CAR ROLLOVER MECHANISMS AND INJURY OUTCOME

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ABSTRACT

The study focused on the mechanisms which result in passenger cars over turning. Approximately 21% of the car occupant fatalities examined in the UK's Co-operative Crash Injury Study (CCIS) experienced a rollover. However rollovers are shown to be complex events, which can occur with or without impact(s) and are not always the principal cause of the resulting occupant injuries.

The study differentiates the different types of rollovers and presents the influencing factors which precede them. Rollover events are divided into three categories: simple rollovers which don't involve a significant impact; rollovers followed by impact(s); and impacts followed by rollovers.

The research correlated the cars' dynamic motion immediately prior to the initiation of the roll, the mechanisms which caused the car to roll and the consequences with respect to occupant injury. A significant proportion of the cars were identified as 'sliding' laterally to some degree prior to the roll and off-road soft surfaces such as grass or earth were the most frequent roll initiators. Cars were also described as skidding or having lost control prior to leaving the road or striking a kerb or other roadside object or other vehicle. For this reason Electronic Stability Control (ESC) systems were identified as an important countermeasure with respect to potentially preventing a proportion of future rollover accidents.

Occupants, who were either fully or partially ejected from their cars, were strongly linked to severe injury outcome. Seat belts (ideally used in conjunction with other restraint devices designed to prevent either all or part of the occupants' body leaving the car through window apertures during the rollover) were shown to be effective.

INTRODUCTION

The data source for this paper is the UK's Co-operative Crash Injury Study (CCIS), which is one of Europe's largest car occupant injury causation studies (www.ukccis.org).

The programme of research started in 1983 and continues to investigate real-life car accidents. Multi-disciplinary teams examine crashed vehicles and correlate their findings with the injuries the victims suffered to determine how car occupants are injured. The objective of the study is to improve car crash performance by continuing to develop a scientific knowledge base, which is used to identify the future priorities for vehicle safety design as changes take place.

CCIS investigates and interprets real-world car occupant injury crashes retrospectively. Police reported injury road traffic crashes from defined geographical areas of England are reviewed to establish if they meet the CCIS sample criteria. The basic selection criteria used for the accidents presented in this analysis were:

- The accident must have occurred within the investigating teams geographical area
- The vehicle must be a car or car derivative
- The vehicle must have been less than 7 years old at the time of the accident
- The vehicle must have at least one occupant who is injured (according to the police)
- The vehicle must have been towed from the scene of the accident.

Accidents were investigated according to a stratified sampling procedure, which favoured cars that met the age criteria and contained a fatal or seriously injured occupant as defined by the British Government definitions of fatal, serious and slight. Where possible all crashes that met the criteria and involved a CCIS classified fatal or seriously injured occupant were investigated. Random selections of accidents involving slight injury were also investigated, up to a target maximum.

Vehicle examinations were undertaken at recovery garages several days after the collision. An extensive investigation of the cars' residual damage and structural loading along with detailed descriptions of the restraint system characteristics and any occupant contact evidence was recorded using the CCIS data collection protocols. This process allows the nature and severity of the impact(s) and/ or rollover damage to be precisely documented so different crash types can be compared.

Where practical the investigation teams visit the scenes of rollover crashes a day or two after the crash and gather evidence with respect to the highway and environmental factors.

Car occupant injury information was collected from hospital records, coroners' reports and questionnaires sent to survivors. The casualties' injuries were coded using the Abbreviated Injury Scale [1]. AIS is a threat-to-life scale and every injury is assigned a score, ranging from 1 (minor, e.g. bruise) to 6 (currently untreatable). The Maximum AIS injury a casualty sustains is termed MAIS. The scale is not linear; for example, an AIS 4 is much more severe than two AIS scores of 2.

The casualties' characteristics (age, gender, seat belt use) and injury information were correlated with the vehicle investigation evidence. This methodology allows the causes and mechanisms of the injuries to be documented.

Accidents investigated between December 2002 and September 2008 were included in the analysis (CCIS Phases 7 and 8 – to data release 8h).

RESULTS AND DISCUSSION

The relationship between impact type and injury severity for the car occupants in CCIS is shown in Table 1. In total, of the 8,526 occupants recorded in CCIS with known MAIS, 1,341 (16 %) were in cars which rolled over.

Table 1.
Impact types and injury severity for car occupants in CCIS

Type of Collision	Survivors (MAIS)			Killed	Total
	0	1	2+		
Single impact					
Frontal	642	1840	740	137	3359
Right side	204	601	172	61	1038
Left side	128	334	142	84	688
Rear	49	204	18	8	279
Multiple impact	256	856	303	112	1527
Rollover	176	776	284	105	1341
Other	9	7	4	4	24
Total	**1464**	**4618**	**1663**	**511**	**8256**

Rollovers are over-represented for occupants with higher injury severities, especially for occupants who were killed: of the 511 fatally injured occupants, 105 (21 %) were in rollovers.

Single vehicle accidents made up 38% of all accidents which resulted in serious or fatal injury (MAIS 2+) in the CCIS dataset. Rollovers occurred in 7% of multi-vehicle and 41% of single vehicle accidents. Of all the rollover accidents, 73% were single vehicle accidents.

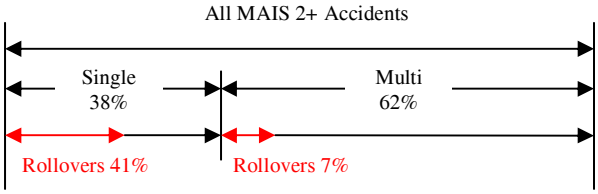

Figure 1. Proportion of single and multi vehicle accidents that result in rollovers

CCIS examines cars and car derivatives (light goods/commercial vans). Comparing the proportions of different vehicle types involved in CCIS accidents showed that 31% of off-road vehicles rolled over compared to 9% of estate cars.

