporting initial symptoms. These claims entitled the occupant to a payment of 2000 SEK (about 210 €). The symptoms >1 month category included both those who possibly recovered after one month or later and those later classified as sustaining a permanent medical impairment (PMI).
- PMI was considered as: occupants with medical records of PMI and claiming compensation for injury symptoms, divided by all those reporting initial symptoms. This classification is set after approximately one year, although it usually takes longer to determine a final degree of PMI.

***Grouping based on seat design***

To obtain a reliable statistical result regarding the risks used, insurance claim data for seats of similar design were grouped (Table 1). For some of these groups, traditional seats and anti-whiplash seat designs, as well as older and newer models from the same car manufacturer, were included. Heavy and light cars were excluded to reduce differences in average vehicle weight between groups (Table 1).

***Sled test data***

All sled tests included in this study were conducted at Autoliv, Sweden, from 2004 to 2006, and at Thatcham, UK, between 2003 and 2006 according to the SRA and Folksam seat performance rating procedure and the International Insurance Whiplash Prevention Group (IIWPG), respectively. In addition, tests were carried out at Thatcham in 2012 according the Euro-NCAP test protocol. The main differences between the series included were the make and build level of the H-point machine, the Head Restraint Measuring Device (HRMD) and the BioRID II. Table 2 lists the conditions in the sled tests used to represent each group. All criteria/parameter values used in the analysis were taken from a single seat test from each seat group. The following seat test data selection criteria were applied:

1. Primarily Thatcham data were selected; the H-point machine with an HRMD had dimensions close to the standard tool used today.
2. When multiple tests from Thatcham were available for a seat group, the number of accidents with initial symptoms was used to select the test for use in further analyses.
3. When the dataset first selected provided results deemed as outliers when compared with the median values within the particular vehicle model, the dataset was discarded and another chosen.

TABLE 1

GROUPS DEFINED IN THIS STUDY: N IS THE NUMBER OF CASES INCLUDED; F IS THE PROPORTION OF FEMALES; M IS THE WEIGHTED AVERAGE VEHICLE WEIGHT. THE YEAR RANGE REPRESENTS THE YEARS THE CAR MODEL WAS SOLD IN SWEDEN.

| **Ford with STD, n = 382, f = 52%, m = 1324 kg** | |
|---|---|
| Focus | 99-05 |
| Mondeo | 93-99 |

| **Hyundai with STD, n = 195, f = 67%, m = 1247 kg** | |
|---|---|
| Accent | 99-06 |
| Atos | 04-03 |
| Atos | 98-03 |
| Elantra | 04- |
| Elantra | 96-03 |
| Getz | 03- |
| Matrix | 01- |
| Santa Fe | 00-05 |
| Sonata | 01-05 |

| **Mercedes with STD, n = 191, f = 44%, m = 1477 kg** | |
|---|---|
| A-class | 98-04 |
| C-class | 93-01 |
| E-class | 96-01 |
| CLK | 02-06 |
| E-class | 02-06 |

| **Opel with STD, n = 500, f = 51%, m = 1416 kg** | |
|---|---|
| Astra | 98-04 |
| Corsa | 00-06 |
| Meriva | 03- |
| Omega | 94-03 |
| Vectra | 89-95 |
| Vectra | 96-98 |
| Zafira | 99-04 |

| **Peugeot with STD, n = 397, f = 57%, m = 1325 kg** | |
|---|---|
| 206 | 98-05 |
| 306 | 93-01 |
| 307 | 01- |
| 406 | 96-04 |
| 605 | 90-98 |
| 607 | 99- |
| 307 | 01- |

| **Saab with STD older, n = 504, f = 49%, m = 1460 kg** | |
|---|---|
| Saab 900 | 88-93 |
| Saab 9000 | 85-97 |

| **Saab with STD newer, n = 150, f = 50%, m = 1453 kg** | |
|---|---|
| Saab 900 | 94-98 |

| **Saab with SAHR, n=354, f=51%, m=1595 kg** | |
|---|---|
| Saab 9-3 | 98-02 |
| Saab 9-5 | 98-09 |
| Saab 9-3 | 03-11 |

| **Toyota with STD, n = 579, f = 59%, m = 1343 kg** | |
|---|---|
| Avensis | 98-02 |
| Camry | 97-01 |
| Corolla | 98-02 |
| Picnic | 97-01 |
| Previa | 00-05 |
| RAV4 | 95-99 |
| Starlet | 97-99 |
| Lexus IS 200/300 | 05- |

| **Toyota with WIL, n = 1136, f = 63% m = 1317 kg** | |
|---|---|
| Auris | 07- |
| Avensis | 03-08 |
| Avensis Verso | 01-05 |
| Camry | 01-03 |
| Corolla | 02-07 |
| Corolla Verso | 02-03 |
| Corolla Verso | 04-10 |
| Prius | 00-03 |
| Prius | 04-09 |
| Rav4 | 00-04 |
| Rav4 | 05- |
| Yaris and Yaris Verso | 99-05 |
| Yaris | 05- |

| **Volvo with STD old, n = 1057, f = 49%, m = 1419 kg** | |
|---|---|
| 700 | 82-98 |
| 900 | 91-98 |

| **Volvo with STD, n = 676, f = 50%, m = 1497 kg** | |
|---|---|
| S40/V40 | 96-99 |
| 850 | 91-97 |
| V70 | 97-00 |

| **Volvo with WHIPS, n = 305, f = 46%, m = 1540 kg** | |
|---|---|
| C30 | 06- |
| S40/V40 | 00-03 |
| S40/V50 | 04- |
| S60 | 01-99 |
| V70 | 00-06 |
| V70 | 07- |
| S80 | 98-06 |
| S80 | 07- |

| **VW group with STD small, n = 163, f = 64%, m = 1168 kg** | |
|---|---|
| Seat Ibiza/Cordoba | 99-02 |
| Seat Ibiza | 03- |
| Skoda Fabia | 00- |
| VW Polo | 02- |

