

VEHICLE ROLLOVER – AN IMPORTANT ELEMENT IN MULTIPLE IMPACT CRASHES

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ABSTRACT

European field data have shown that vehicle rollovers do not usually occur in isolation. More frequently, they occur as part of more complex accident sequences involving multiple impacts. In most cases, the rollover event does not occur at the beginning of the crash sequence. Instead, the rollover is usually preceded by one or more impacts.

This paper describes a detailed analysis of multiple impact crashes that involve rollover and considers the nature, characteristics and sequencing of the impacts and rollover events involved.

INTRODUCTION

Much of the analysis published on the subject of vehicle rollover events implies that rollovers either occur as isolated events or are always the most harmful event in any more complex impact sequence. Traditionally, it has been a common practice in the U.S. for any crash in which a rollover occurs to be classed as a rollover accident, irrespective of the occurrence or severity of any other impacts in the crash sequence¹. It is believed that this practice came about, at least partly, because of limitations in the way in which crash event sequences are recorded in the FARS database (which began in 1975).

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

The authors have already reported on a preliminary analysis of European multiple impact crashes at the 2001 IRCOB conference². This study investigated multiple impacts at a general level and, in particular, explored the importance of different

groups of multiple impacts in the total accident population.

With regard to rollover, they reported that single isolated rollover events (i.e. those occurring without the occurrence of any impacts) were relatively infrequent in both UK and German in-depth accident databases (see Table 1).

Impact Type	German Data	UK Data
Single Front	43.6%	45.0%
Single Side	19.3%	17.0%
Single Rear	10.2%	4.0%
Single Rollover	0.4%	5.0%
Multiple Impact	26.5%	29.0%
Total %	100.0%	100.0%
Total N	5472	9288

Table 1: Distribution of impact configurations for German and UK data (all injury levels).

[Taken from Reference 2].

Rollovers occurring during more complicated crash sequences (i.e. those involving rollovers and one or more impacts) were more common. In such impact sequences, the rollover element most commonly occurred following an initial impact (for example see Table 2). Only a small proportion of cases involved an impact sequence that started with a rollover event.

	N	%
Rollover followed by Impact(s)	102	14%
Impact followed by Rollover (and subsequent impacts)	618	86%
Total	720	100%

Table 2: Distribution of accidents involving rollovers and impacts according to impact sequence. [UK data taken from Reference 2]

The research described in the current paper extends this work, exploring the occurrence and

characteristics of rollover events during more complex, multiple impact sequences.

METHODOLOGY

This study uses data from the UK's Co-operative Crash Injury Study (CCIS) and the analysis covers cases investigated from 1998 to 2002. The CCIS study has been described in detail by Mackay et al³ and further details can be found at www.ukccis.org.

It is planned to carry out a similar analysis of in-depth German data for a future publication.

ANALYSIS AND DISCUSSION

The database contains details of 7163 occupants where details of the crash sequence are known. 1012 of these (14%) experienced a rollover at some point during their crash sequence. For those with injuries at the AIS3 level or higher, 13% experienced a rollover during the crash sequence (see Table 3).

It can be concluded from this that rollover is a relatively infrequent event and that the occurrence of rollover, per se, does not appear to be associated with high injury risk. However, it should be mentioned that the selection criteria for those cases examined in CCIS result in the sample being strongly biased towards accidents involving fatal and serious injuries. It is possible that, if the complete accident population was analysed, then the frequency of rollovers (including those resulting in slight or no injuries) could be higher than the CCIS sample suggests.

	No Rollover	Rollover	Total
All Injury Levels	6151 (86%)	1012 (14%)	7163 (100%)
MAIS 3+	730 (87%)	109 (13%)	839 (100%)

Table 3: Occurrence of rollover events during the crash sequence.

However, accidents involving a rollover element are complex events in which the rollover can occur at any stage of the crash sequence.

1	Rollover before impact
2	Rollover after impact
3	Rollover with no impact
4	Rollover between impacts

Table 4: Codes used in CCIS for recording the timing and occurrence of rollover.

In CCIS, the timing of a vehicle rolling over is recorded using the four classifications shown in Table 4. In all cases, a rollover is defined as a rotation of at least 90 degrees about the longitudinal or lateral axis of the vehicle.

Looking at distribution of rollovers according to these CCIS classifications (see Figures 1 and 2), it can be seen that, for both occupants at all injury levels and for those sustaining MAIS3+ injuries, most of the rollovers (around 60%) occur after an initial impact. The second most common group, rollovers occurring without an impact, accounts for approximately one third of rollovers.