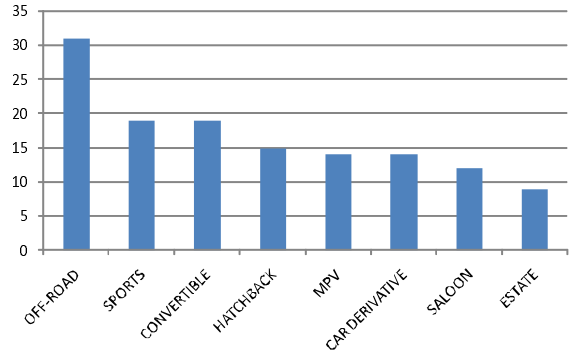

Figure 2. Percentage of vehicles by type which rolled over

Table 2 categorises the occupants involved in rollovers into four distinct groups, depending on whether there was a significant impact as well as the rollover, and whether that impact occurred before or after the roll. Fay et al. [2] presented similar results and also commented that:

'In practice, the characteristics of vehicle rollover can be more complicated than such analysis suggest because of the large number of vehicles which experience multiple events in crash sequences, including combinations of impacts and rollover events.'

Table 2.
Categories of rollover

Type of Rollover	Survivors (MAIS)			Killed	Total
	0	1	2+		
Rolled before 1st impact	15	79	31	20	145
Rolled after last impact	96	390	149	54	689
Rolled without any impacts*	59	289	92	25	465
Rolled between impacts	6	17	11	6	40
Other	-	1	1	-	2
Total	**176**	**776**	**284**	**105**	**1341**

* Significant impacts

Depending on exactly what caused them to roll, the groups where a rollover occurred before an impact are the groups of casualties for whom the rollover may have been prevented if an active safety system, such as ESC, was fitted to the vehicle [3]. A limitation of this analysis was that the fitment of ESC systems was not correlated with the pre-roll vehicle dynamics. Future work is planned to account for these systems and to quantify their real world effects and potential limitations.

The following diagrams (Figure 3 and Figure 4) show how the data was grouped for the analysis from this point on. The occupants were split by severity, with the "non-injured" and "slight" casualties (MAIS 0-1) separated from the "serious and killed" (MAIS 2-6) casualties. It should be noted that there was one occupant who had a MAIS of 1, who was killed; this occupant has been included in the "serious and killed" group of casualties.

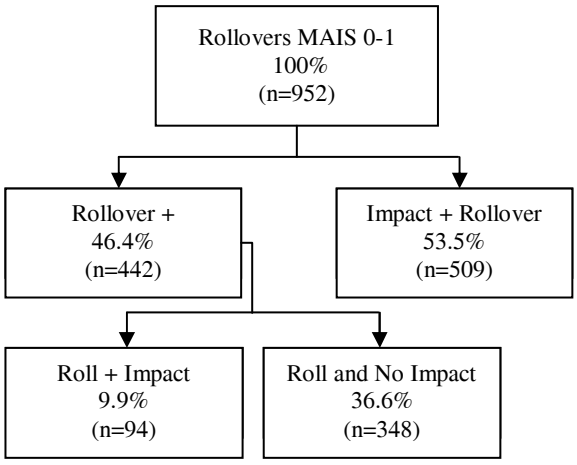

Figure 3. Distribution of rollover types for occupants with no or slight injuries

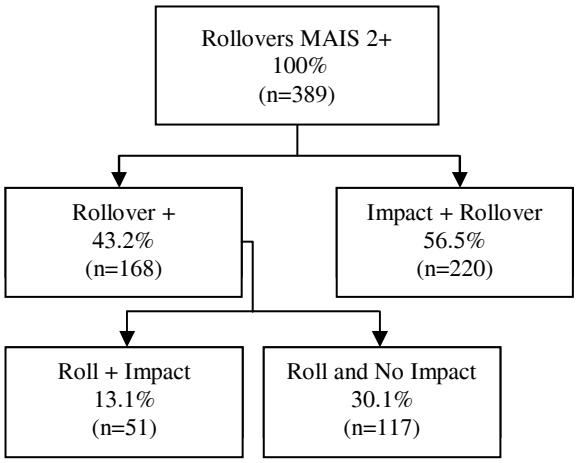

Figure 4. Distribution of rollover types for occupants with serious or fatal injuries

Occupants who had a roll then an impact, and a roll but no impact, are subsets of the "Rollover +" group – occupants where the rollover occurred first. This was the first group of occupants studied to see which factors influenced or caused their cars to roll. The characteristics of the pre-roll events were then compared with the respective injury outcomes. The occupants in the two subsets of roll this group encompasses were also analysed.

Following this, the occupants in vehicles which had an impact first, then rolled over, were investigated.

Rolled first

This section investigates the characteristics of the rollovers where the rollover occurred before an impact, or where there was no impact. Table 3 shows how the cars' attempted manoeuvres related to the direction of travel of the cars immediately before the rollover, for the occupants whose car rolled before any impact (or rolled and did not have an impact).

A large number of these vehicles were travelling on left and right bends, and were sliding (they had lost control). These vehicles accounted for 204 (33 %) of the occupants in cars which rolled over first. These are occupants where it is possible that ESC may have prevented the rollover and resultant injuries, by preventing the initial loss of control. A further 136 (22%) casualties were in cars described as attempting to proceed 'Forwards', but were also known to be sliding or have lost control prior to rolling. The precise reasons for these vehicles having lost control

were not always known, but included poor manoeuvres and avoidance actions such as swerving to negotiate obstacles/ other vehicles. It is reasonable to assume that a proportion of these incidents could have been prevented if ESC was fitted to all the cars.