| **VW group with STD medium, n = 440, f = 56%, m = 1314 kg** | |
|---|---|
| Audi A3 | 96-03 |
| AUDI TT | 98-02 |
| Seat Toledo/Leon | 99-04 |
| Skoda Octavia | 97-04 |
| VW Bora | 99-04 |
| VW Golf | 98-04 |

| **VW group with STD large, n = 683, f = 47%, m = 1468 kg** | |
|---|---|
| Audi A4 | 95-00 |
| Audi A6 | 95-97 |
| Audi A6 | 98-05 |
| Skoda Superb | 02- |
| VW Passat | 97-05 |

| **VW group with RHR, n = 181, f = 58%, m = 1473 kg** | |
|---|---|
| Audi A3 | 03-04 |
| Audi A3 | 05-06 |
| Audi A4 | 01-06 |
| Audi A6 | 05-06 |
| Audi TT | 03-05 |
| Seat Altea | 05- |
| Seat Toledo/Leon | 05- |
| Skoda Octavia | 05- |
| VW Touran | 03- |
| VW Golf/Jetta | 04- |
| VW Passat | 05-07 |

In addition to an analysis of representative values, a median criteria/parameter value for each seat group was also analyzed. The analysis using median values was carried out to study bias in the selection of the representative tests (for each of the seat groups). Additional details for the calculation of median injury criteria and parameter values can be seen in Appendix 3.

The sled acceleration chosen was the median risk and median frequency pulse [11-12], with a velocity change of 16 km/h, an average acceleration of 5.5 g, and a triangular shape with a 10 g peak.

The parameters measured and calculated were those previously suggested by SRA/Folksam and IIWPG (Appendix I). In addition, head relative T1 displacement data, expressed in a coordinate system attached to the T1 unit, were retrieved from film analyses.

TABLE 2
CAR MODEL, TYPE OF SEAT SYSTEM, YEAR THE SEAT WAS TESTED, TEST FACILITY, BIORID II VERSION, H-POINT MACHINE, INITIAL HORIZONTAL HEAD-TO-HEAD-RESTRAINT DISTANCE (BACK SET).

| Groups | Model | Sales. year | WAD mitigation system[1] | Year tested | Test Facility | BioRID II version | H-point machine[2] | Back set (mm) |
|---|---|---|---|---|---|---|---|---|
| Hyundai | Santa Fe | 00-05 | None | 2004 | Thatcham | G | AA | 61 |
| Ford | Focus I | 99-06 | None | 2004 | Autoliv | E | TS | 55 |
| Mercedes | C-class | 93-01 | None | 2004 | Thatcham | G | AA | 55 |
| Opel | Astra | 98-04 | None | 2004 | Thatcham | G | AA | 72 |
| Peugeot | 206 | 98-05 | None | 2004 | Thatcham | G | AA | 76 |
| SAAB | 900 | 94-98 | None | 2006* | Autoliv | G | AA | 30 |
| | 9000 | 85-97 | None | 2012* | Thatcham | G | AA | 48 |
| | 9-5 | 98-09 | SAHR | 2004 | Thatcham | G | AA | 56 |
| Toyota | Corolla | 98-02 | None | 2005* | Autoliv | E | TS | 65 |
| | Yaris | 99-05 | WIL | 2004 | Thatcham | G | AA | 66 |
| Volvo | 700/900 | 82-98 | None | 2012* | Thatcham | G | AA | 17 |
| | V70 | 97-00 | None | 2006* | Autoliv | G | AA | 74 |
| | V/S70 | 00-06 | WHIPS | 2004 | Thatcham | G | AA | 32 |
| VW small | VW Polo | 02- | None | 2004 | Thatcham | G | AA | 63 |
| VW medium | Seat Altea | 04- | None | 2004 | Thatcham | G | AA | 65 |
| VW large | Skoda Superb | 02- | None | 2004 | Thatcham | G | AA | 85 |
| VW RHR | Audi A6 | 05-06 | RHR | 2005 | Autoliv | E | TS | 55 |

[1]NONE NO SYSTEM ACTIVATED BEFORE OR DURINGY IMPACT
[1]RHR REACTIVE HEAD RESTRAINTS
[1]SAHR SAAB ACTIVE HEAD RESTRAINT, VERSION 1 AND 2
[1]WHIPS WHIPLASH PROTECTION SYSTEM
[1]WIL WHIPLASH INJURY LESSENING
[2]TS REFERS TO TECHNOSPORTS, INC., USA
[2]AA REFERS TO AUTOMOTIVE ACCESSORIES, LTD., UK
*SEAT TESTED USED

***Linear regression***

A linear regression model was adopted to provide an idea of how parameters correlated with estimated risks. To measure how well the model fit, a coefficient of determination, the $r^2$ value, was calculated.

The regression line was determined by fitting a line to the data. Single outliers have a profound influence on the slope of the regression line and the value of the correlation coefficient, $r^2$. For this reason data were plotted and outliers identified.

***Estimation of sensitivity***

A study of the sensitivity of inclusion or exclusion of some selected data points was carried out. Here, one of the 17 datasets was removed and the correlation coefficient $r^2$ value calculated. This was repeated for all possible combinations for which each data point was excluded once. The maximum and minimum values calculated are presented in the Results section as a measure of sensitivity for each data point in the analysis.

## III. RESULTS

Linear regression for representative dummy test data and WAD risk were conducted for 35 parameters. Those that had the best correlations ($r^2$) between the peak value of the parameters and the two categories of risks, symptoms and impairment are presented in Table 3-5. In Table 3 representative data for males and females combined are provided. In Table 4 representative data for females only are provided. In Table 5 median

data for males and females combined are presented. In all tables three values are provided for each parameter and measure of risk: "Complete" refers to an analysis in which all 17 data points were included; Maximum and Minimum refer to the values obtained in the analysis carried out when one of the 17 datasets was systematically removed. For male data, no correlations above 0.3 could be found, and for this reason results are not presented in detail. In addition the risks of symptoms and impairment versus a few selected parameters and injury criteria are shown in Figs. 1-4.

