CHARACTERISTICS OF ROLLOVER CRASHES

Jack McLean
Craig Kloeden
Giulio Ponte
Centre for Automotive Safety Research
The University of Adelaide
Australia
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ABSTRACT

Rollover crashes are investigated to identify ways in which active and passive safety solutions might be applied most effectively. Results of at-scene investigations of rural crashes by a research team and police reports of all crashes are reviewed. 236 crashes to which an ambulance was called, including 64 rollover cases, were investigated in the at-scene study, conducted on rural roads in South Australia. During a similar period police reports were compiled on 163,578 crashes, including 2,653 rollover cases. Injuries were sustained in 50% of the rollover cases but in only 18% of all other reported crashes (crashes resulting in a casualty or property damage of more than $1,000 were required to be reported). About half of the single vehicle rollover crashes in both studies occurred on straight roads; in the at-scene study after the vehicle drifted onto the unsealed shoulder. In almost every such case the vehicle yawed out of control before rolling. This is illustrated by photographs of the yaw marks and the final position of the vehicles, together with scale plans of these vehicle motions. The percentage of crashes which resulted in rollover increased with the posted speed limit: 5% at 80 km/h to 31% at 110 km/h. Vehicle factors relevant to crash and injury causation are also addressed. Combining information from these two studies overcomes to some extent their individual limitations, of small sample size in one instance and less detailed data in the other. These studies illustrate, among other matters, the type and frequency of situations in which stability control can be expected to prevent rollover crashes in a region where the roads are rarely wet, together with the importance of limiting travelling speed.

INTRODUCTION

This paper is based on information on crashes reported to or investigated by the police in South Australia, together with data from an in-depth study of 236 crashes to which an ambulance was called on rural roads within 100 km of the city of Adelaide. South Australia covers an area of over one million square kilometres (Texas is almost 700,000) and has a population of 1.12 million, of whom 73 per cent live in the Adelaide metropolitan area.

METHOD

The in-depth study was conducted by the Road Accident Research Unit (now renamed the Centre for Automotive Safety Research, CASR) between March 1998 and February 2000. Unit personnel attempted, usually successfully, to reach the scene of the crash before the vehicles were moved. Vehicle positions and damage were recorded and the site was mapped and photographed. Participants and witnesses were interviewed in most cases, initially at the scene in some cases and later in follow up interviews. In some fatal cases, where the vehicle positions had been marked by the Police Major Crash Investigation Unit, the CASR investigating team examined the crash scene within 24 hours. This had the effect of increasing the proportion of fatal crashes in the sample.

The sample of crashes investigated is not fully representative of all crashes occurring in the study area because the investigating teams were on call more frequently during daylight hours from Monday to Friday than on weekends. Similarly, night time crashes were under represented, apart from Thursday and Friday nights. However, characteristics associated with single vehicle rollover crashes can reasonably be compared with corresponding characteristics associated with other types of crash in this sample.

Some comparisons are made with data on all crashes reported to the police in South Australia which are held in the Traffic Accident Reporting System (TARS). These comparisons are influenced by the inclusion of crashes in the metropolitan area of Adelaide in the State-wide TARS data and by differences due to the study area including most of the populated hill country in the State.

RESULTS

Rollover Alone and After a Collision

Sixty four of the 236 crashes resulted in a vehicle rolling over. There were 19 cases in which a vehicle rolled without any prior collision. Another 21 of these rollovers occurred following a collision with another vehicle and in the remaining 24 single vehicle rollover crashes the vehicle rolled after a collision with a tree or an embankment (Table 1). However, it should be noted that in many of these single vehicle rollovers after a collision with a fixed object it is probable that the vehicle would have rolled over in any event had the collision not occurred.

Table 1.
Rollover crashes and prior collisions

Prior Collisions	Number of Crashes
No prior collision	19
Collision with fixed object	24
Collision with other vehicle	21
Total	64

Road and Traffic Factors

Almost half (49%) of the single vehicle rollover crashes occurred on straight sections of road, with about two thirds of the remainder on right hand curves (Table 2). (Note that traffic keeps to the left in Australia.) The percentage on straight roads was slightly higher (57%) in the State-wide police data (TARS) cases which may be due partly to chance variation but also to the topography of the in-depth study area which, as noted above, covered a much higher proportion of hill terrain than the whole State, which is mainly flat and hence with mostly straight roads. The vehicle movements on straight roads that typically resulted in rollover are described later in this paper.

Table 2.
Road alignment in single vehicle rollover crashes compared to all other crash types

Road Alignment	Rollover	Other	Column % Rollover	Column % Other
Straight	21	117	48.8	60.6
Right curve	13	45	30.2	23.3
Left curve	9	31	20.9	16.1
Total	43	193	100.0	100.0

* Note: Traffic keeps to the left in Australia.

The default open road speed limit in South Australia is 100 km/h, with most major highways zoned at 110 km/h. Consequently, it is not surprising that 81 per cent of these 43 single vehicle rollover crashes occurred on roads having a speed limit of at least 100 km/h (Table 3). However, eight of the single vehicle rollover crashes on 100 km/h roads occurred on bends having a posted advisory speed ranging from 25 to 80 km/h. Two of the 16 crashes on 110 km/h roads occurred on bends where an advisory speed was posted (65 and 75 km/h).

As noted, 81 per cent of these single vehicle rollover crashes occurred on 100 or 110 km/h roads. This is very close to the State-wide figure of 84 per cent for single vehicle rollover crashes. Single vehicle rollover crashes increase as a percentage of all crashes at the higher speed limits, both in the in-depth study data and the State-wide TARS data, to the extent that 30 per cent of all crashes on 110 km/h speed limit roads are single vehicle rollovers, compared with less than 20 per cent on 100 km/h roads (Table 3).

