Restraint System Safety Diversity in Frontal Impact Accidents

David Hynd, Jolyon Carroll, Richard Cuerden, Dion Kruse, Ola Böstrom

Abstract The frontal impact safety of cars sold in Europe is regulated by the performance requirements of UN Regulation 94. This crash test includes two dummies that represent an average sized male driver and front seat passenger.

This study identifies the possible casualty gains that might be achieved in the UK if the legislative test was altered to use a 5th percentile female dummy or a 95th percentile male, or that could be realised by using performance requirements that represent older occupants better. The effect on casualty numbers that might be achieved through the introduction of advanced "smart" restraint systems was also considered.

Correlating real world accident data with sled test results it was found that casualty gains could be achieved for small or large occupants, or could be realised by using injury criteria that better represent older occupants. However, in conservative estimates these were not found to be beneficial overall for the UK population.

A "smart" restraint system, which could be tuned to the range of test conditions and occupant sizes used in two frontal impact test procedures was found to offer a slight benefit. The magnitude of the benefit may increase for a fully adaptive smart restraint system compared with a simpler system.

Keywords Accident data, Benefit analysis, Frontal impact, Occupant diversity, Smart restraint system.

I. INTRODUCTION

Throughout Great Britain, there were a total of 208,648 reported road casualties of all severities in 2010 [1]. 1,850 people were killed, 22,660 were seriously injured and 184,138 were slightly injured. It should be noted that the number of casualties in Great Britain is still this high despite a continuing trend of a reduction in the number of road casualties every year since 2000. Of these casualties, car users still account for almost 10,000 killed or seriously injured casualties each year.

When considering the types of impacts causing injuries to car occupants, the group of impacts where the front of the car is struck first is larger than any other group of crashes defined by initial direction of impact. Frontal impacts account for almost half of the car occupant fatalities and those occupants who are slightly injured, and more than half of the seriously injured casualties. This makes frontal impacts a priority for research into crash avoidance, severity mitigation and injury prevention.

Currently the frontal impact safety of cars sold in Europe is regulated by the performance requirements of UN Regulation 94. Performance limits are set for the front seat occupants (crash test dummies) in a full-scale test where the car is driven into a wall with a deformable element facing at 56 km/h. By setting limits for the occupant loading, the structural performance of the car as well as the effectiveness of the occupant restraint system is assessed. As a result of this test and also the implementation of the Euro NCAP frontal impact test (similar to that of Regulation 94, but carried out with at a slightly higher impact speed of 64 km/h), advances have been seen in maintenance of the occupant compartment integrity during such an impact. Occupant safety has also improved through the use and refinement of airbags and other restraint system components.

Recent research has now raised the possibility that the protection designed into current restraint system technologies may be optimised for the younger mid-sized male occupants [7]. This is likely to reflect the way in which these are the occupants most closely represented by the dummy used in the crash test. It can be assumed, therefore, that the balance of societal benefit afforded by restraint systems is likely to be influenced by the exact test conditions under which a vehicle is evaluated (impact speed and configuration, dummy being

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used and assessment criteria)[12]. This suggestion raises the possibility that the societal benefit afforded by restraint systems could be increased, or at least changed to improve the situation for other occupant groups, if the vehicle had to meet a different test condition.

The specific objectives of this study were therefore to:

- Quantify the casualty gain that might be achieved through using different injury criteria, injury risk functions, or crash test dummies that represent user groups other than those represented by the current 50th percentile male dummy;
- Quantify the change in risk to, and the casualty effect on, the 50th percentile male as a consequence of this shift (i.e. evaluate any possible disbenefit for this occupant group);
- Indicate the effect on casualty numbers that might be achieved through the introduction of advanced “smart restraint systems” (that tailor their restraint energy management to the biomechanical limits of female, older and small stature occupants).

II. METHOD

The objectives, as given in the previous section, were interpreted into different options relating to changes that could be made to the frontal impact Regulation 94 impact test procedure.

For this reason, four test options were defined. These would alter the current test by:

1. Using the 5th percentile dummy instead of the mid-sized 50th percentile dummy (as currently specified);
2. Using the 95th percentile dummy;
3. Changing the injury criteria of the current 50th percentile male dummy; and
4. Testing for a smart restraint system.

The method for this study was split into four sections: a state-of-the-art review; initial accident analysis; sled testing; and finally the benefit and disbenefit estimates.

State-of-the-Art Review

This review collected information available in published journals and conference papers, claims of system effectiveness from manufacturers, and crash test data to determine the current state and future possibilities for restraint systems. The performance of current restraint systems was investigated using information available from the literature, as well as the results from the National Highway Traffic Safety Administration (NHTSA) Vehicle Crash Test Database. The database was queried to identify matching frontal impact crash tests where either the stature of the front seat dummies or the collision severity was varied, for the same make and model of vehicle, so that the performance of the restraint system in differing situations could be evaluated. Among other things, the review was used to define the standard restraint system used in the test programme, and a specification for a smart restraint system that could be realised in the short-term.

Initial Accident Analysis

The main purpose of this section of the accident analysis work was to define and explore target populations of vehicle occupants who are either well-protected or poorly-protected in frontal impacts. These results were used to help decide what sled tests needed to be performed, and also provided a framework for the later estimates of benefit and disbenefit.

The initial part of this analysis defined the overall frontal impact casualty population using the national STATS19 database, which records details of traffic accidents reported to the Police in Great Britain. This database was used to estimate the number of frontal impact casualties there would be in a “Regulation 94 compliant fleet”, by assuming that if the entire car fleet were compliant with current frontal impact legislation that the distribution of fatal, serious and slight injury would be the same as it was for the vehicles which were already compliant with Regulation 94. This meant that throughout the analysis only Regulation 94 compliant cars were considered, and the results could still be scaled to the national level. Compliance with Regulation 94 was determined based on the date of registration of the vehicle, which was required to be October 2003 or newer.

The national accident data were then used to define groups of well-protected and poorly-protected occupants. This was done by splitting the casualties by age, gender, object hit and seating position, and comparing the proportion of casualties who were killed or seriously injured in the different groups. In this way, five groups of poorly-protected occupants and four groups of well-protected occupants were defined.