Table 3.
Manoeuvre prior to event versus direction of travel at start of event – rolled first

Cars' direction of travel at the start of event	Manoeuvre prior to event				Total
	Forwards	Left bend	Right bend	Other/ unknown	
Forwards	107	37	31	24	199
Forwards & sliding to R	67	60	19	9	155
Forwards & sliding to L	49	8	63	3	123
Rearwards	-	4	-	-	4
Rearwards & sliding to R	2	4	6	-	12
Rearwards & sliding to L	3	1	-	-	4
Purely sideways to R	9	11	12	1	33
Purely sideways to L	6	3	17	-	26
Unknown	42	1	-	11	54
Total	**285**	**129**	**148**	**48**	**610**

Table 4 shows the initiating factor of the rollovers. The most frequent initiation of the rollovers for all injury severities was grass/earth or some other soft surface.

Table 4.
Roll initiation – rolled first

Roll initiation influence	**Survivors (MAIS)**			**Killed**	**Total**
	0	**1**	**2+**		
Kerb	14	62	24	7	107
Gradient up	2	11	12	3	28
Gradient down	8	31	11	3	53
Grass/ earth or soft surface	30	158	47	23	258
Tarmac/ hard surface	14	67	15	4	100
Other vehicle	1	7	2	1	11
Safety barrier/ low structure	-	8	3	-	11
Fence/ high structure	-	3	1	2	6
Sharp turning or spinning	3	11	5	2	21
Not known	2	10	3	-	15
Total	**74**	**368**	**123**	**45**	**610**

With the exception of "tarmac / hard surface", "other vehicle" and "sharp turning or spinning", the initiating factors all indicate that the vehicle left the carriageway, or struck something on the edge of the carriageway.

Table 5 shows the direction of roll of the vehicle, and the seating position and injury severity of the occupants.

Table 5.
Direction of roll by seating position and injury severity – rolled first

Direction of roll	**Survivors (MAIS)**			**Killed**	**Total**
	0	**1**	**2+**		
Roll to Right					
Driver	21	122	40	19	202
Front passenger	9	46	11	3	69
Rear passenger	9	30	15	2	56
Not known	-	1	-	-	1
	39	***199***	***66***	***24***	***328***
Roll to Left					
Driver	10	89	39	15	153
Front passenger	8	40	8	3	59
Rear passenger	14	26	3	2	45
Not known	1	1	-	-	2
	33	***156***	***50***	***20***	***259***
Rear over front					
Driver	-	7	4	-	11
Front passenger	1	2	1	-	4
Rear passenger	-	2	-	-	2
Not known	-	-	-	-	0
	1	***11***	***5***	***-***	***17***
Front over rear					
Driver	1	1	-	1	3
Front passenger	-	-	-	-	0
Rear passenger	-	-	-	-	0
Not known	-	-	-	-	0
	1	***1***		***1***	***3***
Not known	***0***	***1***	***2***	***0***	***3***
Total	**74**	**368**	**123**	**45**	**610**

The majority of the casualties (96 %) either rolled right to left or left to right. In order to simplify the analysis of roll direction and seating position in the car, the offside occupants in cars which rolled to the right were combined with the nearside occupants in cars which rolled to the left, and vice versa, to create two groups. Only seat belted occupants were selected. The injury severity of these groups is shown in Table 6.

Table 6.
Roll direction and seating position – rolled first

Roll direction and seating position	**MAIS 0&1**	**MAIS 2-6**	**Total**
Seated on side adjacent to direction of roll	133 78.7%	36 21.3%	169
Seated on opposite side to direction of roll	115 72.3%	44 27.7%	159
Total	248	80	328

This shows that occupants seated on the opposite side to the direction of roll (for example, drivers whose cars rolled from right to left) tend to be more severely injured. This may be related to the kinematics of the occupants at the moment the roof makes contact with the ground – the occupant seated on the opposite side

to the roll will accelerate towards the roof more than the occupant seated on the same side to the roll.

Figure 5 shows the direction of the force which initiated the roll, and also shows whether the vehicle rolled to the left or rolled to the right.

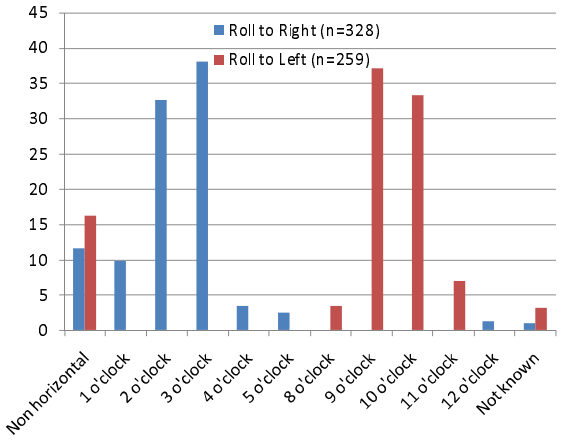

Figure 5. Direction of roll initiation force – rolled first

The majority of the rolls to the right had an initiation direction of force of 2 or 3 o'clock. The majority of rolls to the left had an initiation direction of force of 9 or 10 o'clock.

Figure 6 shows the point of action of the initiation forces, with two thirds of the initiation forces of rolls to the right and left applied to both the respective wheels.