As can be seen in Table 3, the PMI risk and risk of symptoms >1 month both showed correlations with the maximum NIC and OC rel. T1 x-displacement. The maximum L1 x- and z-accelerations showed a limited correlation to both risks. Maximum head rel. T1 y-rot. (extension) and T1 x-acceleration showed a correlation with the risk of symptoms >1 month. When one of 17 data points was disregarded in the regression analysis, $N_{km}$ also correlated slightly with both risks. In general the correlations ($r^2$ values) were higher for symptoms >1 month than PMI. Notably, HCT and HRV showed small or only limited correlation to the risks.

The number of insurance claims were about half for females (Table 4), and the symptom and impairment risk estimates are less confident; maximum NIC, OC rel. T1 x-displacement and head rel. T1 y-rot. (extension) were the only parameters showing a correlation at an $r^2$ level above 0.40 with the risk estimates used in this study.

A mathematical method for selecting the most representative test when more than one test was available for each seat group was neither developed nor used. The selection of the most representative test could have introduced some bias. Therefore a complimentary analysis was carried out using the median value for each parameter of all available seat test data for each seat group (Table 5). As can be seen by comparing the results in Tables 3 and 5, differences in correlation values between the representative and median injury criteria and the parameter values as measured in the dummy were small. When median values were used, the NIC appear to correlate less to the risk of PMI and symptoms >1 month than when representative data were used. The reverse was found for some of the other parameters, e.g. maximum L1 x-acceleration and T1 x-acceleration.

In Figs. 1-4, the lines between data points show groups of seats with and without anti-whiplash systems for which grouped data were available. These lines were included to enable a comparison between parameter values and calculated risks, with a reduced influence of factors such as chassis design characteristics of the car make, car owner characteristics specific for the make and, in part, vehicle weight.

When anti-whiplash systems were introduced all car producers reduced NIC values considerably with the exception of the VW group (Fig. 1). The reduction in symptom and impairment risks for the VW group may have been achieved by a combination of the reduction of other parameters or criteria values. Despite these differences between seat groups, it appears that seat designs producing a NIC lower than 25 $m^2/s^2$ bear a risk of less than approximately 7% of causing PMI (normalized to year 2005) following a rear-end impact with initial symptoms (Fig. 1).

TABLE 3

CORRELATION ($R^2$) BETWEEN THE PEAK VALUE OF THE PARAMETERS AND SYMPTOM AND IMPAIRMENT RISKS FOR MALES AND FEMALES TOGETHER, REPRESENTATIVE DATA.

| Table 3: Male and Female data/ | Permanent Medical Impairment | | | Symptoms > 1 month | | |
|---|---|---|---|---|---|---|
| Parameter | Complete | Maximum | Minimum | Complete | Maximum | Minimum |
| NIC | 0.59 | 0.72 | 0.51 | 0.72 | 0.75 | 0.63 |
| OC rel T1 x-disp. (retraction) | 0.42 | 0.48 | 0.35 | 0.39 | 0.52 | 0.33 |
| L1 x-acc. | 0.42 | 0.58 | 0.34 | 0.32 | 0.37 | 0.27 |
| Pelvis z-acc. | 0.40 | 0.51 | 0.20 | 0.19 | 0.28 | 0.11 |
| L1 z-acc. | 0.37 | 0.63 | 0.27 | 0.14 | 0.34 | 0.07 |
| Head rel. T1 y-rot. (extension) | 0.35 | 0.42 | 0.31 | 0.53 | 0.58 | 0.47 |
| Nkm | 0.33 | 0.43 | 0.22 | 0.38 | 0.50 | 0.25 |
| T8 x-acc. | 0.28 | 0.42 | 0.20 | 0.29 | 0.45 | 0.21 |
| T8 z-acc. | 0.22 | 0.37 | 0.12 | 0.07 | 0.19 | 0.01 |
| U.N.Fx (head rw) | 0.19 | 0.30 | 0.09 | 0.23 | 0.32 | 0.11 |
| L.N.Fx (head fw) | 0.17 | 0.28 | 0.01 | 0.22 | 0.31 | 0.00 |
| L.N.My (negative) | 0.16 | 0.24 | 0.08 | 0.20 | 0.30 | 0.09 |
| U.N.My (positive) | 0.15 | 0.22 | 0.06 | 0.04 | 0.09 | 0.00 |
| T1 x-acc. | 0.15 | 0.30 | 0.05 | 0.40 | 0.60 | 0.26 |

TABLE 4

CORRELATION ($R^2$) BETWEEN THE PEAK VALUE OF THE PARAMETERS AND SYMPTOM AND IMPAIRMENT RISKS FOR FEMALES ONLY, REPRESENTATIVE DATA.

| **Table 4: Female data/** | **Permanent Medical Impairment** | | | **Symptoms > 1 month** | | |
|---|---|---|---|---|---|---|
| Parameter | Complete | Maximum | Minimum | Complete | Maximum | Minimum |
| NIC | 0.34 | 0.44 | 0.21 | 0.69 | 0.75 | 0.59 |
| OC rel T1 x-disp. (retraction) | 0.31 | 0.46 | 0.22 | 0.20 | 0.24 | 0.14 |
| L1 x-acc. | 0.28 | 0.39 | 0.18 | 0.25 | 0.31 | 0.17 |
| Nkm | 0.26 | 0.39 | 0.15 | 0.25 | 0.34 | 0.11 |
| T8 z-acc. | 0.25 | 0.33 | 0.15 | 0.22 | 0.34 | 0.13 |
| L.N.Fx (head fw) | 0.20 | 0.32 | 0.01 | 0.27 | 0.36 | 0.02 |
| T1 y-rot. (rearward) | 0.19 | 0.29 | 0.08 | 0.20 | 0.33 | 0.10 |
| Pelvis z-acc. | 0.17 | 0.26 | 0.08 | 0.07 | 0.12 | 0.04 |
| Head rel. T1 y-rot. (extension) | 0.16 | 0.24 | 0.11 | 0.50 | 0.59 | 0.29 |
| L.N.Fz (tension) | 0.15 | 0.38 | 0.08 | 0.00 | 0.05 | 0.00 |
| T8 x-acc. | 0.15 | 0.29 | 0.07 | 0.16 | 0.26 | 0.11 |