The next stage of the analysis explored these nine groups of occupants in more detail, using the in-depth accident data available from the Co-operative Crash Injury Study (CCIS). This in-depth data enabled important information such as the location and severity of the impact and the injury distribution of the casualties to be determined. It also enabled occupants who could not be affected by changes in frontal impact legislation, such as those not wearing a seat belt, to be removed from the sample.

Sled Testing

Based on the state-of-the-art review and the initial accident analysis, a series of sled tests were defined and performed, and the results analysed. The conditions for the tests were chosen based on the information collected in both the state-of-the-art-review and the initial accident analysis. This included consideration of components which would be incorporated in either a conventional or a smart restraint system.

The restraint system used in the tests was based on a typical "standard" system defined in the state-of-the-art review; the alterations in test conditions were designed to determine how such a system could be optimised to different impact conditions, and the benefit and disbenefit this may have for the occupants.

The different tests varied the dummies (using the Hybrid-III dummies and the THOR dummy), the crash pulse and the load limiter applied to the seat belt. Tests were carried out at speeds of either 56 or 40 km/h to match the current legislative test speed and to be representative of the collision severity at which the majority of serious thorax injuries occur respectively [2].

The results of the sled tests were analysed and used to define the likely effects on injury risk of optimising the restraint system for different sized occupants. This knowledge was then fed into the benefit and disbenefit estimates.

Sled test set-up

- The steering wheel including the airbag was taken from a modern vehicle. The airbag had dual stage inflation and was asymmetrical.
- Dual pretensioners were used.
- Three different load limiter behaviours were simulated in the testing:
  - A default 4 kN load limiter. This type of limiter started at a force level of 2 to 2.5 kN and rose up to a maximum of 4 kN at which point no further increase in force was allowed;
  - A 2.5 kN load limiter; and
  - A progressive load limiter (LLP) that started at 2 kN and increased to 7 kN, depending on the amount of belt paid out.
- In addition to the offset deformable barrier test pulse, as is representative of a Euro NCAP or R94 test, a test pulse representing a full-width impact was also used in six tests. These tests were again carried out at speeds of either 40 or 56 km/h.
- To aid with the analysis of dummy penetration into the restraint system string potentiometers were attached through the seat back between a fixed mounting on the sled and the back of the dummy (either at the top of the thorax or to the pelvis).
- The dummies were instrumented to record the following channels of data: head acceleration (x, y, and z axes); upper neck forces and moments (x, y, and x axes); lower neck forces and moments (x, y, and x axes); chest acceleration (x, y, and z axes); chest deflection; sternum acceleration (x-only); pelvis acceleration (x, y, and z axes).

Benefit and Disbenefit Estimates

The knowledge obtained from the state-of-the-art review and the sled testing was combined and applied to the accident data in order to estimate the likely benefit and disbenefit of altering current legislation so that restraint systems were optimised for occupants other than a 50th percentile young male.

In order to estimate the effect of changes to the regulatory tests, four alternatives to the current test were defined. These were: testing with the 5th percentile female dummy; testing with the 95th percentile male;

changing the injury criteria in the chest region; and testing for a smart restraint system.

The likely effects of these four options on the injury severity of 110 occupants in the in-depth accident data were then considered. These 110 occupants were chosen at random from seven groups of occupants where the number of cases available was large enough for the results to be scaled to the national level. Each case was examined in detail and the probability that the severity of the occupants' injuries would increase or decrease for each of the four options was estimated. In each case at least two researchers independently estimated a probability of a change in injury severity due to each option; where the probabilities differed a consensus was reached through group discussion. These estimates were based on the results from the sled testing and assumptions on how manufacturers may optimise restraint systems for the four different test options. For each case, an optimistic and a pessimistic estimate of the likely change of injury severity was assigned to the occupant. These were considered to represent the range of uncertainty in the likelihood of a change of injury severity.

The estimated benefit and disbenefit for the occupants in the case studies were then scaled to the Regulation 94 compliant population of casualties that was defined in the initial accident analysis. This gave an estimated change in the number of fatal, serious and slightly injured car occupants if the current regulatory test was replaced with one of the four defined options. In addition, the change in the number of casualties if the four options were added to the current legislative test requirements was estimated. It should be noted that the CCIS sample includes only cars that were towed away from the crash location; therefore, this approach assumes that the majority of cases which involved serious thorax injuries were tow-away.

III. RESULTS

State-of-the-Art Review

The state-of-the-art review identified that most studies (e.g. [2]) now show that thorax injuries are the most significant cause of life threatening injuries in frontal impacts. This observation is supported by the fact that the risk of serious head and face injuries has reduced considerably with the introduction of front airbags as has been encouraged by Regulation 94 and Euro NCAP [3]. Occupant age was identified as the primary factor affecting the risk of injury, and thorax injury in particular, with the risk increasing for increasing age amongst adult front seat occupants [4]-[5].

Shorter occupants were identified as being at increased risk of injury compared with average size males in dummy tests [6]-[7] and numerical modelling studies [8]-[9], but the evidence from accident studies was less conclusive [4, 10]. This may be due to the relatively low recording rate of occupant height in some studies, or to the presence of strong confounding factors such as age. Furthermore, female front seat passengers were identified as a relatively high risk group, which may also be influenced by size and age considerations.

The accident analyses reviewed typically identified serious thorax injuries occurring to belted front seat occupants at collision severities lower than current legislative and consumer information tests [2, 11]. This was consistent with the results of the vehicle crash test studies that were reviewed, which showed that chest compression injury measurements often did not reduce greatly with reduced collision severity in the range 40 to 64 km/h. In fact, in some tests the injury risk was higher at 40 km/h than at higher velocities, even for 50th percentile male crash test dummies. The tests reviewed also indicated a higher risk of injury for 5th percentile female occupants than 50th percentile male occupants. However, it should be noted that matching crash test data with identical vehicles tested at different collision severities or with different dummy sizes was limited to a small number of vehicle models.

Detailed information on restraint system technologies and deployment rates in the fleet were documented and used to define a typical 'standard' restraint system used in the majority of recent vehicle models, as well as a 'smart' restraint system that could adjust restraint performance for different sizes of occupant and collision severities. Full information on the restraint system technologies, including an analysis of the penetration of these technologies in the UK fleet, may be found in [12].

