An Assessment Of Real World Steering Wheel Intrusion Characteristics And Their Implications For Head And Face Injuries To Restrained Drivers In Frontal Impacts

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ABSTRACT

Field study accident data were analysed to determine the effect of the steering wheel on head/face injuries to restrained drivers in frontal impact. 50% of restrained drivers had sustained injury to those regions and the steering wheel was shown to play a major part in the causation of those injuries. Facial contusion and laceration was the most common injury for those drivers sustaining only minor injury to the head/face from the wheel. Of those sustaining more major injury, the head became the more important body region. When collision severity was considered, the likelihood and severity of head/face injuries from direct wheel contact was shown to increase with the Equivalent Test Speed and those injuries were much more likely than not at speeds above 40 km/h. Wheel rearward and upward displacement and thus compromise of the head ride down envelope was also seen to increase with collision severity. However, for speed changes up to 50 km/h only 2.3% of wheels showed residual displacement upward and/or rearward greater than 12 cm, with the implication that most of the steering systems in the sample had restricted wheel displacement close to the present and proposed legislative standard. The role of wheel intrusion into the head ride down envelope was shown to have an important bearing on the likelihood of head/face injury. For the same collision severity, substantially more restrained drivers sustained head/face injury under conditions of moderate and high compromise of that envelope than those experiencing negligible compromise. As this was the case even at the lower collision severities, it is suggested that real benefits in head/face injury reduction would follow if rearward and/or upward wheel displacement were reduced still further than that permitted and proposed for the Barrier Test. Future consideration of the relationship between collision severity, wheel displacement and head/face injury severity is recommended, taking account of front impact distribution and individual characteristics of drivers and steering systems.

INTRODUCTION

The importance of the steering wheel as an injury source for the head and face of restrained drivers in frontal impact has been cited by several authors (5, 6, 7, 9, 10)*. This is because the restrained drivers torso is held in position while the head arcs forward and downward towards the steering wheel. In addition the slack inherent in the operation of many inertia reel mechanisms allows some forward excursion of the occupant before full restraint occurs. Given this situation, obviously any movement of the steering wheel into the head ride down envelope is undesirable. Current European legislation regarding steering wheel intrusion in frontal impact was initially conceived to mitigate chest injury to the unrestrained driver through E.C.E. Regulation 12. (3)* regarding horizontal movement of the wheel into the passenger compartment in the frontal Barrier Test. However, because the head and face are less tolerant than the chest regarding blunt impact injury, this legislation has little relevance for the restrained driver in all but the most severe collisions. Although the requirement has been modified to allow provision for a test involving a hemispherical headform as defined in E.C.E. Regulation 21, this has been an optional proviso. (4)*. and only comparatively recently has the process begun to mandate it.

As the introduction of the seat belt law in Britain on January 31 1983 had the effect of raising the usage rate to around 95% for front seat occupants (2)*, the problem of head/face contact on the wheel has been highlighted in that country for almost ten years.

In view of the apparent head trajectory adopted by restrained drivers in frontal impacts, it seems probable that some control on upward movement of the steering wheel would also be helpful. It is understood that some restriction on upward wheel movement in the frontal Barrier Test has now been proposed. Therefore the present study examined not only wheel rearward displacement , but this together with upward movement in order to gain some insight into how wheel movement affects head/face injury to restrained drivers in Real World frontal impact.

FIELD DATA

Since November 1983 a stratified sample of car occupant collisions has been examined in the East and West Midlands region of England. The former is predominantly rural and the latter urban. The sampling includes all fatalities, 50% of police reported serious cases and about 12% of slight injury accidents, involving passenger cars less than six years old. The vehicles are inspected soon after the accident and crash data correlated with occupant injury data obtained from hospital records, H. M. coroners reports and from questionnaires sent to the occupants themselves. The overall methodology is described elsewhere (8)*. Records were available for the period November 1983 to August 1990. This yielded 3440 accidents available for analysis.