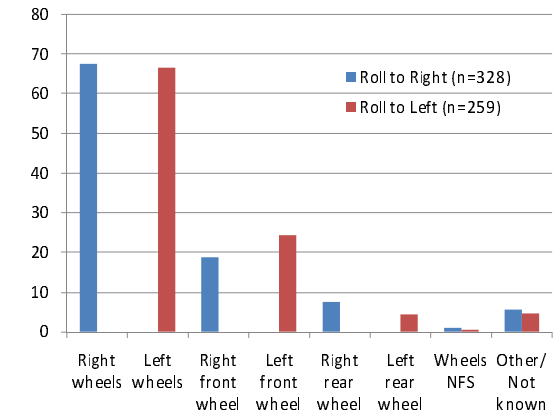

Figure 6. Point of action of initiation force – rolled first

Figure 7 shows the surface on which the vehicles that rolled over landed. There is virtually no difference between the landing surface and the direction of roll, implying cars leave the carriageway to the left and right evenly.

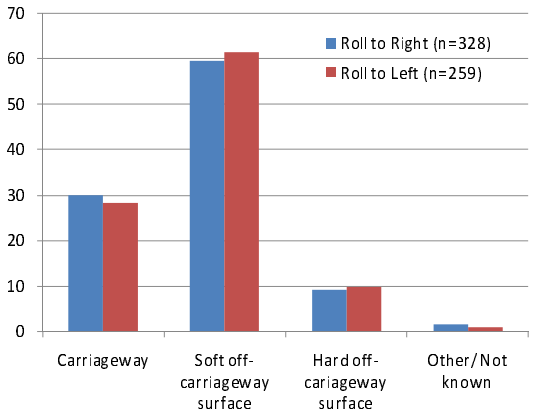

Figure 7. Landing surface – rolled first

Roll and no impact

The "roll and no impact" group is a subsection of the "rolled first" group. This section analyses the characteristics and consequences of rolls where there was no impact.

Figure 8 shows the relationship between the number of rolls and the injury severity of the occupants. The number of rolls is recorded as multiples of 0.25, where 0.25 rolls would be a roll onto the side, 0.5 rolls would be a roll onto the roof, etc.

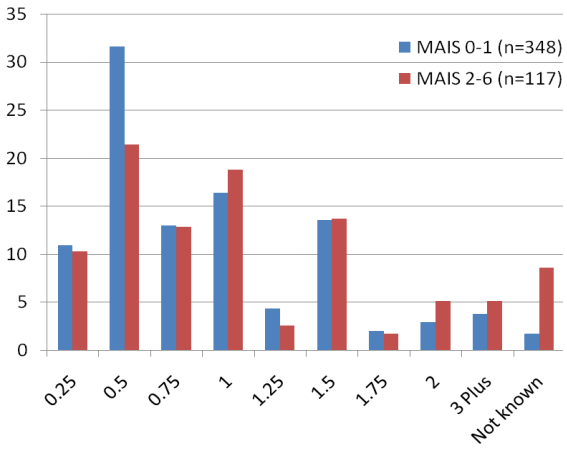

Figure 8. Number of rolls by severity – roll and no impact

Occupants in vehicles which rolled two or more times tend to be more severely injured, although there were relatively few vehicles that rolled this often. Slightly injured occupants are over-represented in vehicles which rolled 0.5 times.

Figure 9 shows the relationship between injury severity of the occupants, and whether their vehicle was airborne during the rollover.

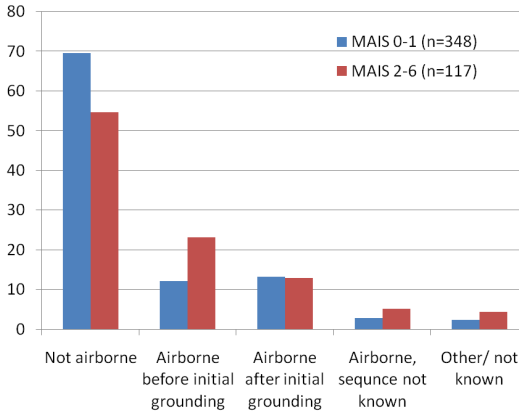

Figure 9. Severity of occupants and whether vehicle was airborne – roll and no impact

The relationship between injury severity and whether the vehicle was airborne is clearer than the relationship between the number of rolls. Of the occupants with MAIS 0-1, the vehicle was not airborne for almost 70 % of the occupants. For occupants with MAIS 2-6, the vehicle was not airborne for 55 % of the occupants.

For the vehicles which rolled, the most frequent area of most significant damage was the roof (47 % in total, 47 % of MAIS 0-1 occupants, and 45 % of MAIS 2-6 occupants). Table 7 explores the relationship between ejection and seat belt use for the occupants in a vehicle which rolled but had no other impact.

Table 7.
Ejection and seat belt use – roll and no impact

Ejection	**Seat belt use**			**Total**
	Used	Not used	Not known	
None				
MAIS 0-1	231	31	82	344
MAIS 2-6	42	16	15	73
	273	***47***	***97***	***417***
Full				
MAIS 0-1	1	1	-	2
MAIS 2-6	1	17	-	18
	2	***18***	***-***	***20***
Partial				
MAIS 0-1	3	-	-	3
MAIS 2-6	17	4	4	25
	20	***4***	***4***	***28***
Total				
MAIS 0-1	235	32	82	349
MAIS 2-6	60	37	19	116
	295	**69**	**101**	**465**

It is clear that seat belt use and full ejection in rollovers are strongly related. 75 % of occupants who were not ejected were wearing a seat belt, compared to only 10 % of occupants who were fully ejected. Occupants who were fully ejected were also much more likely to have severe injuries; 18 % of occupants who were not ejected had MAIS 2-6, compared to 90 % of occupants who were fully ejected.