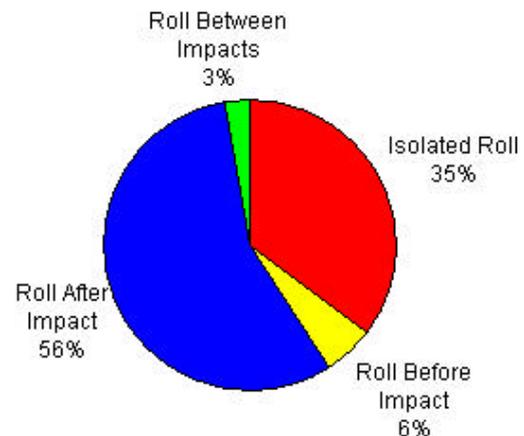


Figure 1: Distribution of rollovers according to crash sequence (All occupants N=1012).

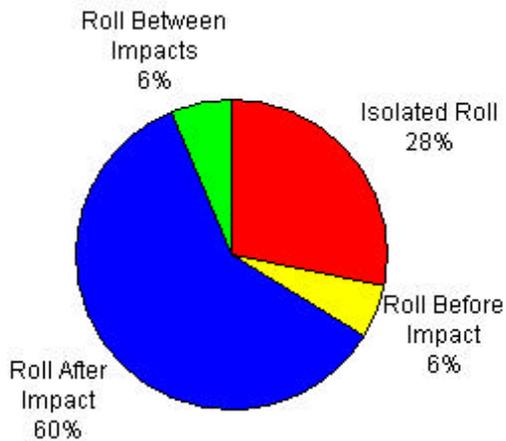


Figure 2: Distribution of rollovers according to crash sequence (MAIS 3+ occupants only N=109).

Because the remaining two groups (rollovers before and between impacts) are relatively small, it was decided to re-group the rollover classifications into two groups:

- A) Accident sequences which start with a rollover** (includes rollovers occurring without an impact and rollovers occurring before impact). In all of these cases, the rollover was the first event in the crash sequence and the occurrence of any subsequent impacts can be regarded as a random outcome, dependent on the proximity of other vehicles and fixed objects, etc.
- B) Accident sequences in which a rollover event follows an initial impact** (includes rollovers occurring after impact and rollovers occurring between impacts). In all of these cases, an impact was the first event in the crash sequence and the occurrence of any subsequent impacts after the rollover can be regarded as a random outcome.

In the following sections, the seat belt wearing rates for various types of crash and injury outcome will be examined. It is therefore useful to consider the significance of these against the overall seat belt wearing rate for the entire sample. This is shown in Table 5. In this sample, approximately two thirds of occupants were known to be restrained.

	Belted	Not Belted	Not Known
All Occupants	65.81%	11.34%	22.85%
All Occupants with MAIS3+ Injuries	66.51%	19.67%	13.83%

Table 5: Seat belt wearing status for occupants in the CCIS database.

A) ACCIDENT SEQUENCES WHICH START WITH A ROLLOVER

Taking the first group of rollover events (i.e. those impact sequences which started with the rollover element), a number of characteristics of the crashes were investigated.

Number of rolls The first characteristic explored was the number of rolls that the occupants experienced. There is no universal method for quantifying the severity of rollover events but the number of rolls undergone can give some indication of the energy available at the start of the roll. On the other hand, a vehicle entering a very high energy roll can be brought to rest after a very small degree of rotation by the presence of other vehicles or fixed objects. In CCIS, the number of rolls is assessed to the nearest quarter turn (ie 0.25 of a complete vehicle roll). The analysis is shown in Table 6.

Number of rolls	All Occupants		Occupants with MAIS3+ Injuries	
	N	%	N	%
0.25	39	9.44%	4	10.81%
0.5	152	36.80%	10	27.03%
0.75	26	6.30%	1	2.70%
1	52	12.59%	4	10.81%
1.25	14	3.39%	2	5.41%
1.5	52	12.59%	3	8.11%
1.75	2	0.48%	0	0.00%
2	7	1.69%	0	0.00%
More than 2	19	4.60%	3	8.11%
Not Known	50	12.11%	10	27.03%
Total	413		37	

Table 6: Number of rolls experienced by occupants in accident sequences starting with a rollover.

The most frequent number of rolls is 0.5 (i.e. with the vehicle ending up on its roof) and most occupants experienced one complete roll or less. The situation was similar for those occupants with more serious injuries but in these cases, the proportion for whom the number of turns could not be determined is significantly higher.