Many studies identified the possible role of 'smart' or 'adaptive' restraint systems in providing better restraint performance for non-50th percentile male, younger occupants. It is apparent that age is primarily a factor in determining the effectiveness of such systems, not in tuning the restraint system itself. This is because the smart restraint system should be tuned to provide the maximum protection within the constraints of occupant distance from the steering wheel (or dashboard) and collision severity for all occupants, regardless of age. This may provide benefits for all ages of adult occupant at low collision severity, but there may be relatively little benefit for older occupants at higher collision severities.

The smart restraint system defined for the benefit analysis is made up from components that are already available in the market. A number of vehicles already contain some or all of these components, although the degree to which they are available may be dependent on the market in which the vehicle is sold. It is considered, therefore, that such a restraint system can be defined as 'near-to-market' and therefore as a suitable solution to improved front seat occupant safety diversity, which may be encouraged by possible updated legislative requirements.

Initial Accident Analysis

The number of casualties in a Regulation 94 compliant fleet was calculated by assuming that the total number of casualties would be the same as for the actual car fleet, but that the proportion of fatal, serious and slight casualties would equal that for the Regulation 94 compliant cars. For example, 8.6% of casualties in Regulation 94 compliant cars were seriously injured. Applying this percentage to the total number of casualties in the fleet (355,880) gives a value of 30,758. This is the estimated number of serious casualties there would be if the entire fleet were compliant with Regulation 94.

The total breakdown of seating position, object hit, age and gender for the casualties in Regulation 94 compliant cars in STATS19 was reviewed. For each combination of conditions within these variables the proportion of fatal and serious accidents was derived. On the basis of these proportions the combinations were ranked. The ranked combinations were split into three sections and colour coding was used to select conditions with relatively high and low proportions of killed and serious injuries. The collections of accident condition combinations were then combined to form larger groups with common features, which are summarised in Table I, with the high and low proportions of killed and serious injuries shown with red and green highlighting respectively. This final step to rationalise the combinations of conditions was subjective and it may have been possible for other groups to have been derived, although the groups produced did have very distinct risks (high or low) of fatal and serious injuries. It should be noted that impacts with "Not tree or HGV/bus" include impacts with cars, LGVs, narrow objects (e.g. road signs, traffic signals, lamp posts or telegraph/electricity poles) and wide objects (e.g. bus shelter or crash barrier).

A total of nine groups was identified; five of these have a higher than usual KSI proportion, and four have a lower than usual KSI proportion. The "remaining groups" include groups of occupants who did not fit into any of the other groups, or who did not appear to be particularly poorly or well protected (such as drivers and front seat passengers aged 50-59). The "unknown" group includes casualties where the type of object hit was unknown.

Although rear seat passengers make up a relatively small proportion of the casualty population, they have been identified as four separate groups. This is because the characteristics of rear seat passengers seemed to differ from those of drivers and front seat passengers, and they are one of the only groups where gender seemed to be an important differentiating factor.

It should be noted that KSI proportion alone cannot say whether a group is well protected or poorly protected, because there are factors which cannot be accounted for using the national data. For example, some of the poorly protected groups may have had higher speed crashes compared to some of the other groups, or may have had lower seat belt wearing rates. It should also be noted that although seat belt wearing rates of adult rear seat passengers have risen in the last 10 years, they are still lower than seat belt wearing rates in the front seats. Less than 80 % of adults in the rear of cars wear a seat belt, compared with approximately 95 % of drivers and front seat passengers.

TABLE I
TARGET POPULATIONS IDENTIFIED FROM NATIONAL DATA

Group	Seating position	Impact object	Gender	Age	Number of casualties: Fatal	Serious	Slight	Total	KSI proportion
A	Any	Bus/HGV	Any	Any	72	292	1879	2243	0.16
B	Any	Tree	Any	Any	79	462	1600	2141	0.25
C	Any	Not tree or HGV/bus	Any	0-16	4	154	2805	2963	0.05
D	Driver/FSP	Not tree or HGV/bus	Any	17-49	66	1763	25727	27556	0.07
E	Driver/FSP	Not tree or HGV/bus	Any	60-70+	92	763	5458	6313	0.14
F	RSP	Not tree or HGV/bus	Any	50-70+	16	105	485	606	0.20
G	RSP	Not tree or HGV/bus	Female	17-49	2	68	1096	1166	0.06
H	RSP	Wide object	Male	17-49	1	13	67	81	0.17
I	RSP	Car-Car	Male	17-39	3	51	606	660	0.08
X	Remaining groups				24	431	4592	5047	0.09
	Unknown groups				75	1200	11294	12569	0.10
Total					**434**	**5302**	**55609**	**61345**	**0.09**

The target populations identified in Table I were explored using the in-depth accident data in CCIS. The same selection criteria were applied to the CCIS database to create a combined frontal impact sample which contains all occupant ages, genders, seating positions and objects hit. All of the occupants in this sample were analysed together, then split into the groups defined in Table I, to see what differences there were between the different groups.

The proportion of people wearing a seat belt was found to be much higher for slight/uninjured occupants than those receiving more serious injuries. Approximately 90% of the slight/uninjured occupants were wearing seat belts, compared to approximately 75% of those with MAIS 3+ injuries. From this point onwards, all of the people who were not wearing a seat belt were removed from the sample.

No significant differences were found in the distribution of occupant gender or seating position for different injury severities. No significant differences were found for the distribution of occupant height or weight with different injury severities, however it should be noted that height and weight were unknown for a large proportion of occupants in CCIS.

The distribution of occupant age and injury severity clearly showed that occupants aged 60 and older were over represented in the more serious injury categories.

There were some significant differences in the distribution of direction of force, where more serious injuries were over represented in 12 o'clock and 1 o'clock impacts, compared to 11 o'clock impacts. This could be because of the large proportion of drivers in the sample, who may receive worse injuries in a 1 o'clock impact compared to an 11 o'clock impact, because of the increased risk of injury from contact with the side of the occupant compartment.

Sled Testing

As noted above, three different load limiter behaviours were simulated in the test work. This behaviour was characterised by measuring the belt forces close to the shoulder belt anchorage and on the same side close to the lap belt anchorage point.

The function of the shoulder belt load limiter is described by the shoulder belt forces as shown in Figure 1, for the offset barrier pulse tests with the Hybrid III 50th percentile dummy. It can be seen that the measured forces are very similar in the first 20 ms of the impact after which differences develop.