TABLE 5

CORRELATION ($R^2$) BETWEEN THE PEAK VALUE OF THE PARAMETERS AND SYMPTOM AND IMPAIRMENT RISKS FOR MALES AND FEMALES TOGETHER, MEDIAN DATA.

| **Table 5: Male and Female data/** | **Permanent Medical Impairment** | | | **Symptoms > 1 month** | | |
|---|---|---|---|---|---|---|
| Parameter | Complete | Maximum | Minimum | Complete | Maximum | Minimum |
| NIC | 0.49 | 0.71 | 0.40 | 0.64 | 0.72 | 0.55 |
| L1 x-acc. | 0.43 | 0.57 | 0.39 | 0.45 | 0.51 | 0.40 |
| Pelvis z-acc. | 0.40 | 0.51 | 0.33 | 0.31 | 0.42 | 0.22 |
| OC rel T1 x-disp. (retraction) | 0.38 | 0.47 | 0.31 | 0.43 | 0.55 | 0.37 |
| Head rel. T1 y-rot. (extension) | 0.27 | 0.36 | 0.23 | 0.50 | 0.54 | 0.43 |
| T8 z-acc. | 0.23 | 0.45 | 0.16 | 0.05 | 0.19 | 0.00 |
| T1 y-rot. (rearward) | 0.23 | 0.33 | 0.18 | 0.09 | 0.17 | 0.03 |
| T1 x-acc. | 0.21 | 0.38 | 0.10 | 0.50 | 0.63 | 0.37 |
| L1 z-acc. | 0.20 | 0.43 | 0.15 | 0.16 | 0.47 | 0.07 |
| T8 x-acc. | 0.18 | 0.34 | 0.13 | 0.23 | 0.39 | 0.13 |
| Nkm | 0.16 | 0.26 | 0.06 | 0.33 | 0.47 | 0.18 |
| Pelvis x-acc. | 0.16 | 0.25 | 0.05 | 0.11 | 0.18 | 0.01 |

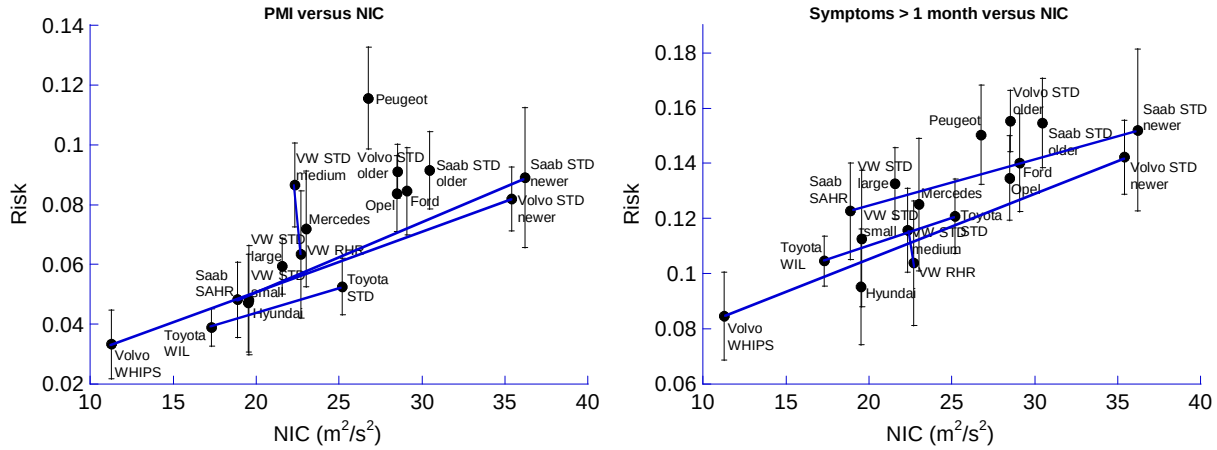


Fig. 1. Risk of PMI and risk of symptoms >1 month versus maximum NIC for seventeen groups as defined in Table 1 (average ± 1 SE). Representative dummy values were used for the two diagrams.

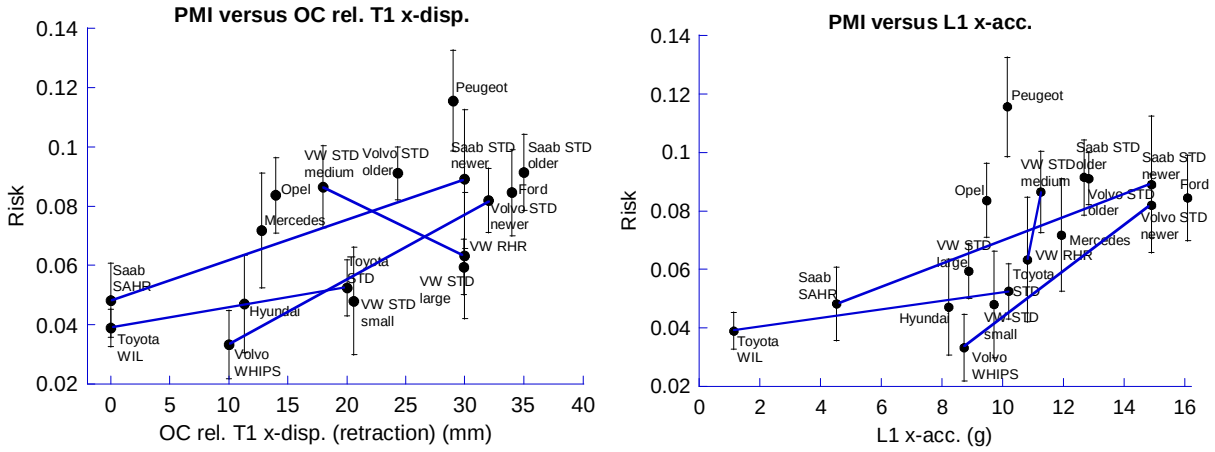


Fig. 2. Risk of PMI versus maximum rearward Occipital Condyle rel. T1 x-displacement (left) and maximum L1 x-acceleration (right) for seventeen groups as defined in Table 1 (average ± 1 SD). Representative dummy values were used for the two diagrams.