Severe injury was also common among occupants who were partially ejected, with 89 % having MAIS 2-6. However the seat belt use of these occupants was relatively high, at 83 % which implies that seat belts prevent full ejection, but other systems (e.g. curtain airbags) are also required in order to prevent partial ejection.

Table 8 and Table 9 show the AIS 2+ and AIS 3+ injuries received by the occupants in cars which rolled over with no other impact.

Table 8.
Proportion of occupants with AIS 2+ injuries, by seat belt use and body region – roll and no impact

Injured ISS body region Percentage AIS 2+	Seat belt used	Seat belt not used	Seat belt use not known
MAIS 2+ (n)	60	37	19
Head AIS 2+	45%	56.8%	36.8%
Face AIS 2+	1.7%	2.7%	10.5%
Thorax AIS 2+	25%	59.5%	36.8%
Abdomen AIS 2+	13.3%	21.6%	21.1%
Limbs AIS 2+	51.7%	67.6%	47.4%
External AIS 2+	8.3%	-	5.3%

Table 9.
Proportion of occupants with AIS 3+ injuries, by seat belt use and body region – roll and no impact

Injured ISS body region Percentage AIS 3+	Seat belt used	Seat belt not used	Seat belt use not known
MAIS 2+ (n)	60	37	19
Head AIS 3+	23.3%	48.6%	26.3%
Face AIS 3+	-	2.7%	-
Thorax AIS 3+	15%	48.6%	26.3%
Abdomen AIS 3+	5%	10.8%	10.5%
Limbs AIS 3+	15%	24.3%	31.6%
External AIS 3+	1.7%	-	-

For seat belted occupants, the most frequent AIS 2+ and AIS 3 + injuries were to the head and the limbs. For non-belted occupants, the most frequent AIS 2+ injuries were to the head, thorax and limbs, and the most frequent AIS 3+ injuries were to the head and thorax. Occupants not wearing a seat belt generally had more injuries to more body regions, and the

proportion of thorax injuries especially increased for occupants not wearing a seat belt.

Table 10 shows how the injury severity of front seat occupants depended on the direction of the roll. Only occupants wearing a seat belt were selected for this table.

Table 10.
Roll direction and seating position – roll and no impact

Roll direction and seating position	MAIS 0&1	MAIS 2-6	Total
Seated on side adjacent to direction of roll	105 80.8%	25 19.2%	130
Seated on opposite side to direction of roll	83 72.8%	31 27.2%	114
Total	188	56	244

This shows that occupants seated on the opposite side to the direction of roll (for example, drivers whose cars rolled from right to left) tend to be more severely injured.

For seat belted occupants only, no statistical relationship was found with respect to the number of rolls, surface rolled onto, initiation influence or initiation type when comparing MAIS 0-1 and MAIS 2-6 occupants. However, the proportion of occupants in airborne vehicles was greater for MAIS 2-6.

Roll followed by impact

The group of occupants whose vehicle rolled before having an impact is also a subset of the occupants who rolled first. However, this group of 145 occupants is relatively small compared to the number who rolled over without an impact, so less detail is presented. Also, because these vehicles had an impact following the rollover, it is difficult to distinguish the injurious effects of the rollover from those of the impact.

Figure 10 shows the relationship between the number of rolls of the vehicle and the injury severity of the occupants. This shows no clear relationship between the two variables, but the vehicles as expected rolled fewer times than those which rolled without subsequent impact(s).

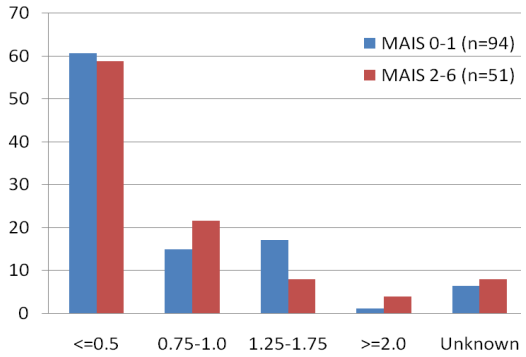

Figure 10. Number of rolls by severity – roll followed by impact

Figure 11 compares the injury severity of the occupants to whether their vehicle was airborne.

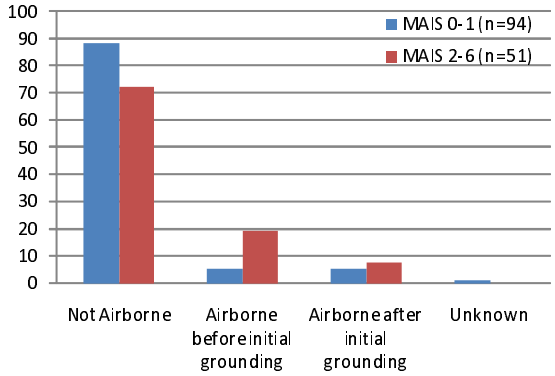

Figure 11. Severity of occupants and whether vehicle was airborne – roll followed by impact

As for rollovers with no impact, the severity is greater in rollovers where the vehicle has become airborne.

For the occupants in vehicles which rolled over then had an impact, the principal damage was to the roof of the car (61 cases, 16 MAIS 2+); the left (20 cases, 5 MAIS 2+) and right (18 cases, 6 MAIS 2+). This shows that principal damage is less often to the roof when the vehicle has an impact as well as a roll.

Table 11 shows the relationship between seat belt use, ejection, and injury severity for the occupants in rollovers followed by an impact.