METHODOLOGY

The field data was interrogated for frontal impacts between 11 and 1 on the clock where, the vehicle structure had been engaged and a driver seat belt had been in use during the impact. Where possible an equivalent test speed (abbreviated to ETS) was calculated from vehicle crush measurements and stiffness coefficients. This was used as an indicator of collision severity. Steering wheel displacements in the horizontal and vertical plane were considered as movement which would most compromise the driver head ride down envelope. This data was of course a measure of residual movement and did not take into account dynamic displacement during the crash phase. Where possible, driver contact points within the vehicle were assessed and injury codes assigned to each body region using The Abbreviated Injury Scale, 1985 Revision. (1)*.

RESULTS

Overall Sample Selection

The cause of primary vehicle damage was used to describe the range of impact type for the 3440 crashed vehicles. (table 1)

Table 1. Impact Type

Cause of Primary Vehicle Damage	N	%
Front Impact	2067	60%
Side Impact	890	25.9%
Rear Impact	172	5.0%
Rollover	191	5.6%
Swipes	77	2.3%
Other	36	1.0%
Unclassified	6	0.2%
Total	3440	100%

(Swipes = impacts where the vehicle structure was not fully engaged by the struck object).

Front impacts (clearly the most common impact configuration) were further classified by direction of principal force. (table 2)

Table 2. Direction of Principal Force on the Clock Direction (front impacts)

	10	11	12	1	2	Total
No of Impacts	45	281	1363	339	39	2067
%	2.2%	13.6%	65.9%	16.4%	1.9%	100%

The more oblique impacts at 10 and 2 do not form a large proportion of the frontal impact range (4.1%) and were not considered in this analysis. Of the frontal impacts at directions 11, 12, and 1 there were 1481 cases where driver seat belt use was conclusively proven (74.7%). Those cases were used to examine the overall injury patterns for the restrained drivers.

First, in order to give an indication of the collision severity for the 1481 cases, the Crash 3 computer programme was used to calculate an equivalent test speed for the vehicles. The ETS could be calculated in 1153 (78%) cases. Figure 1 shows that 75% underwent an equivalent speed change below 48 km/h. It should be remembered that, in terms of occupant injury risk 48 Km/h is a severe impact.

Overall Injury Outcome

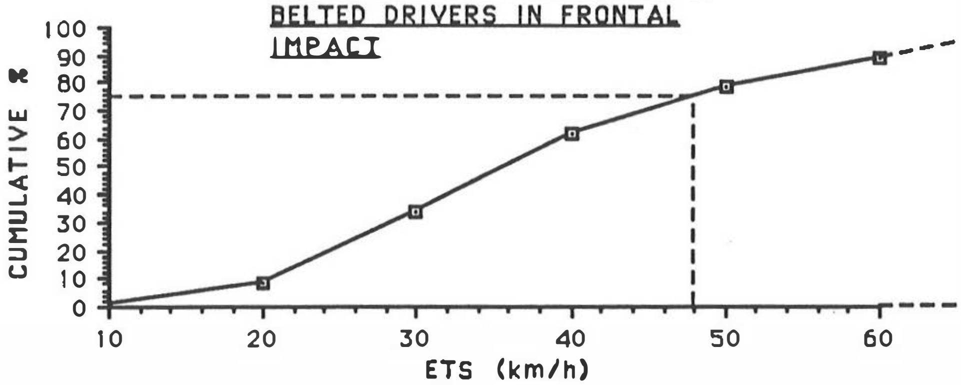
Injury outcome was now considered for the 1471 restrained drivers and in particular for injury to the head/face region. Table 3 shows the distribution of the highest AIS from that region along with those from other body regions. The most serious injury levels of AIS 3 and above have been classed together as one group. Neck includes only surface and soft tissue injuries while Cervical Spine injuries have been included under Spine. Upper extremes include the arms, hands and shoulders while the lower extremes include the thighs, legs and feet.