The chest deflection results for the Hybrid III 50th percentile male dummy tests are shown in Figure 2. The restraint system set-ups which did not allow the chest to bottom out through the airbag had a peak deflection of between 25.4 and 25.7 mm. In the test with the 2.5 kN load limiter at 56 km/h the deflection peak value was 31.2 mm. This is still well within the regulatory limit of 50 mm.

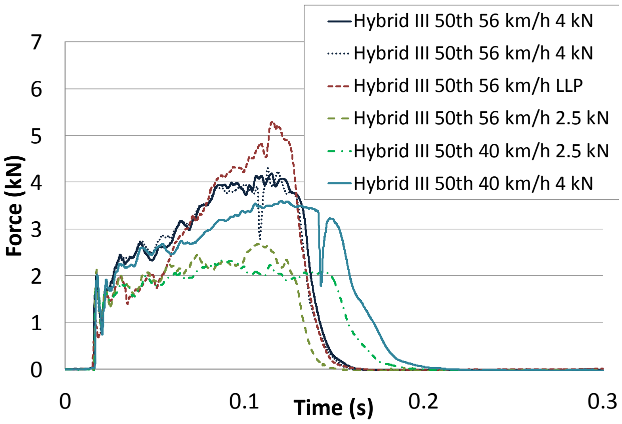

Fig. 1. Hybrid III 50th percentile male shoulder belt forces

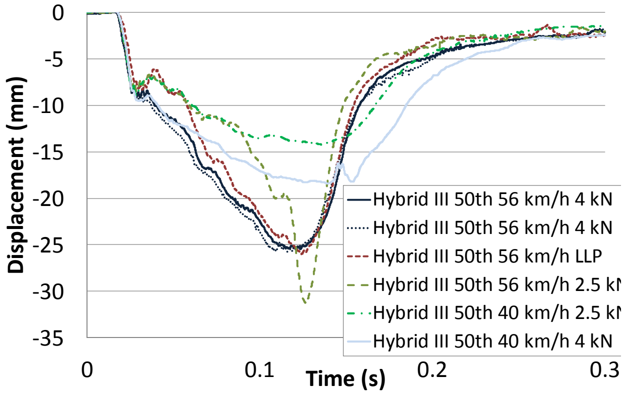

Fig. 2. Hybrid III 50th percentile male chest deflections

The shoulder belt forces from the Hybrid III 5th percentile female tests with an offset pulse are shown in Figure 3. With the 5th percentile female in a 56 km/h test, the LLP paid out much less belt than with the 50th percentile dummy and maintained a much lower shoulder belt force. This suggests that there may be scope for reducing the load limit level when concentrating on small occupants in this severity of impact.

The chest deflection responses for the 5th percentile female tests are provided in Figure 4. The peak deflection from the 40 km/h test (16.2 mm) was substantially smaller than the 56 km/h test with the LLP (26.1 mm). The highest peak acceleration for the 5th percentile female occurred in the 56 km/h test with the 2.5 kN load limiter. As with the 50th percentile male dummy, it seems that the 2.5 kN limit allowed too much forward excursion of the occupant. As a result there is a sharp peak (29.7 mm) in the deflection response around 125 ms, where the contact with the airbag and steering wheel became stiffer. However, this peak produced through bottoming out still falls below the threshold for chest deflection of 41 mm.

At 26.1 mm, the chest deflection for the Hybrid III 5th percentile female in the 56 km/h test with the LLP is almost identical to that for the 50th percentile male, of 26.0 mm in the equivalent test. However, with the same deflection measurements, the risk of injury for the 5th percentile female would be greater than for the 50th percentile male.

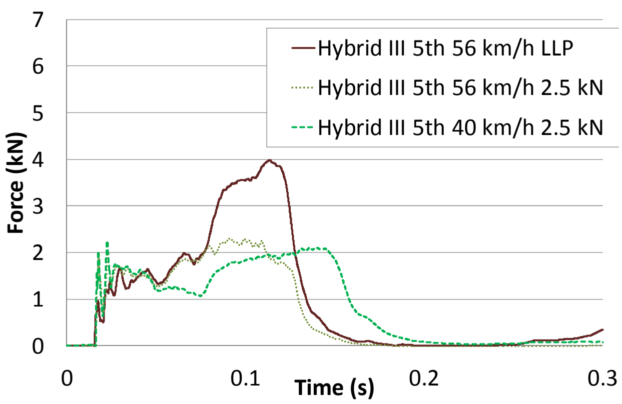

Fig. 3. Hybrid III 5th percentile female shoulder belt forces

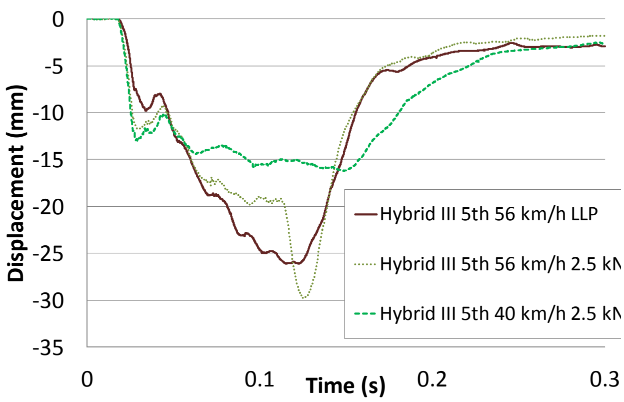

Fig. 4. Hybrid III 5th percentile female chest deflections

The forces measured on the shoulder portion of the seat belt during the 95th percentile male dummy tests with an offset pulse are shown in Figure 5. The function of the load limiters is being used fully with the larger dummy. Despite differences in the load limiter forces between the 4 kN load limiter and LLP, the dummy results showed similar loading to the head, upper neck and chest (Figure 6). Peak values were markedly reduced in the 40 km/h test with the 2.5 kN load limiter.