Table 11.
Ejection and seat belt use – roll followed by impact

Ejection	Seat belt use			Total
	Used	Not used	Not known	
None				
MAIS 0-1	71	5	17	93
MAIS 2-6	22	6	4	32
	93	***11***	***21***	***125***
Full				
MAIS 0-1	-	-	-	0
MAIS 2-6	-	9	1	10
	-	***9***	***1***	***10***
Partial				
MAIS 0-1	1	-	-	1
MAIS 2-6	5	3	1	9
	6	***3***	***1***	***10***
Total				
MAIS 0-1	72	5	17	94
MAIS 2-6	27	18	6	51
	99	***23***	***23***	***145***

All of the occupants who were fully ejected, and for whom seat belt use was known, were not wearing a seat belt. These occupants were all seriously injured or killed.

Table 12 and Table 13 show the proportion of AIS 2+ and AIS 3+ injuries received by the occupants by body region and seat belt use.

Table 12.
Proportion of occupants with AIS 2+ injuries, by seat belt use and body region – roll followed by impact

Injured ISS body region Percentage AIS 2+	Seat belt used	Seat belt not used	Seat belt use not known
MAIS 2+ (n)	27	18	6
Head AIS 2+	52%	72%	50%
Face AIS 2+	11%	6%	-
Thorax AIS 2+	59%	72%	67%
Abdomen AIS 2+	19%	33%	17%
Limbs AIS 2+	56%	50%	50%
External AIS 2+	4%	-	17%

Similarly to rollovers without impacts, the injuries were dominated by head, thorax and head injuries. Occupants who were not wearing a seat belt had more injuries to more body regions, especially head and thorax injuries.

Table 13.
Proportion of occupants with AIS 3+ injuries, by seat belt use and body region – roll followed by impact

Injured ISS body region Percentage AIS 3+	Seat belt used	Seat belt not used	Seat belt use not known
MAIS 3+ (n)	27	18	6
Head AIS 3+	48%	61%	50%
Face AIS 3+	-	6%	-
Thorax AIS 3+	44%	61%	67%
Abdomen AIS 3+	4%	28%	-
Limbs AIS 3+	15%	17%	-
External AIS 3+	-	6%	33%

Impact followed by roll

Rollovers which occurred after an impact are likely to be different to rollovers which occurred before an impact or with no impact. Because this paper concentrates on the causes and consequences of rollovers, factors which are likely to be affected by the initial impact as well as the rollover, and where the effects of each cannot be distinguished (for example, roll direction and injury severity by seating position) have not been analysed here.

Table 14 shows the relationship between the manoeuvre prior to the impact, and the car's direction of travel at the start of the event. Compared to rollovers which occurred before / without an impact, a smaller proportion were sliding and travelling around a bend (16 % compared to 33 %). This suggests that the prevention of loss of control by ESC would have a relatively smaller effect of reducing rollover for these occupants. Similarly, the casualties described as in cars travelling 'Forwards' and sliding laterally to some degree represent about 28% of the "Impact followed by roll" group. These crashes often involved the car striking another vehicle or object and losing control or spinning before rolling over. ESC is likely to offer less benefits in these situations compared with the rolled first group.

Table 14.
Manoeuvre prior to event versus direction of travel at start of event – impact followed by roll

Cars' direction of travel at the start of event	Manoeuvre prior to event				Total
	Forwards	Left bend	Right bend	Other/ unknown	
Forwards	178	46	27	34	285
Forwards & sliding to R	74	15	11	18	118
Forwards & sliding to L	58	11	30	14	113
Rearwards	4	2	2	4	12
Rearwards & sliding to R	5	-	-	-	5
Rearwards & sliding to L	2	9	-	-	11
Purely sideways to R	39	16	3	11	69
Purely sideways to L	19	5	19	3	46
Unknown	42	2	2	24	70
Total	421	106	94	108	729

Table 15 shows the initiating factor of the rollovers by the injury severity of the occupants.

Table 15.
Roll initiation – impact followed by roll

Roll initiation influence	**Survivors (MAIS)**			**Killed**	**Total**
	0	**1**	**2+**		
Kerb	10	43	12	2	67
Gradient up	2	15	6	3	26
Gradient down	8	30	16	4	58
Grass/ earth or soft surface	24	86	33	16	159
Tarmac/ hard surface	13	78	15	2	108
Other vehicle	14	62	15	10	101
Safety barrier/ low structure	12	43	28	9	92
Fence/ high structure	5	19	18	8	50
Sharp turning or spinning	9	14	11	1	35
Other	-	6	-	2	8
Not known	5	11	6	3	25
Total	102	407	160	60	729

Compared to rollovers which occurred before / without an impact, the proportion of rollovers initiated by impact with another vehicle was much greater. However, grass/earth or soft surface was still the most frequent initiating factor.

Figure 12 and Figure 13 show the direction of the initiation force and the point of action of this force respectively.

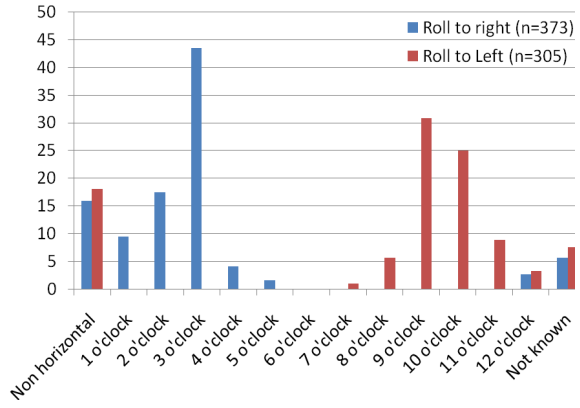

Figure 12. Direction of roll initiation force – impact followed by roll

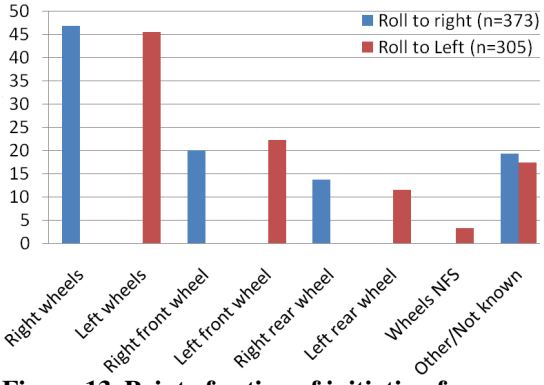

Figure 13. Point of action of initiation force – impact followed by roll

The majority of rolls to the right and left are still caused by initiation forces to the left and right wheels respectively.