Table 3. Distribution of highest AIS by body region

Region	AIS 0	AIS 1	AIS 2	AIS 3+	AIS N/K	Total
Head/ Face	723 49.5%	426 29.2%	225 15.4%	87 5.9%	20 -	1481 100%
Neck (excl cervical spine)	1405 96.2%	50 3.4%	2 0.1%	4 0.3%	20 -	1481 100%
Chest	773 52.9%	473 32.4%	130 8.9%	84 5.8%	21 -	1481 100%
Abdomen and Pelvis	1119 76.6%	258 17.7%	36 2.5%	48 3.2%	20 -	1481 100%
Spine	1152 78.9%	277 18.9%	20 1.4%	12 0.8%	20 -	1481 100%
Upper Extremes	887 60.8%	394 27%	138 9.5%	40 2.7%	22 -	1481 100%
Lower Extremes	724 49.6%	536 36.7%	107 7.3%	92 6.4%	22 -	1481 100%

Where injury could be rated, half of the restrained drivers (50.5%) sustained an injury to the head/face region. Injury to the lower extremities also occurred with a similar frequency while the next most frequently injured region was the chest (47.1%). However, when the more serious injuries of AIS 2 and above were considered the head/face region then became the highest at risk, where 21.3% of drivers had a highest AIS value of 2 or more.

Figure 1. CUMULATIVE DISTRIBUTION OF ETS FOR 1153 INJURED/UNINJURED BELTED DRIVERS IN FRONTAL IMPACT



Injury Contacts

Where possible, injury producing contacts have been identified based upon the driver trajectory and upon contact evidence found in the vehicles. Details of contacts causing highest head/face injury severity are shown in table 4. The total sums to more than the number of drivers because some received more than one injury type at the highest AIS level.

Table 4. Contacts causing highest head/face AIS

Contact	N	%
Screen	51	5.9%
Facia	13	1.5%
Steering Wheel	570	65.7%
A-Pillar	42	4.8%
Front Door Structure	11	1.3%
Roof	13	1.5%
Other Occupant/Luggage	5	0.6%
Flying Glass	24	2.8%
Bonnet	11	1.2%
Struck Object	20	2.3%
Other Contacts	37	4.2%
2 Points of Contact	71	8.2%
Not Known	121	——
Total	989	100 %

For the injuries where a contact could be identified, table 4 shows that the steering wheel was the most frequently struck component. It was noted however that injuries associated with Two points of contact tended to occur at the higher crash severities as did contacts with the bonnet and struck object intruding into the passenger cell.

The Nature of Injuries caused only by the Steering Wheel

In some cases the steering wheel acted in conjunction with some other component to produce injury and in these instances it was not certain which component exerted the greatest influence. For that reason the remainder of the analysis examined only head/face injuries caused directly by the wheel for the restrained drivers in our frontal impact sample. Additionally, the few drivers whose injuries may have been confounded by rear loading from occupants or luggage were also excluded. The types of injury associated with the most severe head/face injury from wheel only contact, is shown in figure 2 for the 418 restrained drivers who sustained at least one injury from the wheel alone. For some drivers, a combination of head and face injury had contributed to the highest AIS score. In all the cases a standard retractor belt was judged to have performed satisfactorily.

261 drivers sustained a highest head/face AIS score of 1 from direct wheel contact, Figure 2(a). Of these, the face was the most common site of injury with 55.6% of those drivers sustaining facial contusions and 45.6% sustaining facial lacerations. 127 drivers sustained injury at the highest AIS 2 level, Figure 2(b), where the head became the most frequently injured region. Half of those drivers suffered short periods of unconsciousness (not usually more than fifteen minutes). Head injury was also common for the 30 drivers who experienced a highest injury at the AIS 3+ level, Figure 2(c). Prolonged unconsciousness with some type of neurologic deficit was the most frequent injury sustained by 43.3% of the drivers in that group and the more serious skull fractures and brain injuries were also common.

Factors influencing head/face injury from the steering wheel alone

This part of the analysis examined the effects of collision severity and wheel intrusion on head/face injury causation for the 418 restrained drivers described in the previous section. However, in addition it was also necessary to consider the conditions under which it was certain no head/face injury was sustained from a contact on the wheel. Table 3 showed that there were 723 drivers who fell into this category. Giving a combined sample of 1141 cases.