Direction	All Occupants		Occupants with MAIS 3+ Injuries	
	N	%	N	%
To Right	183	44.31%	15	40.54%
To Left	184	44.55%	14	37.84%
Rear over front	11	2.66%	2	5.41%
Front over rear	3	0.73%	0	0.00%
Not Known	32	7.75%	6	16.22%
Total	413		37	

Table 7: Direction of the rollover experienced by occupants in accident sequences starting with a rollover.

Direction of roll The second characteristic explored was the direction of the rollover event compared to the axes of the vehicle. This analysis is shown in Table 7. It can be seen that the majority of occupants experienced rolls around the longitudinal axis of the vehicle, almost equally split between those rolling to the right (i.e. clockwise)

and those to the left (ie anticlockwise). The situation was again similar for those occupants with more serious injuries but in these cases, the proportion for whom the direction of rotation could not be determined is higher.

Characteristics of impacts following the initial rollover An additional characteristic considered was the nature of the impact for the small number of cases where the rollover was followed by an impact. Of the 56 cases, 14 suffered an impact to the rear of the vehicle, 9 to the front, 17 to the sides, 13 to the top and 1 to the underside. For occupants suffering MAIS3+ injuries, three of the impacts were to the sides, 1 to the front and 2 to the top of the vehicle.

Table 8 shows the distribution of objects struck in the impacts following an initial rollover. At both levels of injury, the most frequent objects struck were fixed objects (both wide and narrow).

	All Occupants	Occupants with MAIS 3+ Injuries
Car	10	1
2-Wheeler	0	0
Light Truck	0	0
Heavy Truck/Bus	1	0
Narrow Fixed Object (eg Pole)	17	3
Wide Fixed Object	24	2
Unknown	4	0

Table 8: Objects struck in impacts following an initial rollover.

Severity of rollover versus severity of impact In the CCIS cases, the investigators are asked to consider whether or not “*the damage to the vehicle caused by the rollover is likely to have more of an influence on the injuries sustained by the vehicles occupants, than the damage caused by an impact.*”

For these 56 cases, the responses were equally divided between those where it was judged that rollover was more harmful than an impact and those where it was judged less harmful. At the MAIS3+ injury level, in only 1 case out of the 6 the rollover was considered more harmful than the impact.

Ejection of occupants It is known that ejection from the vehicle constitutes a significantly increased risk of injury during rollover events. The occurrence of ejection for occupants in the accident

sequences starting with a rollover is shown in Table 9.

Ejection	All Occupants		Occupants with MAIS3+ Injuries	
	N	%	N	%
No	384	92.98%	26	70.27%
Yes	20	4.84%	8	21.62%
Suspected	9	2.18%	3	8.11%
Total	413	100.00%	37	100.00%

Table 9: Occurrence of ejection (complete or partial) for occupants in accident sequences starting with a rollover.

Nearly 5% of occupants were known to have been ejected and there were a further 2% for whom ejection was suspected. The rate of known ejection was very much higher (21%) for those occupants with MAIS3+ injuries. This confirms the view that ejection leads to higher injury risks.

Table 10 shows the number of ejected occupants as a function of their level of ejection (full or partial) and the route of ejection. Slightly more occupants experienced partial ejection than full ejection. None of those experiencing full ejection had confirmed seat belt wearing. For both groups (full and partial ejection), the most common route of ejection was through the side window. This route accounted for half of full ejections and three quarters of partial ejections. This would support the increasing move towards side curtain airbags, that are designed to deploy in rollover events, which help to mitigate this ejection route.

	Full Ejection	Partial Ejection
Side Window	7	12
Rear Window	3	1
Side Door	0	1
Sun Roof	1	1
Not Known	2	1
Total	13	16

Table 10: Degree and route of ejection for occupants in accident sequences starting with a rollover.

Seat belt wearing One of the most effective ways of preventing ejection during rollover events is the use of the seatbelts. The use of seat belts for these cases is shown in Table 11 as a function of level of injury and occurrence of ejection (known or suspected).

It can be seen that the level of belt wearing reduces with both injury level and ejection. This suggests that the simple countermeasure of using the seat belt provided could be effective in reducing both ejection from the vehicle and the severity of the resulting injuries.

	Belted	Not Belted	Not Known
All Occupants	62.71%	9.44%	27.85%
Occupants with MAIS3+ Injuries	59.46%	18.92%	21.62%
All Ejected Occupants (known or suspected)	24.14%	51.72%	24.14%
All Ejected Occupants (known or suspected) with MAIS3+ Injuries	0.00%	63.64%	36.36%

Table 11: Seatbelt wearing status for occupants in accident sequences starting with a rollover. (“Ejection” includes complete and partial ejection).