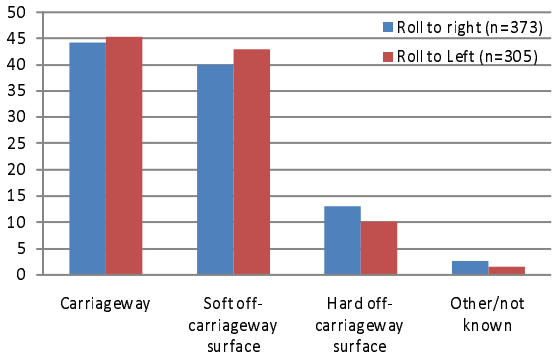

Figure 14. Landing surface – impact followed by roll

Figure 14 shows that the surface the vehicles landed on was not related to the direction of the roll, but the carriageway or road surface was proportionally much

more common (~ 45%) compared to roll first incidents (~ 30%).

Figure 15 shows the relationship between the number of rolls and the MAIS of the occupants.

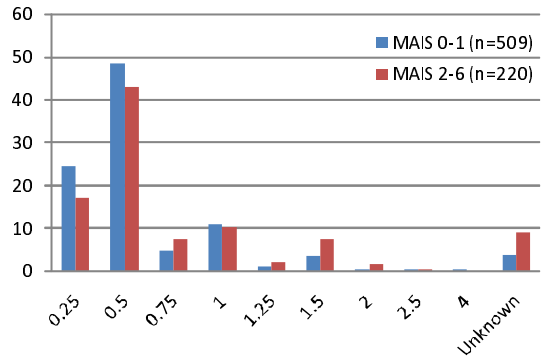

Figure 15. Number of rolls by severity – impact followed by roll

Occupants in a vehicle which rolled 0.25 times and 0.5 times tended to have a lower injury severity compared to these occupants in vehicles with more rolls. However, there is a much clearer relationship between injury severity and whether the vehicle became airborne, which is shown in Figure 16.

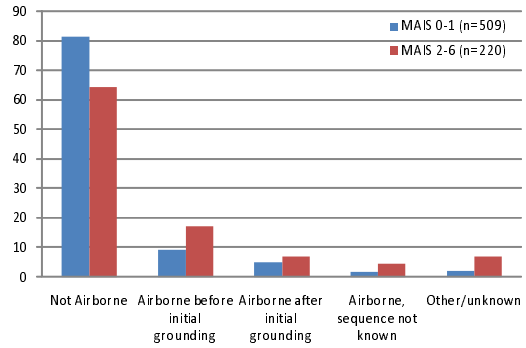

Figure 16. Severity of occupants and whether vehicle was airborne – impact followed by a roll

This figure shows that just over 60 % of the MAIS 2-6 occupants were in a vehicle which did not become airborne, compared to about 80 % of MAIS 0-1 occupants.

Table 16 explores the relationship between seat belt use, ejection and injury severity.

Table 16.
Ejection and seat belt use – impact followed by roll

Ejection	Seat belt use			Total
	Used	Not used	Not known	
None				
MAIS 0-1	310	61	124	495
MAIS 2-6	100	36	31	167
	410	***97***	***155***	***662***
Full				
MAIS 0-1	-	4	-	4
MAIS 2-6	4	20	2	26
	4	***24***	***2***	***30***
Partial				
MAIS 0-1	5	2	3	10
MAIS 2-6	10	9	6	25
	15	***11***	***9***	***35***
Unknown				
MAIS 0-1	-	-	-	0
MAIS 2-6	-	2	-	2
	-	***2***	***-***	***2***
Total				
MAIS 0-1	315	67	127	509
MAIS 2-6	114	67	39	220
	429	***134***	***166***	***729***

As seen for all other types of rollover impact, the risk of ejection was much greater for occupants who were not wearing a seat belt, and the injury severity of all ejected occupants tended to be higher than for occupants who were not ejected.

Table 17 and Table 18 show the AIS 2+ and AIS 3+ injuries received by the occupants in cars that rolled following an impact.

Table 17.
Proportion of occupants with AIS 2+ injuries, by seat belt use and body region – impact followed by roll

Injured ISS body region Percentage AIS 2+	Seat belt used	Seat belt not used	Seat belt use not known
MAIS 2+ (n)	114	67	39
Head AIS 2+	42.1%	61.2%	43.6%
Face AIS 2+	10.5%	6.0%	5.1%
Thorax AIS 2+	45.6%	46.3%	41.0%
Abdomen AIS 2+	26.3%	25.4%	17.9%
Limbs AIS 2+	50.0%	49.3%	48.7%
External AIS 2+	1.8%	1.5%	7.7%

Table 18.
Proportion of occupants with AIS3+ injuries, by seat belt use and body region – impact followed by roll

Injured ISS body region Percentage AIS 3+	Seat belt used	Seat belt not used	Seat belt use not known
MAIS 3+ (n)	114	67	39
Head AIS 3+	26.3%	41.8%	28.2%
Face AIS 3+	-	1.5%	2.6%
Thorax AIS 3+	36.8%	37.3%	35.9%
Abdomen AIS 3+	9.6%	9.0%	7.7%
Limbs AIS 3+	11.4%	22.4%	12.8%
External AIS 3+	-	1.5%	5.1%

Like occupants in other rollovers, the injuries were dominated by injuries to the head, limbs and thorax. However, unlike occupants in the other types of rollover, the proportion of unrestrained occupants receiving thorax, abdomen, or limb AIS 2+ injuries, and thorax or abdomen AIS 3+ injuries, was very similar to the proportion received by occupants wearing a seat belt. This was due in part to the nature of these accidents, where, for example some casualties experienced significant side impacts involving direct loading of their torso before their car rolled over.