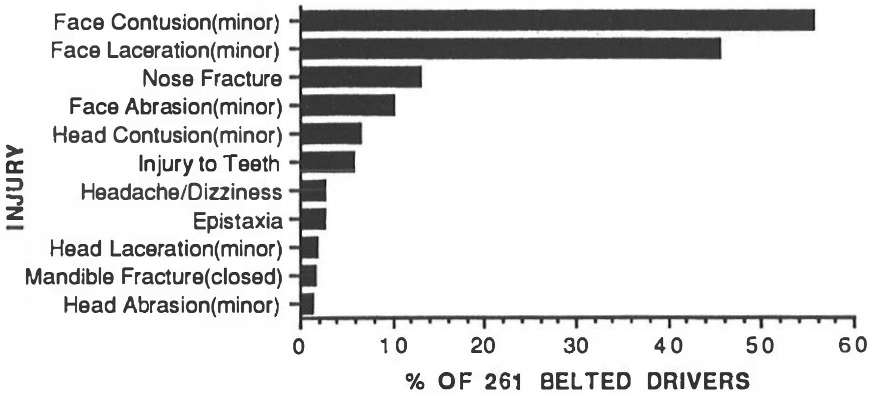
Collision Severity and Injury Severity

An equivalent test speed was known for 941 (82.5%) of the 1141 cases. For the restrained drivers, proportions of highest injury severity to the head/face are shown against banded ETS in figure 3, together with the median ETS for each injury severity level. The lowest speed change at which injury occurred was 11 km/h. It can be seen that apart from AIS 3+ injury, those of all other severities occurred throughout the speed change range. Perhaps not surprisingly there is a trend towards a higher incidence of the more severe head/face injuries as ETS increases. It is interesting to note that at speeds under 40 km/h the likelihood of an injury to the head/face from the wheel alone is small compared to that of receiving no injury. Once impact severity rises above this, figure 3 indicated that occupants were more likely to sustain wheel injury to that body region than not.

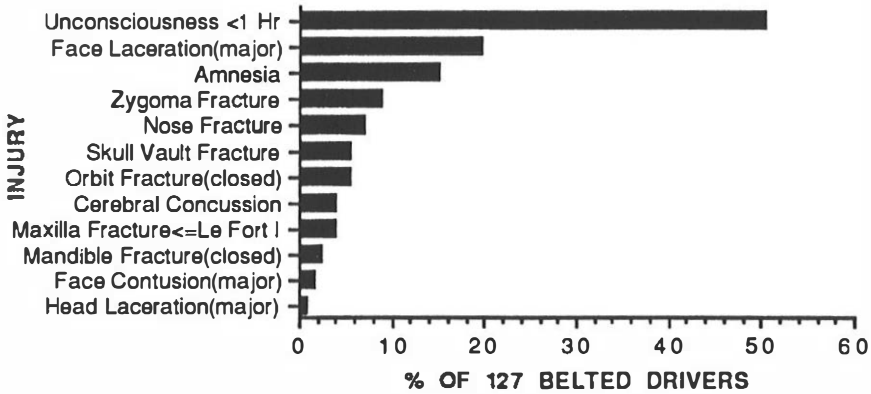
Classification of Wheel compromise of head/face ride down envelope

The residual displacement of each steering wheel at impact was measured along three perpendicular axes from its centre. This allowed assessment of any displacement rearwards, upwards and to the left or right. Here only rearward and upward displacement was considered as those are the directions most likely to have compromised the head/face ride down envelope in a frontal collision. In table 5, displacement has been banded into three categories for each plane of movement. The first band of <2 cm represents negligible compromise of the ride down envelope, while the limit of 12 cm between the second and third bands was chosen to closely reflect the limit of permitted horizontal movement and the proposed limit for vertical movement (12.7 cm) in the standard frontal barrier test. All 1141 steering columns in the sample complied with E.C.E. regulation 12.