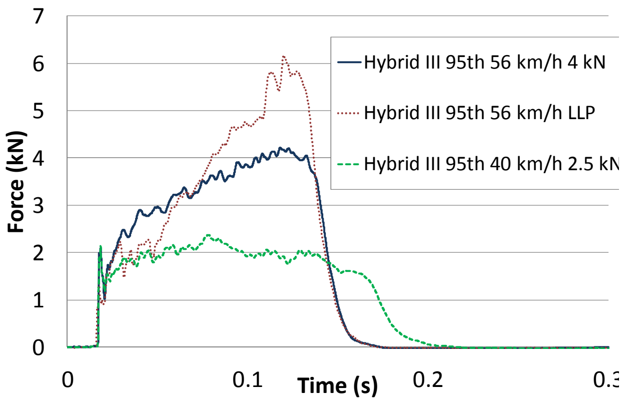

Fig. 5. Hybrid III 95th percentile male shoulder belt forces

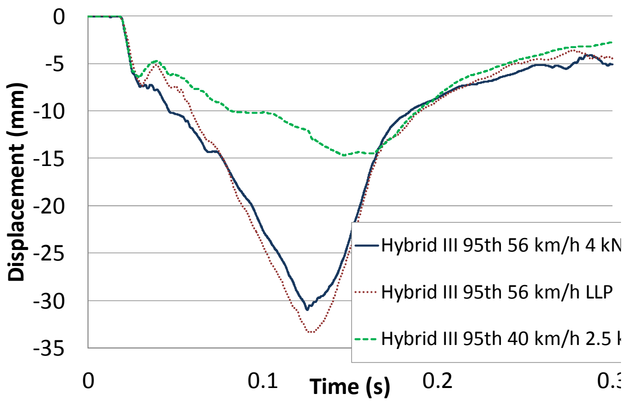

Fig. 6. Hybrid III 95th percentile male chest deflections

For all equivalent tests, the THOR gave greater thoracic displacements than the Hybrid III (Figure 7 cf. Figure 8), though the pelvis displacements were broadly comparable with those of the Hybrid III.

The displacement measurements seem to confirm the concern that a dummy with improved biofidelity may undergo greater thoracic excursion (in tests with an offset deformable barrier deceleration pulse) than the Hybrid III 50th percentile dummy.

When comparing the video footage from equivalent Hybrid III and THOR tests, it appeared that the THOR was better able to wrap around the shoulder portion of the seatbelt. This rotation about the belt (in the z-, or spinal axis for the dummy) seemed to aid the greater excursion of the head and chest seen with the THOR compared with the Hybrid III.

It should be noted that the attachment of the string potentiometers to the top of the thorax was not identical for the THOR and Hybrid III because the dummy designs around the top of the thorax are not identical. However, the different attachments would not be expected to account for the additional 20 to 40 mm of excursion as seen here with the chest displacement measurements, noting that the channel is set to zero pre-impact.

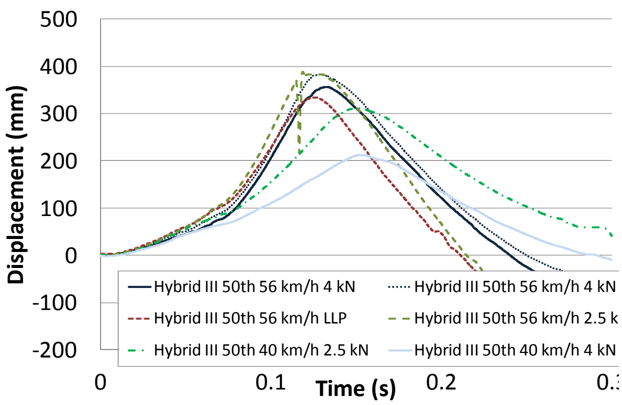

Fig. 7. Hybrid III 50th percentile male chest displacement measurements

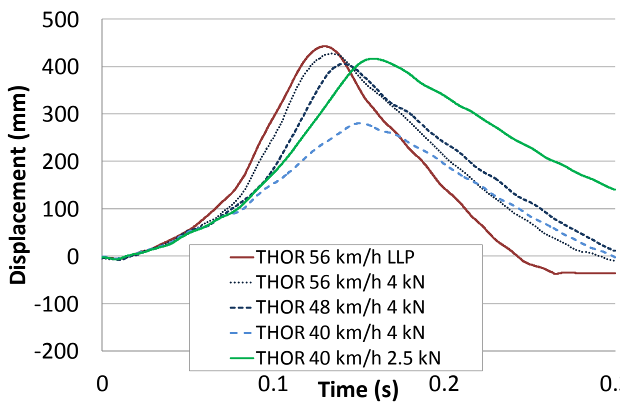

Fig. 8. THOR chest displacement measurements

The key findings from the tests programme relating to the project objectives and restraint system tuning options were:

1. Small occupant
   a. Current restraint systems do not seem to give equivalent protection against the risk of injury for small occupants compared with mid-sized occupants.

   b. Minor tuning of the load limiting level used with a small occupant may be possible to improve occupant protection in regulatory test-like impacts.
   c. Fully deployed airbag size (and maybe stiffness) would have to be controlled better (reduced or softened) to optimise restraint system performance for a small occupant. Such a change would be critical in low severity impacts where initial bag interaction loading could dominate over later inertial movement into the restraint system.
   d. Use of a small airbag is likely to be disbeneficial for other occupant sizes which currently rely upon the airbag to limit the final phase of excursion during an impact (of airbag deployment severity). Without such a large airbag, those occupants who are not small would be at risk of hard head and chest contacts with parts of the vehicle interior.
2. Large occupant
   a. Current restraint systems do not seem to give equivalent protection against the risk of injury for large occupants compared with mid-sized occupants.
   b. The space available in front of a 95th percentile driver with a conventional steering wheel airbag suggests that restraint system efficacy for larger than mid-sized occupants could be improved with a larger airbag.
   c. Use of a larger airbag would be expected to be disbeneficial for occupants sitting closer to the front of the vehicle. They could incur 'bag slap' where initial loading from the airbag during the inflation phase could be injurious. This may cause head and neck injuries which otherwise may not have occurred, or have been of a lesser severity.
3. Older occupant
   a. Reduction of the load limit can be beneficial in optimising the use of the available space in the occupant compartment to decelerate the occupant. This can lead to lower chest loading from the belt and lower risk of thoracic injury.
   b. However, a lower load limit can be disbeneficial for all sizes of occupants in moderate and high severity crashes where, with current load limiting technology, a possibility exists for them to make a hard contact with the vehicle interior. This would entail a higher risk of thoracic or head injury. To reduce this risk it would be necessary to adjust the load limit for the accident severity and occupant size using a smart or adaptive restraint system.
4. Smart system
   a. In terms of chest deflection, it seems to be advantageous to decrease the level at which the shoulder belt is limited for low severity accidents. A smart system would be able to react to a crash pulse and if it is low severity, reduce the load limit accordingly (and safely).
   b. Smart systems would also be able to manage airbag size accordingly for the size and seating position of an occupant.
   c. With the most basic of smart systems it could be possible that occupants with unusual height and weight combinations may not be adequately catered for. This could lead to inappropriate tailoring of the restraint system and disbenefit.
   d. Also, further reliance upon crash severity estimation leads to the risk of inappropriate deployment with poor vehicle interaction (e.g. under or overrun). Without additional testing of the system algorithms, a smart system could perform less well than a current system in exceptional crash circumstances.
5. General
   a. A full-width impact can give greater loading to the vehicle occupants than offset impacts, depending on the nature of the object struck.
   b. The chest of the Hybrid III dummy didn't move forward in this test series as much as the THOR, for equivalent tests. Assuming that the THOR has better biofidelity than the Hybrid III this suggests that excursion estimates made with the Hybrid III may be underestimates compared with the human occupant. Restraint systems designed with a very tight tolerance to hard contact based on Hybrid III testing may not prevent such a contact for a human.