Distribution of injuries Table 12 shows the distribution of AIS3+ injuries according to the body regions used in the calculation of Injury Severity Scores. The body regions most frequently injured at this severity are the head and thorax. A more detailed analysis of the injury types and causation is outside the scope of the current paper.

Head	21
Face	0
Thorax	15
Abdomen	3
Limbs	7
External	1
All	37

Table 12: Number of occupants suffering AIS3+ injuries in each body region (in accident sequences starting with a rollover).

B) ACCIDENT SEQUENCES WHICH START WITH AN IMPACT

In a similar manner to the analysis of the accident sequences which started with a rollover described above, the characteristics of crashes involving rollovers but beginning with an impact were investigated starting, in these cases, by considering the initial impact.

	All Occupants		Occupants with MAIS3+ Injuries	
	N	%	N	%
Back	41	6.84%	2	2.78%
Front	222	37.06%	24	33.33%
Left	174	29.05%	20	27.78%
Right	154	25.71%	23	31.94%
Other	8	1.34%	3	4.17%
	599	100.00%	72	100.00%

Table 13: Location of the initial impact for occupants in sequences involving a rollover after an impact.

Characteristics of the initial impact Table 13 shows the location of the initial impact on the car. Although the most common location is the front of the car, the front and the two sides are not significantly different in frequency, all accounting for around 30% of the impacts. However, when considering the database in its entirety (i.e. including all the cases where no rollover occurred and where rollover occurred before impact), frontal impacts accounted for around 57% of all first impacts whilst impacts to the left and right sides accounted for 14% and 18% respectively. This suggests that vehicles are less likely to roll after being struck at the front than they are after a side impact.

Object struck The objects struck in the initial impact are summarised in Table 14. The most common object struck (at both injury levels) is another car but there are also a significant number of impacts against fixed objects (both narrow and wide).

	All Occupants	Occupants with MAIS 3+ Injuries
Car	227	28
2-Wheeler	3	0
Light Truck	14	3
Heavy Truck/Bus	39	1
Narrow Fixed Object (eg Pole)	119	17
Wide Fixed Object	185	22
Unknown	12	1

Table 14: Object struck in sequences involving a rollover after an impact.

Comparing these results with those for the impacts following rollovers (see Table 8), the proportion of impacts with cars is significantly higher.

This suggests that when rollovers occurs, they are more likely to be triggered by impacts with cars but arrested by impacts against fixed objects (such as poles or crash barriers).

Number of rolls Table 15 shows the number of rolls experienced by the occupants in the rollovers that followed these initial impacts. As was the case with the rollovers at the start of the impact sequences, see Table 6, the most common number of rolls was 0.5 turns, accounting for around 40% of events.

Number of rolls	All Occupants		Occupants with MAIS3+ Injuries	
	N	%	N	%
0.25	153	25.54%	13	18.06%
0.5	222	37.06%	29	40.28%
0.75	20	3.34%	1	1.39%
1	85	14.19%	12	16.67%
1.25	12	2.00%	1	1.39%
1.5	35	5.84%	3	4.17%
1.75	2	0.33%	1	1.39%
2	9	1.50%	3	4.17%
More than 2	8	1.34%	1	1.39%
Not Known	53	8.85%	8	11.11%
Total	599		72	

Table 15: Number of rolls experienced by occupants in accident sequences involving a rollover after an impact.

Direction	All Occupants		Occupants with MAIS 3+ Injuries	
	N	%	N	%
To Right	299	49.92%	29	40.28%
To Left	257	42.90%	36	50.00%
Rear over front	11	1.84%	2	2.78%
Front over rear	2	0.33%	0	0.00%
Not Known	30	5.01%	5	6.94%
	599	100.00%	72	100.00%

Table 16: Direction of the rollover experienced by occupants in accident sequences involving a rollover after an impact.

Direction of roll The direction of the rollovers is summarised in Table 16. As with the cases where the impact sequence started with a rollover (see Table 7), the vast majority of the rollovers

following impact were around the longitudinal axis of the vehicle, approximately evenly split between rolls to the right and the left.

Severity of rollover versus severity of impact

For these 599 cases, the responses were almost equally divided between those where it was judged that rollover was more harmful than an impact and those where it was judged less harmful (302 less harmful, 285 more harmful, 12 not known). At the MAIS3+ injury level, in 26 cases out of the 72 the rollover was considered more harmful than the impact.

Ejection of occupants The occurrence of ejection for occupants in the accident sequences starting with an impact is shown in Table 17.