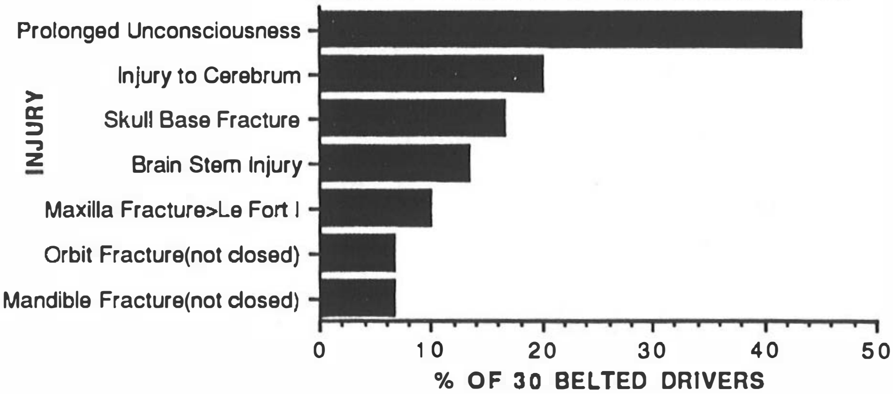
Figure 2. (a) DISTRIBUTION OF INJURIES FROM THE STEERING WHEEL ALONE FOR DRIVERS WITH HIGHEST AIS 1 TO THE HEAD/FACE