Benefit and Disbenefit Estimates

The potential benefit and disbenefit of the following four possible changes to UNECE Regulation 94 were considered:

5th percentile dummy

- Use the 5th percentile female dummy in the driver and/or front passenger seat positions instead of the current 50th percentile male dummy
- Assumed that this dummy would be placed in a seating position close to the wheel (for the driver) and a position close to the dashboard for the front seat passenger
- Assumed that manufacturers will fit a smaller airbag, and tune the restraint system accordingly for this test (instead of the existing regulatory test)

95th percentile dummy

- Use the 95th percentile dummy in the driver's seat instead of the current 50th percentile male dummy (retaining the 50th percentile dummy in the front seat passenger position)
- Assumed that this dummy would be placed in a seating position far back from the wheel
- Assumed manufacturers will fit a larger, potentially stiffer, airbag, and tune the restraint system accordingly for this test (instead of the existing regulatory test)

Change injury criteria

- Reduce the threshold of the injury criteria in the chest region to represent older occupants
- Assumed manufacturers will reduce the load limit on the seat belt (based on this test, in isolation)

Smart system

- Assumed that a smart restraint system will be fitted to the driver and/or front seat passenger positions
- The smart system has knowledge of occupant weight, seating position, and some information on the severity of the crash, and can adjust the airbag and load limit accordingly. It was assumed that the smart restraint system would be tuned to cover two occupant sizes and collision severities, for which two legislative test procedures would be required

It should be noted that the first three options assume a change to the current Regulation 94 test procedure or evaluation criteria, not an additional test to supplement the current test using 50th percentile male crash test dummies. For the fourth option, a second legislative test at a different collision severity and with different dummy sizes would likely be necessary to encourage fitment of smart systems. For a first assessment it was assumed that a smart system would be tuned to accommodate the occupants and collision severity in two test procedures, e.g. the current Regulation 94 test procedure at 56 km/h with a 50th percentile male Hybrid III dummy, and an additional test at 40 km/h with a 5th percentile female dummy.

The potential benefits and disbenefits of these possible changes to the UNECE Regulation 94 frontal impact crash test requirements were estimated based on a random sample of accident cases from the groups identified as currently well-protected or relatively poorly protected (see Table I). These were the only groups considered large enough to scale up to the national level. A total of 110 accident cases were able to be analysed on a detailed case-by-case basis within the project budget, which were considered to be representative due to the random sampling scheme.

The case-by-case assessment of the potential effects of the changes was based on an understanding of the performance of frontal impact restraint systems in the literature, reinforced by the results of the test programme with a 'standard' restraint system representative of restraint systems in the majority of recent vehicles. This enabled the position, size and age of the occupant, their injuries and injury causation, the exact location, direction and severity of impact, the structural performance of the vehicle, and performance of the fitted restraint system, all to be taken into account when estimating the probability that the injury severity would change. Benefits were estimated based on an optimistic and a pessimistic interpretation of the possible changes in casualty outcome for each accident case that was reviewed.

The changes in number of casualties expected as a result of the options are shown in Table II in the Appendix. The table shows the change in the number of fatal, serious and slight casualties predicted for the seven casualty groups that were identified as well or poorly protected in the initial accident analysis.

There were some clear trends when the benefit and disbenefit of the four options were considered:

- When changing the dummy in the driver and front seat passenger seats to the 5th percentile female, a benefit was usually estimated when the occupant in the accident case was seated far forwards, and when they were relatively small and likely to benefit from a smaller airbag. However, the majority of occupants in the cases were either seated in mid-position or far back, and were larger; in many of these cases the severity of the impact was enough that if the bag were made smaller, there was the possibility that it would offer less protection than the original bag for these occupants.

- When changing the dummy in the driver position to the 95th percentile male, a benefit was generally expected when the driver was seated far back, because for these occupants the larger airbag may have offered better protection. However, similar to the previous option, there were many more occupants seated in the mid-position or far forward. For many of these occupants, it was estimated that the larger airbag could increase their injuries, rather than reduce them, because these occupants would be occupying the space that the larger airbag was deploying into.
- Changing the injury criteria in the chest region was estimated to give benefit in some severities of collision where injuries were caused by the seat belt, particularly skeletal injuries of the chest in elderly occupants. However, for larger occupants, or occupants in higher severity crashes, there was the possibility of the occupant travelling further forwards due to the reduced load limit and bottoming out the airbag, leading to worse injury. It was also considered unlikely that there would be any benefit in low severity crashes where the load on the seat belt was likely to be lower than the reduced load limit. For vehicles that already had a “green” Euro NCAP rating in the chest region no benefit was estimated because these vehicles would already meet the altered injury criteria.

For the two options that change the dummy size, even optimistically it was estimated that there would be an overall disbenefit for drivers, and pessimistically this disbenefit was greater. Although it was estimated that the front seat passenger groups would fare better than drivers if the dummy was changed to a 5th percentile female, the predicted optimistic benefit is still very small and there is still the possibility of an overall increase in the number of fatal and serious casualties.

There is a similar split between drivers and front seat passengers if the injury criteria in the chest region were changed. A disbenefit was estimated for drivers, while there was a possibility of an overall benefit for front seat passengers.