A similar relationship also appears present for the maximum OC rel. T1 x-displacement (Fig. 2) and maximum L1 x-acceleration (Fig. 3). For the former parameter it appears that approximately 20 mm retraction relative to T1 as expressed in a rotating T1 coordinate system results in a risk of PMI of 7% or less when there are initial symptoms. For the latter parameter it appears that L1 accelerations should be kept under about 11g to maintain a risk of PMI below 7% in an occupant having had initial symptoms.

Correlation between the maximum T1 x-acceleration and the risk of symptoms >1 month was increased largely when one dataset was not used in the determination of correlation; maximum correlations ($r^2$ values) were then 0.60 and 0.63 (Tables 3 and 5). The low correlations obtained when all datasets were used were due to relatively high T1 x-accelerations measured in the Toyota seat with WIL (Fig. 3).

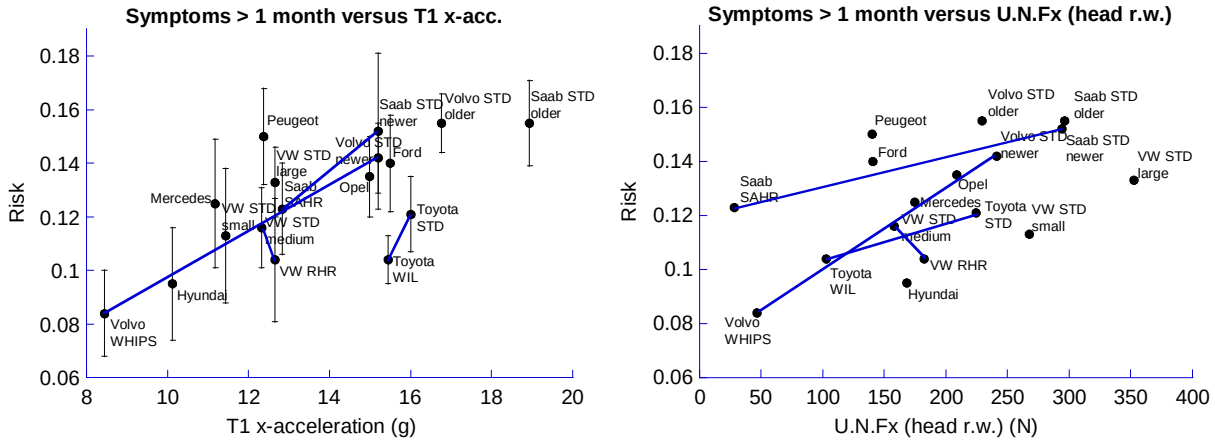


Fig. 3. Risk of symptoms >1 month versus maximum T1 x-acceleration (left) and maximum upper neck shear load (right) for seventeen groups (average ± 1 SE). Median dummy values were used.

Similar to the T1 x-acceleration, the correlation between maximum upper neck shear load (U.N.Fx, head r.w.) and the risk of symptoms >1 month improve when only 16 of the datasets were used in the analysis, although not to the same extent (Tables 3 and 5). Fig. 3 indicates that the correlation improved significantly if two of the datasets (Saab SAHR and Peugeot) were excluded from the analysis.

There seems to be no relationship between HCT and the risk of PMI or symptoms >1 month (Fig. 4) following an accident causing initial symptoms. The diagrams, however, show that for all four car manufacturers, with available data for both standard seats and seats with anti-whiplash systems, the HCTs were lower for the seats with the anti-whiplash systems.

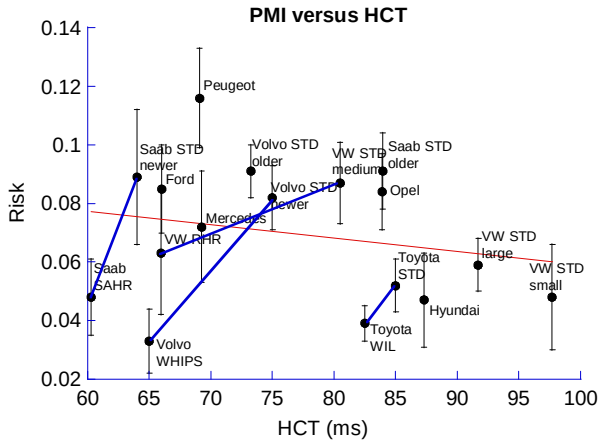


Fig. 4. Risk of PMI versus maximum head contact time for seventeen groups as defined in Table 1 (average ± 1 SE). Median dummy values were used. Linear regression line fitted.

## IV. DISCUSSION

By grouping seat models with and without anti-whiplash designs for each car manufacturer, a better statistical analysis could be performed than if individual seat models were compared. To minimize any influence of car mass or car body structure, vehicles with similar weight and vehicle body characteristics for each car manufacturer were grouped. The anti-whiplash designs included in the analysis were designed to reduce head-to-head restraint distance, yield or absorb energy, or both, in a controlled manner. By using insurance data, we can conclude that the anti-whiplash seat designs reduce the risk of sustaining whiplash injuries. Saab showed a reduction of 46%, Toyota a reduction of 26%, VW group (medium) a reduction of 27% and Volvo a reduction of 59% of PMIs (Fig. 1). By analyzing results, one can make the following observations:

- Saab has managed to lower the value for all parameters measured by introducing SAHR except for maximum rearward T1 angular displacement and lower neck load compression.
- Toyota managed to lower the values of all parameters measured except for some of the neck loads.
- Volvo reduced all parameters measured except for maximum compressive neck loads. The head contact time (HCT) varied considerably between tests with Volvo WHIPSs seats.
- VW group RHR seats were found to have lower values for some of the parameters studied than VW non-reactive seats. An example of this is the criteria of lower neck loads (LNL).