(b). DISTRIBUTION OF INJURIES FROM THE STEERING WHEEL ALONE FOR DRIVERS WITH HIGHEST AIS 2 TO THE HEAD/FACE



(c) DISTRIBUTION OF INJURIES FROM THE STEERING WHEEL ALONE FOR DRIVERS WITH HIGHEST AIS 3+ TO THE HEAD/FACE



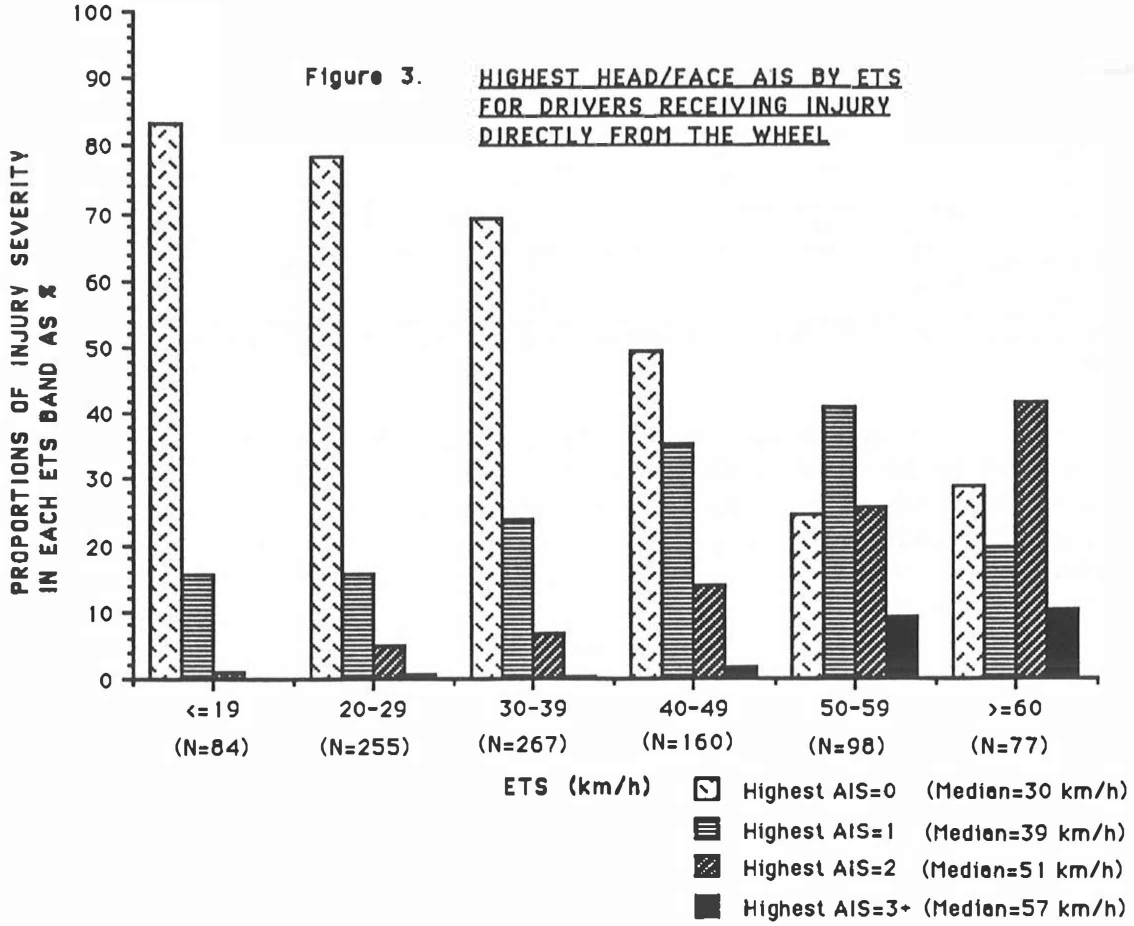


Figure 3. HIGHEST HEAD/FACE AIS BY ETS FOR DRIVERS RECEIVING INJURY DIRECTLY FROM THE WHEEL

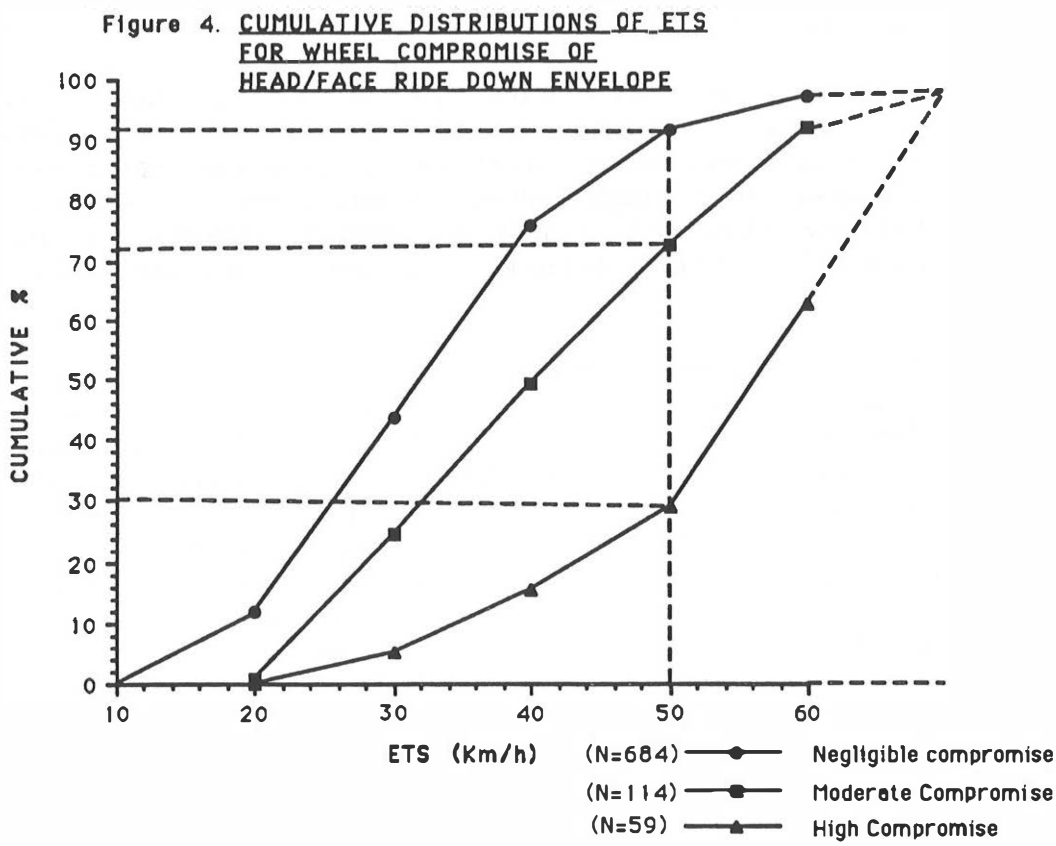


Figure 4. CUMULATIVE DISTRIBUTIONS OF ETS FOR WHEEL COMPROMISE OF HEAD/FACE RIDE DOWN ENVELOPE

Table 5. **Banded rearward and upward wheel displacement**

DISPLACE-MENT	Up (cm)				
Rear (cm)	**<2**	**2-12**	**>12**	**Not Known**	**Total**
<2	848 (81.5%)	52 (5.0%)	12 (1.2%)	1	913
2-12	24 (2.3%)	50 (4.8%)	15 (1.4%)	8	97
>12	12 (1.2%)	17 (1.6%)	10 (1.0%)	17	56
Not Known	3	7	5	60	75
Total	887	126	42	86	1141

Numbers in parentheses = % of total where displacement in both directions was known (1040).