The smart restraint system incorporates features from all three of the other options and in most cases will at least maintain the protection level of occupants who were already well protected. By altering the size of the airbag and load limit based on occupant weight and seating position, it could also offer a benefit to smaller and larger occupants sitting closer and further away respectively. As such, the smart system was the only system where optimistically a benefit was estimated for all of the seven groups of casualties. However, even for this system there was a possibility of disbenefit for drivers in the pessimistic estimates.

The smart restraint system also offered some additional benefit in low speed crashes, because if the system could detect that the impact was low severity it could reduce the load limit to a lower value than that available to the “change injury criteria” option. However, even for the smart system, there were some instances where there was a possibility that it may lead to a disbenefit. These instances typically involved occupants with an unexpected stature for their seating position, such as large occupants sitting close to the wheel.

Overall, the potential benefits of changing the dummy from 50th percentile male to either 5th percentile female or 95th percentile male were estimated to be negative for drivers, and most likely negative for front seat passengers. This is because, while there may be benefits for some shorter or taller occupants, any potential disbenefits that may occur due to focussing on one extreme of the occupant size range may occur to a relatively large proportion of occupants.

The main potential benefit was from smart restraint systems, which could adjust their response to the height (or seating position) of the occupant, and the collision type and severity. However, it should be noted that the fitment of smart restraint systems is unlikely to occur in the majority of the fleet with only a single test condition enforced in legislation. A second legislative test at a different collision severity and with different dummy sizes is likely to be necessary to encourage fitment of these systems.

An additional review was undertaken to estimate the potential benefits or disbenefits if two test procedures were used, assuming that one test procedure is identical to the current Regulation 94 test and one introduced either a different size of occupant or different injury risk functions. The changes in number of casualties associated with the four options and this scenario are shown in Table III in the Appendix. In this case it was assumed that protection would be at least equivalent to current protection levels, so no disbenefit should occur and occupants other than the younger 50th percentile male have the possibility for improved protection. Each of the dummy size and injury criteria changes was therefore associated with a reduction in serious and fatal injuries.

Finally, an additional smart option was considered. For this estimate it was assumed that two legislative tests would be conducted, e.g. the current Regulation 94 test plus a test at lower speed with 5th percentile female dummies. However, in addition to this, it was also assumed that the manufacturer would ensure that the smart system is tuned to all occupant heights and weights, and collision types and severities, even those outside the range of the two possible legislative tests. For instance, a small occupant with higher than average mass for their height would receive no disbenefit because the system would account for the difference between their mass and the mass of the dummy used in the test. In this case, both the optimistic and pessimistic estimates were for a reduction in fatal and serious injuries.

IV. DISCUSSION

The results showed that two test procedures would be required to encourage the development of restraint systems with overall benefit for car occupants. For this analysis, it was assumed that the smart restraint system would adjust for the occupant sizes and impact severities used in two legislative crash tests, e.g. the current Regulation 94 test, plus a second test at a lower speed with 5th percentile female dummies in a forward seating position. This leaves a small risk that the system would be sub-optimal outside the range of conditions tested. For those accidents which occur with conditions where the restraint system was sub-optimal the occupants may be at risk of having an increased injury severity, that is, moving to a more serious injury level (e.g. from slight to serious). For instance, a small occupant with a 5th percentile seating position would need a higher restraint force than the 5th percentile female dummy if they were significantly heavier than the dummy. Where such deviations from the potential test conditions were seen in the accident cases, the pessimistic estimate of benefit would include the chance that they received a more severe injury, perhaps moving from slight to serious. Because there are lots of slight casualties this leads to a relatively large increase in the absolute number of serious casualties, when multiplied up to the national levels.

The benefit estimates generated within this study are considered to be **conservative**, because:

- The restraint system used in the testing was already well adapted for the 5th percentile female dummy which meant it was already optimised in this particular case. However, it is believed that most systems in current use are less well optimised for a 5th percentile occupant, so the real-world benefits from having a fully adaptive system would probably be greater.
- The benefit/disbenefit estimates could only be made for seven occupant groups where the sample size was sufficient, (out of 42), therefore benefit has only been estimated for 55% of frontal impact casualties. However, it is expected that some benefits would also accrue for other occupant groups. This should be particularly true for a (fully smart) restraint system that could be tuned for a wide range of occupant heights (or seating positions) and weights, and a wide range of frontal collision types and severities. Therefore it is expected that only a smart system would give a net benefit from consideration of the other occupant groups as well as those investigated within this study.
- Any changes expected to the injury severity of an occupant, were reported using the police definitions of fatal, serious and slight. The serious injury category is very broad, covering occupants with very minor injuries through to those who had life-threatening injuries or those who died more than 30 days after the accident. Therefore, substantial changes within this category were masked. Also, it is likely that a change from slight to serious injury severity could be expected more readily than the opposite change from serious to slight. This is because of the broad injury range within the serious category compared with the relatively narrow injury range of the slight category.

V. SUMMARY AND CONCLUSIONS

In order to estimate the effect of changes to the regulatory tests, four alternatives to the current test were defined. These were: testing with the 5th percentile female dummy; testing with the 95th percentile male; changing the injury criteria in the chest region; and testing for a smart restraint system. With respect to the UK casualty population, the conservative estimated benefits and disbenefits for these options were:

5th percentile dummy

- It is likely that there would be an overall disbenefit for drivers.
- For the front seat passenger, the optimistic estimate was that there would be a very small benefit from changing to a 5th percentile female, but the pessimistic estimate was for an overall increase in the number of fatal and serious casualties.

95th percentile dummy

- It is likely that there would be an overall disbenefit for drivers.

Change injury criteria

- For the option to change the chest injury threshold to represent older occupants, it is likely that there would be a disbenefit for drivers.
- For the front seat passenger, the optimistic estimate was that there would be a small benefit from using lower chest injury thresholds to represent older drivers, but the pessimistic estimate was for an increase in serious and particularly fatal injuries.

Smart system (tuned to two test procedures)

- For the option to implement smart restraint systems, the optimistic estimate was for a benefit across all the assessed casualty groups. The pessimistic estimate was for a disbenefit for drivers.
- It should be noted that a second test at a lower speed than Regulation 94 may be required to encourage the fitment of smart restraint systems.