The analysis of these four car groups indicates that, by a general reduction of dummy measurements, the risk of WAD can be substantially reduced. Criteria that appear to better explain WAD-risk were NIC and maximum OC rel. T1 x-displacement (Figs. 1 and 2).

For evaluation of the robustness of the analysis, other groups were included in the analysis. They consisted of Hyundai, Ford, large and small VWs, Mercedes, Opel, Peugeot, and popular but older Saab and Volvo models. The regression analysis including these seats (Table 5) indicated that NIC, L1 x-acceleration and maximum OC rel. T1 x-displacement predicted the risk of PMI as well as the risk of symptoms >1 month following a rear-end impact.

These findings are in partial agreement with other studies on this matter [1, 4, 5, 8], which suggested that the NIC is suitable for assessing seat performance in rear-end impacts. Other parameters could predict the risk of symptoms >1 month when suspected outliers were removed (Table 3 and Fig. 3). For T1 x-acceleration the correlation was 0.60 when the Toyota seat with a WIL dataset was disregarded in the analysis. Possibly the T1 x-acceleration can be used to predict risk of symptoms and impairments; this suggestion is in line with those put forth by Linder et al. [1]. For Head rel. T1 y-rot. (extension) the correlation was 0.58 when the Opel dataset was disregarded.

Ono et al. [8] drew, with some exceptions, conclusions similar to those in this study; however, they used a different approach. Ono and co-authors reconstructed many rear-end impacts using a detailed mathematical human model. Their study suggested that the NIC and neck loads, especially upper neck shear load and moment and lower neck axial load, should be used in the evaluation of seat performance in rear-end impacts.

The findings of the present study were, however, not in line with the study by Zuby and Farmer [7], who found no correlation between dummy measurements and claim rates. A few tentative explanations for these

differences have been found. First, in their study the number of insurance cases for most of the car models was high. However, for some car models included in their analysis, only 30 cases of rear-end impacts were available in the insurance database. The estimated risks for these models were uncertain, since the outcome of a single accident can greatly influence the estimated risks used in the correlation study. Second, there are probably variations in the insurance data between the study by Zuby and Farmer and the present study. These variations could be associated with differences in injury coding, such as in compensation for property damage, compensation for injury claims, and the social welfare system. Third, in the present study representative sled test datasets were used in the analysis for some of the groups included. However, this was done only when there was more than one crash test dataset available for a particular vehicle model, or when the dataset first selected provided results deemed an outlier in comparison with the median values of the datasets for the same group. For most groups the selection of dataset used in the analysis was based on facts unrelated to parameter values. Fourth, Zuby and Farmer used risk of symptoms in rear-end impacts, whereas this study used risk of persistent symptoms when occupants exhibited initial symptoms following rear-end impacts. While these four differences may be small, they can, in combination with methods used to assess correlations in these two studies, both known to be very sensitive to outliers, provide a very different level of correlation, and as such, explain the divergence between the two studies.

In general BioRID II datasets from Thatcham were given priority since they had access to an H-point machine with an HRMD very close in its dimensions to the standard tool used today. The Thatcham datasets thereby enable the inclusion of tests carried out more recently. Two datasets were included in this analysis for which an older and uncalibrated H-point machine with HRMD was used (Table 2). When multiple tests from Thatcham providing fair seat performance data were available for a group, the number of accidents with initial symptoms was used to select the test to be used in further analyses. The test associated with the largest number of entries in the insurance database for the group was used. Despite this selection process, a “representative” dataset for some groups was chosen and used in the analysis of correlation. This occurred when more than one dataset was available for a particular vehicle model from Thatcham, or when the dataset first selected provided results deemed as outliers compared with the median values of the datasets for the same group. This selection procedure could have contributed to the fact that we could identify correlations, whereas studies in the past could not.

By introducing the fourth mentioned selection, we facilitated the inclusion of the more representative tests in the correlation analysis. The differences between the seats within one single seat group could be due to introductions of small changes in design over the time span. These differences could be due to foam thickness, foam properties, fabric selection, etc. In addition to these reasons, other sources of variability were present during the seat testing, which justify the seat dataset selection approach used here. The largest source was most likely introduced by the lack of calibration routines for the H-point machine and HRMD used at the time of testing. The test data used in this study were generated by two H-point machines which could probably explain the differences in the head-to-head restraint distances measured. Another source was the use of two BioRID II versions. The differences between the two build levels were mainly in the position of the spine in relation to the flesh surface.

The sled test data used in this study were generated in different laboratories using almost identical test conditions. In time, some dissimilarities in the test conditions have been identified, which could explain some of the variability observed. This variability introduces errors in the estimates in the present study. It is assumed that a better correlation would be obtained if all seat tests were carried out using the latest test protocol.

In a comparison of real life data and seat test data using individual car model data [10], it was clear that the confidence interval sizes were large in comparison to the range of estimated risk. Hence, it was judged that an analysis using individual car model data is not possible at present.

The main findings of this study are somewhat different from an earlier study using similar methods and data [9]. There are several reasons for this. First, all injury claim data used in this study have been adjusted to the classification of injuries used in 2005, whereas in [9] it was not. Second, there were seventeen groups in this study as compared with twelve in [9]. The inclusion of test and insurance data from older vehicle models introduces challenges; the parameter values were estimated using the BioRID II for seats with a broader spectrum of performance in this study than in the previous studies. The findings in this study confirm those found in [10].