From table 5, up and rear wheel displacement was combined and outlined into three groups reflecting the extent to which head/face ride down space was compromised. The first contained all wheels which had moved < 2 cm rearward and upward. This was termed the ' negligible compromise' group. The second group contained wheels which had moved between 2 and 12 cm rearward and/or upward, this was termed the ' moderate compromise ' group. The third group of wheels exhibited movement rearward and/or upward exceeding 12 cm. This was termed the ' high compromise ' group.

Collision Severity and Wheel Movement

It might be expected that higher collision severities would be related to higher levels of steering wheel compromise of the driver head ride down envelope. To test this, cumulative frequency curves were plotted for the Equivalent Test Speed relating to each of the wheel compromise groups. This had been calculated in 857 (82 %) of the 1040 cases making up those groups and the results are shown in figure 4. The median ETS for the negligible compromise group was 31 km/h, for the moderate compromise group it was 40 km/h and for the high compromise group 57 km/h. When tested against each other the medians were all significantly different at the $p < .05$ level. This suggests that the collision severity is a determining factor in the degree to which the wheel compromises the ride down envelope.

Figure 4 also showed that almost all the wheels (92%) which were displaced less than 2 cm up and rear, were involved in a speed change less than 50 km/h. Additionally most of the moderate compromise movement (72%) occurred below that speed change. By contrast it was also shown that the high levels of compromise were not commonly (30%) related to an ETS below 50 km/h. Of all the wheels considered, 728 (85%) fell under 50 km/h and of these only 17 (2.3%) exhibited residual displacement up and/or back by more than 12 cm.

Collision Severity, Wheel Movement and Injury

One fundamental dilemma facing those who would legislate on component performance for injury mitigation in car crashes basically concerns the relationship between collision severity and component intrusion into the occupant survival space. An example of this dilemma has been illustrated here. For while it was indicated that the likelihood and severity of steering wheel induced head/face injury is related to collision severity , an additional complication arises in that the extent of steering wheel displacement into the driver head ride down envelope was also related to that factor. The most accurate assessment of driver head/face injury from the wheel should consider, both collision severity and extent of head ride down compromise together.

Table 6 shows the % of drivers with wheel induced head/face injury (AIS >= 1) by wheel compromise group and Equivalent Test Speed. This combined data was known for 857 (75%) of the 1141 restrained drivers in the sample.

Table 6. % of restrained drivers with head/face injury by wheel compromise group and ETS

Wheel Compromise	ETS (km/h) <=29	30-39	40-49	50-59	>=60
Negligible Compromise	17% (299)	26.1% (218)	42.3% (111)	63.9% (36)	50% (20)
Moderate Compromise	46.4% (28)	57.1% (28)	63% (27)	81.8% (22)	88.9% (9)
High Compromise	100% (3)	50% (6)	75% (8)	90% (20)	86.4% (22)

(Numbers in parentheses = total number of restrained drivers in each group).

From table 6 it can be seen that, although injury occurred across all levels of compromise and collision severity, for the same collision severity the likelihood of injury was substantially greater where there had been moderate and high wheel compromise of the head ride down envelope, compared to the condition of negligible compromise. However, the difference between moderate and high compromise in relation to injury likelihood is not as apparent.

Regarding present and proposed legislation relating to wheel displacement in frontal impacts, it is interesting to consider the conditions under which moderate wheel compromise occurred (wheels in this group had been displaced up and/or back by 2-12 cm). In those crashes, almost half (46.4%) of the restrained drivers sustained a wheel injury even at a speed change below 29 Km/h and this percentage continued to rise up to and beyond 50 Km/h. Further work would be useful to determine how actual severity of injury varies with the combined effects of impact severity and wheel movement. That however is outside the scope of this analysis.