CONCLUSIONS

Approximately 21% of the car occupant fatalities examined in the UK's Co-operative Crash Injury Study (CCIS) experienced a rollover. However rollovers are shown to be complex events, which can occur with or without impact(s) and are not always the principal cause of the resulting occupant injuries.

The study differentiates the different types of rollovers for MAIS 2+ occupants:

- Rollovers which do not involve a significant impact (30.1%);
- Rollovers followed by impact(s) (13.1%) and
- Impacts followed by rollovers (56.5%).

For cars which rolled first, 33% were described as travelling on bends (turning) and 'sliding' laterally and 22% were described as originally intending to proceed 'Forwards', but had also 'lost control'. ESC was identified as an important countermeasure with respect to potentially preventing a proportion of these rollover accidents. For cars which had an impact before rollover, the potential effectiveness of ESC is likely to be less.

The most common roll initiation influence was off-road soft ground (grass or earth) applying force to both wheels (right or left).

Casualties in cars which became airborne during the roll suffered proportionally more serious injuries.

Occupants, who were either fully or partially ejected from their cars, were strongly linked to severe injury outcome. Seat belts (ideally used in conjunction with other restraint devices designed to prevent either all or part of the occupants' body leaving the car through window apertures during the rollover) were shown to be effective.

ACKNOWLEDGEMENTS

This paper uses accident data from the United Kingdom's Co-operative Crash Injury Study (CCIS) collected during the period 2002 to 2008 (Phases 7s and 8h). Currently CCIS is managed by the Transport Research Laboratory (TRL Limited), on behalf of the United Kingdom's Department for Transport (DfT) (Transport Technology and Standards Division) who fund the project along with Autoliv, Fiat, Ford Motor Company, Nissan Motor Company and Toyota Motor Europe. Previous sponsors include Daimler Chrysler, LAB, Rover Group Ltd, Visteon, Volvo Car Corporation, Daewoo Motor Company Ltd and Honda R&D Europe (UK) Ltd. Data was collected by teams from the Birmingham Automotive Safety Centre of the University of Birmingham; the Vehicle Safety Research Centre at Loughborough University; TRL Limited and the Vehicle & Operator Services Agency (VOSA) of the DfT
Further information on CCIS can be found at http://www.ukccis.org

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SUMMARY TABLES

Table A 1. Severity of injury related to seating position and sex

Seating Position + Sex	Survivors (MAIS) 0	1	2+	Killed	Total
Driver					
Male	64	297	142	62	565
Female	27	174	48	14	263
Not known	1	2	-	-	3
	92	***473***	***190***	***76***	***831***
Front passenger					
Male	20	89	27	10	146
Female	16	84	31	8	139
Not known	6	-	-	-	6
	42	***173***	***58***	***18***	***291***
Rear passenger					
Male	21	60	18	6	105
Female	13	65	18	5	101
Not known	4	2	-	-	6
	38	***127***	***36***	***11***	***212***
Not known	***4***	***3***	***0***	***0***	***7***
Total	**176**	**776**	**284**	**105**	**1341**

Table A 2. Severity of injuries related to seating position and belt use

Seating Position + Belt	Survivors (MAIS) 0	1	2+	Killed	Total
Driver					
Belted	53	359	110	36	558
Unbelted	9	34	44	27	114
Not known	30	80	36	13	159
	92	***473***	***190***	***76***	***831***
Front passenger					
Belted	30	109	37	12	188
Unbelted	2	18	13	5	38
Not known	10	46	8	1	65
	42	***173***	***58***	***18***	***291***
Rear passenger					
Belted	14	54	7	1	76
Unbelted	7	33	25	8	73
Not known	17	40	4	2	63
	38	***127***	***36***	***11***	***212***
Not known	***4***	***3***	***0***	***0***	***7***
Total	**176**	**776**	**284**	**105**	**1341**

Table A 3. Severity of injury related to seating position and age

Seating Position + Age	Survivors (MAIS) 0	1	2+	Killed	Total
Driver					
< 17	1	1	-	-	2
17 – 24	28	172	63	17	280
25 – 39	21	156	66	31	274
40 – 59	21	87	39	20	167
60 +	12	37	20	8	77
Not known	9	20	2	-	31
	92	***473***	***190***	***76***	***831***
Front passenger					
< 17	4	18	4	-	26
17 – 24	5	73	28	9	115
25 – 39	3	25	14	3	45
40 – 59	3	17	7	3	30
60 +	6	17	4	3	30
Not known	21	23	1	-	45
	42	***173***	***58***	***18***	***291***
Rear passenger					
< 17	16	47	9	-	72
17 – 24	9	55	22	6	92
25 – 39	1	8	3	3	15
40 – 59	1	4	1	-	6
60 +	-	7	-	2	9
Not known	11	6	1	-	18
	38	***127***	***36***	***11***	***212***
Not known	***4***	***3***	***0***	***0***	***7***
Total	**176**	**776**	**284**	**105**	**1341**