The benefit of introducing one of these four options as an *additional* test to the current test was also considered. It was assumed that the additional tests would either increase the protection offered to the occupant, or keep it the same as it was with no alteration. This means that no disbenefit was estimated for any of the occupants, but there was the possibility of a benefit. The benefit analysis for this second set of assumptions showed that:

5th percentile dummy

- It was estimated that there would be no change in fatalities and a reduction of up to 25 serious injuries (per annum) for the seven casualty groups that were evaluated in detail.

95th percentile dummy

- It was estimated that there would be no change in fatalities and a reduction of up to 100 serious injuries (per annum) for the seven casualty groups that were evaluated in detail.

Change injury criteria

- It was estimated that there would be a reduction of up to two fatalities and 148 serious injuries (per annum) for the seven casualty groups that were evaluated in detail.

Fully adaptive smart system (tuned to a wide range of occupants and impact severities)

- It was estimated that there would be a reduction of up to 11 fatalities and 271 serious injuries (per annum) for the seven casualty groups that were evaluated in detail.
- This option yielded the maximum predicted benefit based on the seven casualty groups.

As a final point, it should also be noted that the THOR-NT 50th percentile dummy had a greater excursion than the 50th percentile male Hybrid III in the sled tests. The THOR-NT is generally considered to have more humanlike forward excursion response than the Hybrid III. This implies that any optimisation of restraint systems that was based on the excursion of the Hybrid III dummy may allow the head or thorax of real occupants to contact the steering wheel or dashboard through the airbag, even if they were no heavier than the dummy.

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VIII. APPENDIX

TABLE II

Estimated change in the number of casualties in a Regulation 94 compliant fleet for four different test options

(Change to current test procedure; test option 4 may require a second test procedure)

	Test option 1:		Test option 2:		Test option 3:		Test option 4:	
	Fatal casualties							
Casualty group	5th percentile dummy		95th percentile dummy		Change injury criteria		Smart restraint system	
	Optimistic	Pessimistic	Optimistic	Pessimistic	Optimistic	Pessimistic	Optimistic	Pessimistic
Driver, 17-49, male	0	32	0	9	0	17	0	0
Driver, 17-49, female	0	6	0	28	0	7	0	2
Driver, 50-59, male	0	12	0	2	0	5	0	1
Driver, 60+, male	0	17	0	3	0	10	0	1
FSP, 17-49, male	0	2	0	0	0	3	0	0
FSP, 17-49, female	0	1	0	0	0	1	0	0
FSP, 60+, female	0	6	0	0	-2	3	-11	-2
	Serious casualties							
Casualty group	5th percentile dummy		95th percentile dummy		Change injury criteria		Smart system	
	Optimistic	Pessimistic	Optimistic	Pessimistic	Optimistic	Pessimistic	Optimistic	Pessimistic
Driver, 17-49, male	40	924	99	853	125	1014	-38	93
Driver, 17-49, female	27	987	135	868	103	1065	-55	95
Driver, 50-59, male	9	182	13	173	12	204	-21	18
Driver, 60+, male	11	211	-16	198	-13	236	-96	15
FSP, 17-49, male	-1	60	0	0	-5	-3	-10	-1
FSP, 17-49, female	0	93	0	0	-18	-1	-28	0
FSP, 60+, female	-1	30	0	0	-22	-3	-23	0
	Slight casualties							
Casualty group	5th percentile dummy		95th percentile dummy		Change injury criteria		Smart system	
	Optimistic	Pessimistic	Optimistic	Pessimistic	Optimistic	Pessimistic	Optimistic	Pessimistic
Driver, 17-49, male	-40	-955	-99	-862	-125	-1031	38	-93
Driver, 17-49, female	-27	-993	-135	-896	-103	-1072	55	-97
Driver, 50-59, male	-9	-194	-13	-175	-12	-209	21	-19
Driver, 60+, male	-11	-228	16	-202	13	-246	96	-16
FSP, 17-49, male	1	-62	0	0	5	0	10	1
FSP, 17-49, female	0	-95	0	0	18	0	28	0
FSP, 60+, female	1	-36	0	0	24	0	34	3

TABLE III
Estimated change in the number of casualties in a Regulation 94 compliant fleet for four different test options
(New test in addition to current test procedure)

	Test option 1:		Test option 2:		Test option 3:		Test option 4:	
	Fatal casualties							
Casualty group	5th percentile dummy		95th percentile dummy		Change injury criteria		Smart restraint system	
	Optimistic	Pessimistic	Optimistic	Pessimistic	Optimistic	Pessimistic	Optimistic	Pessimistic
Driver, 17-49, male	0	0	0	0	0	0	0	0
Driver, 17-49, female	0	0	0	0	0	0	0	0
Driver, 50-59, male	0	0	0	0	0	0	0	0
Driver, 60+, male	0	0	0	0	0	0	0	0
FSP, 17-49, male	0	0	0	0	0	0	0	0
FSP, 17-49, female	0	0	0	0	0	0	0	0
FSP, 60+, female	0	0	0	0	-2	0	-11	-2
	Serious casualties							
Casualty group	5th percentile dummy		95th percentile dummy		Change injury criteria		Smart system	
	Optimistic	Pessimistic	Optimistic	Pessimistic	Optimistic	Pessimistic	Optimistic	Pessimistic
Driver, 17-49, male	-4	0	-34	0	-8	0	-38	0
Driver, 17-49, female	-19	0	-4	0	-35	0	-55	0
Driver, 50-59, male	0	0	-14	0	-15	0	-21	0
Driver, 60+, male	0	0	-48	-4	-45	0	-96	-6
FSP, 17-49, male	-1	0	0	0	-5	0	-10	-1
FSP, 17-49, female	0	0	0	0	-18	0	-28	0
FSP, 60+, female	-1	0	0	0	-22	0	-23	0
	Slight casualties							
Casualty group	5th percentile dummy		95th percentile dummy		Change injury criteria		Smart system	
	Optimistic	Pessimistic	Optimistic	Pessimistic	Optimistic	Pessimistic	Optimistic	Pessimistic
Driver, 17-49, male	4	0	34	0	9	0	38	0
Driver, 17-49, female	19	0	4	0	35	0	55	0
Driver, 50-59, male	0	0	14	0	15	0	21	0
Driver, 60+, male	0	0	48	4	45	0	96	6
FSP, 17-49, male	1	0	0	0	5	0	10	1
FSP, 17-49, female	0	0	0	0	18	0	28	0
FSP, 60+, female	1	0	0	0	24	0	34	3