It is unlikely that only a single parameter could fully assess the risk of symptoms and impairments to all the various injury mechanisms suggested for rear-end impact testing. The results of this study support the use of several parameters.

Insurance records in this study were used to calculate the risk of developing symptoms lasting longer than one month or PMI, in case of initial symptoms. These records have, in combination with BioRID II test data, been used to suggest parameters for use in future rear-end impact tests. Preferably the risk measure used should be calculated as the risk of symptoms >1 month or PMI in rear-end impacts. This would increase quality of the risk estimates, since it appears that, for low severity rear-end impacts, initial symptoms are frequently over-reported.

The type of risk measures used influences study results. In general the risk for developing symptoms for >1 month or PMI is proportional to the risk of initial symptoms following a rear-end impact [13]. The current study approach does not disqualify the findings presented. This approach introduces smaller differences between car models with better performance than for those with inferior performance. The risks of initial symptoms in rear-end impacts are not available for all vehicle models included. However, in approximately 35% of rear-end impacts in Sweden with modern cars, initial symptoms were reported. This approximation can be used to relate the risk values found here in case of a collision. It should be noted that the risks presented may not be compared directly to risks in other countries, since each country has its own guidelines for the classification of symptoms and medical impairments.

The BioRID II anthropometry approximates and responds similarly to an average male. Therefore, we anticipated better correlations between male insurance data and BioRID II parameters than for females' insurance data, or combined male and female insurance data. In addition we expected that inclusion of both males and females in the insurance data would introduce scatter in the insurance data. However, correlations were found weaker for males than females, and the best correlations were found for combined male and female insurance data. These results could be due to several things. Firstly, the number of claims in the insurance data was rather low, and for this reason risk estimates were less certain when males and females were analyzed separately. Secondly, one could speculate that the parameters responsible for the reported symptoms and medical impairments were the same for males and females. Thirdly, the BioRID II is slightly shorter and lighter than the average male in Sweden; the dummy is somewhere between males and females in stature and weight. In addition the kinematics of the BioRID II were found to be rather close to those of volunteers that were shorter and lighter than the average male (1.76 m and 71 kg). Hence, the BioRID II responses are probably representative of a person with properties that fall between those of an average male and female in the insurance data. The latter probably does not fully explain the correlations or the lack of correlations found in this study. Collection of additional accident data, to enable an analysis using a larger database, and additional research on rear-end impact biomechanics focusing on gender differences, are recommended and could possibly explain the differences observed in this study.

A perfect correlation was not expected since only a single generic crash pulse was included in the analysis. This generic pulse has been found representative of the crashes in the insurance data. However, adding other pulses and adopting a statistical model that allows a combination of results from multiple crash pulses may provide a better correlation and further justify the results obtained.

A few parameter values were found that did not correlate, or had a limited correlation to the estimated risk or long-term symptoms. Additional analysis revealed that, for some of these parameters, a single dummy test result could be far from the others (outlier) and thereby largely reduce correlation values ($r^2$). This applies to some of the lower and upper neck loads. This could be due to small errors in the particular seat test setup, the properties of the seat tested, or to differences between the dummies used. It may also be that these parameters are suitable to predict risk of symptoms and impairments for some seats but not for others.

## V. CONCLUSIONS

The main finding of this study is that the maximum NIC, the maximum rearward Occipital Condyle x-displacement, as expressed in a coordinate system attached to the T1, and the maximum L1 x-acceleration appear to be the best predictors of neck-related permanent medical impairment and symptoms that persist for more than one month following a rear-end impact. The maximum neck extension and T1 x-acceleration were also found to correlate somewhat to the estimated risks.

Grouped insurance data, based on similarities in the seat system design, were useful since they allowed the establishment of larger groups, which reduced uncertainties in the estimated risks.

The following limits are recommended for use in rear-end impact seat tests with the BioRID II (version g) and when the medium IIWPG crash pulse is used: NIC 25 $m^2/s^2$, maximum L1 x-acceleration 120 $m/s^2$ and maximum Occipital Condyle x-displacement 22 mm. The limits suggested are based on the performance of the groups of seats included in this study. These limits would separate seat models with fair performance from those with moderate to good performance. Other parameters are not ruled out; they may be found useful in seat performance tests when a larger dataset becomes available and when new seat tests are carried out using the latest test routines, a calibrated H-point machine and the newest dummy version.

## VI. ACKNOWLEDGEMENT

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## VIII. APPENDIX

### *A1 Parameters studied*

Table A1 presents the parameters and abbreviations of those included in the analysis in this study.

TABLE A1
PARAMETERS INCLUDED IN THE ANALYSIS IN THIS STUDY.

| |
|---|
| Maximum Neck Injury Criterion (NIC) |
| Maximum neck load criterion ($N_{km}$) |
| Maximum Lower Neck Loads index (LNL) |
| Maximum head x- and z-acceleration |
| Maximum C4 x- and z-acceleration |
| Maximum T1 x- and z-acceleration |
| Maximum T8 x- and z-acceleration (upward and downward) |
| Maximum L1 x- and z-acceleration |
| Maximum pelvis x- and z-acceleration |
| Maximum upper neck loads ($U.N.F_x$ (head r.w.), $U.N.F_z$ (tension) and $U.N.M_y$ (flexion of head)) |
| Minimum upper neck loads ($U.N.F_x$ (head f.w.), $U.N.F_z$ (compression) and $U.N.M_y$ (extension of head) |
| Maximum lower neck loads ($L.N.F_x$ (head r.w.), $L.N.F_z$ (tension) and $L.N.M_y$ (flexion of neck) |
| Minimum lower neck loads ($L.N.F_x$ (head f.w.), $L.N.F_z$ (compression) and $L.N.M_y$ (extension of neck) |
| Maximum rearward Occipital Condyle x-displacement in the T1-frame (OC rel. T1 x-displacement) |
| Maximum upward Occipital Condyle z-displacement in the T1-frame (OC rel. T1 z-displacement) |
| Maximum rearward T1 angular displacement around the y-axis (T1 y-rotation) |
| Maximum head rel. T1 angular displacement around the y-axis (Head rel. T1 y-rotation (flexion)) |
| Minimum head rel. T1 angular displacement around the y-axis (Head rel. T1 y-rotation (extension)) |
| Head Contact Time (HCT) |
| Maximum Head Rebound Velocity rel. to the sled in the x-direction (HRV) |

### *A2 Test data used to estimate the median dummy injury criteria and parameter values*

A mathematical method to select the most representative test when there was more than one test available for each seat group was not developed or used. The selection of the most representative test, as explained in the Materials and Methods section, could have introduced some bias. Therefore, complimentary analyses were carried out using the median value for each parameter for each parameter of all available seat test data (Table A2).