DISCUSSION

An appreciable proportion of restrained drivers (50.5%) were known to have received head/face injury in frontal impact. This paper set out to examine the effect of the steering wheel on injuries to those body regions. In those impacts, commonly (75%) occurring at speed changes less than 48 Km/h, the steering wheel was identified as the single component most frequently associated with head/face injury. The more serious wheel injuries (AIS >=2) were mainly associated with the head and this probably reflects the fact that a blow to the head is more life threatening than one of equivalent force to the face. Facial contusions and lacerations were however frequent for those drivers sustaining only minor (AIS =1) injuries to the head/face and these should not be discounted because surface injuries to the face are cosmetically more important than those to other body regions.

The role of collision severity was examined in relation to head/face injury from the wheel. Not surprisingly, the frequency and severity of those injuries were seen to increase with the equivalent test speed. Although injury occurred at speed changes as low as 11 Km/h, it became more likely at collision severities of 40 Km/h and above. Interestingly that was the median speed change for static wheel displacement of 2-12 cm up and/or rearward. It was therefore seen to be erroneous to relate wheel induced head/face injuries only to speed change, because the head ride down envelope was also increasingly compromised by wheel displacement as collision severity increased.

Considering wheel rearward and upward displacement at speed changes below 50 Km/h, it was found that only 2.3% of wheels showed static movement in either or both directions in excess of 12 cm. This suggested that most wheels would have complied closely with the present and proposed displacement restrictions in the Barrier Test. The implication here is that the head/face injuries described would not be grossly reduced by the addition of a restriction on steering wheel upward movement.

Controlling for collision severity showed that even for speed changes below 50 Km/h, negligible wheel compromise of the head ride down envelope had substantial benefits in injury reduction to the head/face. Even moderate compromise substantially increased the injury likelihood. From this it is proposed that a reduction in permissible wheel upward and rearward displacement at collision severities below 50 Km/h would go a long way towards reducing that injury risk.

Future work would be useful to examine the interrelationship between collision severity, wheel displacement and head/face injury severity. In addition factors such as the distribution of the frontal impact, the anti intrusion mechanism of the steering system and the driver characteristics of age, sex and height might also play a role in determining injury likelihood and severity. The introduction of the headform test for the steering wheel may provide some improvement to the status quo regarding head/face injury from that component and a retrospective real world study of the results would be desirable. However in the final analysis the aim should be to prevent head strike altogether . If this cannot be engineered with existing components then the air bag and seat belt pre-tensioner may be the most effective measures.

CONCLUSIONS

1. 96% of frontal impacts occurred at directions of force 11, 12 and 1 on the clock. In those impacts 75% of restrained drivers experienced an ETS below 48 km/h.
2. The head/face was one of the most frequently injured body regions for restrained drivers and the most frequent where the AIS was greater than 1. Where an injury producing contact was identified for head/face injuries, the steering wheel was the component most frequently struck.
3. For the head/face, direct wheel contact injuries of a highest AIS 1 comprised mainly facial contusions and lacerations. At the highest injury level of AIS 2 and above, head injury became the more important.
4. The likelihood and severity of wheel induced head/face injury increased with impact severity. The lowest speed at which an injury became most likely was 40 km/h.
5. Increased collision severity was associated with increased wheel encroachment into the head ride down envelope, but of all the wheels experiencing a speed change of 50 km/h or less , only 2.3% showed residual displacement up and/or back of more than 12 cm. That suggested most steering systems in the sample had closely complied with the present and proposed legislative standard for wheel displacement.
6. Given the same collision severity, head/face injury from the wheel was more likely where moderate and high compromise of the head ride down envelope had occurred. compared to negligible compromise of that envelope.
7. Where moderate compromise of the head ride down envelope occurred, almost half the restrained drivers sustained a head/face injury from the wheel even at speed changes below 29 Km/h. This suggests the need for a further reduction in permissible levels of wheel intrusion at collision severities lower than the Barrier Test speed if injury risk is to be reduced.
8. The need for further investigation into the relationship between head/face injury severity, collision severity and wheel intrusion is recommended, taking account of other variables such as frontal impact distribution, steering system type, wheel type and driver sex, age and height.

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