Ejection	All Occupants		Occupants with MAIS 3+ Injuries	
	N	%	N	%
No	550	91.82%	54	75.00%
Yes	20	3.34%	13	18.06%
Suspected	29	4.84%	5	6.94%
Total	599		72	

Table 17: Occurrence of ejection (complete or partial) for occupants in accident sequences involving a rollover after an impact.

Around 3% of occupants were known to have been ejected and there were a further 5% for whom ejection was suspected. The rate of known ejection was very much higher (18%) for those occupants with MAIS3+ injuries. This again supports the view that ejection leads to higher injury risks.

	Full Ejection	Partial Ejection
Windscreen	0	1
Side Window	6	25
Rear Window	1	0
Side Door	1	1
Sun Roof	3	2
From Open Top Car	0	1
Not Known	3	5
Total	14	35

Table 18: Degree and route of ejection for occupants in accident sequences involving a rollover after an impact.

Table 18 shows the number of ejected occupants as a function of their level of ejection (full or partial) and the route of ejection. For these cases, over

70% of ejections were partial – significantly higher than for the first group considered (see Table 10). For both groups (full and partial ejection), the most common route of ejection was again through the side window – further support for side curtain airbags.

Seat belt wearing The use of seat belts for these cases is shown in Table 19 as a function of level of injury and occurrence of ejection (known or suspected).

As with the first group of rollovers, it can be seen that the level of belt wearing reduces with both injury level and ejection. This suggests that the simple countermeasure of using the seat belt provided could be effective in these cases as well.

	Belted	Not Belted	Not Known
All Occupants	64.77%	11.69%	23.54%
Occupants with MAIS3+ Injuries	58.33%	26.39%	15.28%
All Ejected Occupants (known or suspected)	36.73%	34.69%	28.57%
All Ejected Occupants (known or suspected) with MAIS3+ Injuries	22.22%	61.11%	16.67%

Table 19: Seatbelt wearing status for occupants in accident sequences involving a rollover after an impact. (“Ejection” includes complete and partial ejection).

Distribution of injuries Table 20 shows the distribution of AIS3+ injuries according to the body regions used in the calculation of the ISS scores. The body regions most frequently injured at this severity are the head and thorax.

Head	34
Face	0
Thorax	42
Abdomen	7
Limbs	28
External	0
All	72

Table 20: Number of occupants suffering AIS3+ injuries in each body region (in accident sequences involving a rollover after an impact).

Comparing, this injury distribution with that from the cases starting with a rollover (see Table 12), a significant difference can be seen in the number of AIS3+ limb injuries.

CONCLUSIONS

- Vehicle rollovers (occurring as single events) are rare events in Europe, occurring in approximately 5% of accident cases in the UK CCIS database and less than 1% of cases in the German GIDAS database.
- Even when all rollover events are considered (i.e. including those occurring in combination with other impacts), rollovers are still relatively infrequent, only occurring in 14% of the UK crashes in the CCIS database.

A detailed study of the in-depth accident data from the UK's CCIS database has identified the following characteristics of vehicle rollovers during impact sequences:

- Only around one third of all rollovers occur as single, isolated events in the UK. The remainder occur during more complex multiple impact crash sequences.
- In most of these cases, the first event in the sequence is the impact rather the rollover.
- In general, in the UK, rollover can be regarded as a consequence of impact rather than an initiator.
- Most UK vehicle rollovers involve one complete roll or less.
- Most UK rollovers occur about the longitudinal axis of the vehicle, approximately half in each direction.
- Occupant ejection appears to be an important factor when serious injuries are sustained.
- Ejection takes place most frequently through the side windows but is also associated with low seat belt wearing rates.
- Increased seat belt wearing rates and measures to reduce ejection (full and partial) through the side windows are the approaches most likely to reduce injury levels in crash sequences involving rollover.
- The head and thorax are the body regions most frequently injured at AIS3+ level in accident sequences involving rollover.
- The limbs are more frequently injured in those sequences where the rollover follows an initial impact.
- When an impact follows an initial roll, it is frequently against a fixed object (rather than a vehicle) and appears to randomly involve all parts of the vehicle.

- In cases where rollover follows an initial impact, the impacts are split between those against cars and those against fixed objects. A disproportionate number of the initial impacts are against the sides of the vehicle that rolls over (rather than the fronts).
- When all crash sequences involving impacts and rollovers are considered, it is judged that in approximately half of the cases the rollovers were less harmful than the impacts. However, when occupants suffered injuries at the MAIS3+ level, the impact was considered more harmful than the rollover in the majority of cases.

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Further information on CCIS can be found at <http://www.ukccis.org>

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