TABLE A2

CAR GROUPS, CAR MODELS AND PRODUCTION PERIOD, YEAR THE SEAT WAS TESTED, TEST FACILITY, BIORID II BUILD LEVEL, H-POINT MACHINE, INITIAL HORIZONTAL HEAD-TO-HEAD-RESTRAINT DISTANCE (BACK SET).

| Groups | Model | Year tested | Test facility | BioRID II build level | H-point machine[1] | Backset (mm) |
|---|---|---|---|---|---|---|
| Hyundai with STD | Santa FE 00-05 | 2004 | Thatcham | G | AA | 61 |
| | Accent 99-06 | 2004 | Thatcham | G | AA | 68 |
| | Elantra 04- | 2004 | Thatcham | G | AA | 100 |
| Peugeot with STD | 206 98-05 | 2004 | Thatcham | G | AA | 76 |
| | 307 01- | 2006 | Thatcham | G | AA | 51 |
| Mercedes with STD | C-class 93-01 | 2004 | Thatcham | G | AA | 55 |
| | E-class 96-01 | 2004 | Thatcham | G | AA | 46 |
| Opel with STD | Astra 98-04 | 2004 | Thatcham | G | AA | 72 |
| | Meriva 03- (No AHR) | 2004 | Autoliv | E | TS | 105 |
| | Meriva 03- (No AHR) | 2004 | Thatcham | G | AA | 79 |
| Saab with SAHR | 9-5 98-09 | 2004 | Thatcham | G | AA | 56 |
| | 9-5 98-09 | 2004 | Autoliv | E | TS | 40 |
| | 9-3 98-02 | 2006 | Thatcham | G | AA | 40 |
| | 9-3 03- | 2004 | Thatcham | G | AA | 56 |
| | 9-3 98-02 | 2006 | Thatcham | G | AA | 57 |
| Volvo with WHIPS | V/S70 00-06 | 2004 | Thatcham | G | AA | 32 |
| | S40/V40 00-04 | 2004 | Thatcham | G | AA | 47 |
| | S40/V50 04- | 2004 | Autoliv | E | TS | 45 |
| | V/S70 00-06 | 2006 | Autoliv | G | AA | 40 |
| | S60 01-09 | 2004 | Thatcham | G | AA | 47 |
| | S40/V50 04- | 2006 | Thatcham | G | AA | 25 |
| Toyota with WIL | Avensis 03-08 | 2004 | Autoliv | E | TS | 75 |
| | Avensis 03-08 | 2004 | Thatcham | G | AA | 50 |
| | Corolla 02-07 | 2005 | Autoliv | E | TS | 95 |
| | Corolla 02-07 | 2005 | Thatcham | G | AA | 62 |
| | Prius 04-09 | 2005 | Autoliv | E | TS | 72 |
| | Prius 04-09 | 2006 | Thatcham | G | AA | 66 |
| | Corolla Verso 04-10 | 2005 | Autoliv | E | TS | 95 |
| | Yaris 99-05 | 2004 | Thatcham | G | AA | 66 |
| | Yaris 05- | 2006 | Thatcham | G | AA | 92 |
| VW group STD small | Seat Ibiza 03- | 2004 | Thatcham | G | AA | 77 |
| | Seat Ibiza 03- | 2004 | Autoliv | E | TS | 50 |
| | Seat Altea 04- | 2004 | Thatcham | G | AA | 65 |
| | Skoda Fabia 00- | 2004 | Thatcham | G | AA | 101 |
| | VW Polo 02- | 2004 | Thatcham | G | AA | 63 |
| VW group STD medium | Audi A3 96-03 | 2004 | Thatcham | G | AA | 59 |
| | VW Golf/Bora 98-04 | NA | Thatcham | G | AA | NA |
| | Skoda Octavia 97-04 | 2004 | Thatcham | G | AA | 88 |
| VW group STD large | Skoda Superb 02-08 | 2004 | Thatcham | G | AA | 99 |
| | VW Passat 97-05 | NA | Thatcham | G | AA | NA |
| VW group with RHR | VW Touran 03- | 2004 | Thatcham | G | AA | 74 |
| | VW Touran 03- | 2004 | Autoliv | E | TS | 80 |
| | VW Passat 05-07 | 2006 | Thatcham | G | AA | 59 |
| | VW Golf/Jetta 04- | 2004 | Thatcham | G | AA | 66 |
| | VW Golf/Jetta 04- | 2006 | Thatcham | G | AA | 64 |
| | Audi A4 01-06 | 2006 | Thatcham | G | AA | 57 |
| | Audi A3 03-04 | 2004 | Autoliv | E | TS | 80 |
| | Audi A6 05-06 | 2005 | Autoliv | E | TS | 55 |
| | Audi A6 05-06 | 2006 | Thatcham | G | AA | 58 |
| | Audi A6 05-06 | 2004 | Thatcham | G | AA | 57 |
| | Skoda Octavia 05- | 2005 | Autoliv | E | TS | 76 |
| | Skoda Octavia 05- | 2006 | Thatcham | G | AA | 91 |
| | Seat Altea 04- | 2006 | Thatcham | G | AA | 58 |

1TS refers to TechnoSports, Inc., USA; AA refers to Automotive Accessories, Ltd., UK.