The two crashes which occurred on 60 km/h roads, in rural towns, were unusual in that one involved a rigid truck on which the load shifted when cornering and the other an elderly driver whose car ran up onto an embankment for no apparent reason and rolled over.

Some of these crashes were included in a case control study of travelling speed and the risk of crash involvement and so the travelling speed of the vehicle which rolled over had been estimated. (Kloeden et al, 2001) There were two crashes on 100 km/h speed limit roads where the cars were estimated from crash reconstruction to have been exceeding the limit by a wide margin (travelling speeds of 150 and 170 km/h). However there were also cases in which the estimated travelling speed was much less than the posted speed limit, as low as 65 km/h in one crash on a 100 km/h road.

Table 3.
Speed limit by percentage of single vehicle rollover crashes: in-depth study and state-wide

Speed Limit	Rollover Crashes	Other Crashes	% Rollover	% Rollover TARS*
60 km/h	2	32	5.9	0.7
70 km/h	2	4	33.3	1.7
80 km/h	2	32	5.9	4.9
90 km/h	2	7	2.2	7.7
100 km/h	19	81	19.0	18.9
110 km/h	16	37	30.2	30.6
Total	43	193	18.2	6.1

* Note: Crashes resulting in a fatality or injury requiring at least treatment at a hospital in South Australia 1999-2003

Type of Vehicle

A car or car derivative (station wagons and some utilities) accounted for almost three fifths of the vehicles which rolled over in the 64 crashes. (Table 4) What is more interesting, given the relative numbers of vehicles on the roads, is the high percentage (24.6%) of SUV vehicles, and the fact that three of these SUV vehicles were towing trailers. It is relevant to note here that the mean age of the vehicle fleet in Australia is about 11 years and SUVs have become an increasing proportion of that fleet, at least until very recently.

The percentage of semi trailers in Table 4 (10.8%) may be accounted for in part by the comparatively high exposure of these vehicles in terms of distance travelled but the crash circumstances demonstrated their well-recognised deficit in lateral stability compared to other types of vehicle.

Table 4.
Type of vehicle in all crashes resulting in a rollover

Type of Vehicle	Number of Vehicles	% of Vehicles
Car or car derivative	38	58.5
Semi trailer	7	10.8
Light van	1	1.5
Rigid truck	3	4.6
SUV (three towing a trailer)	16	24.6
Total	65	100.0

Note: Two vehicles rolled in one crash (semi trailer & SUV)

The percentage of cars among those vehicles that rolled following a collision with another vehicle (45.5%) was lower than it was among vehicles involved in single vehicle rollovers (65.1%) (Tables 5 and 6). This could indicate that a car is more stable than an SUV in a collision but the number of cases is small and this observed difference is not statistically significant.

Table 5.
Type of vehicle rolling over after colliding with another vehicle

Type of Vehicle	Number of Vehicles	% of Vehicles
Car or car derivative	10	45.5
Semi trailer	3	13.6
Rigid truck	2	9.1
SUV (one towing a trailer)	7	31.8
Total	22	100.0

Note: Two vehicles rolled in one crash (semi trailer & SUV)

Two thirds of the crashes in which a vehicle rolled over involved only that vehicle and almost two thirds (65.1%) of the vehicles in these single vehicle rollovers were cars (Table 6).

Table 6.
Type of vehicle in single vehicle rollover crashes

Type of Vehicle	Number of Vehicles	% of Vehicles
Car or car derivative	28	65.1
Semi trailer	4	9.3
Light van	1	2.3
Rigid truck	1	2.3
SUV (two towing a trailer)	9	20.9
Total	43	100.0

The relative involvement of cars compared to other vehicles (mostly SUVs) differed markedly however depending on whether or not the vehicle struck a fixed object, usually a tree, before rolling over. In the cases involving no prior impact, 42.1 per cent of the vehicles were cars whereas the corresponding percentage for cars in rollover crashes with a prior impact was 83.3 per cent (Tables 7 and 8, respectively). The crash circumstances indicated that a rollover would still have occurred in many of these cases had there been no collision with a fixed object.

Table 7.
Type of vehicle in single vehicle rollover crashes without a prior collision with a fixed object

Type of Vehicle	Number of Vehicles	% of Vehicles
Car or car derivative	8	42.1
Semi trailer	3	15.8
Rigid truck	1	5.3
SUV (two towing a trailer)	7	36.8
Total	19	100.0

Table 8.
Type of vehicle in single vehicle rollover crashes with a prior collision with a fixed object

Type of Vehicle	Number of Vehicles	% of Vehicles
Car or car derivative	20	83.3
Semi trailer	1	4.2
Light van	1	4.2
SUV	5	26.3
SUV	2	10.5
Total	24	100.0

The numbers of cases involving SUV vehicles in Tables 7 and 8 are too small to provide a reliable comparison with the corresponding data for cars presented in the previous paragraph but the

percentages are consistent with SUV vehicles rolling over before they have travelled out of control far enough to collide with a fixed object. The percentage of each of the above types of vehicle involved in a single vehicle rollover is compared with all vehicles of that type involved in the crashes investigated in the in-depth study in Table 9. The two types of vehicle that have by far the highest rate of single vehicle rollover, given involvement in a crash, are SUVs and semi trailers. This is consistent with the corresponding State-wide TARS data, as far as the types of vehicle can be compared. Once again, the higher percentage of all types of vehicle involved in single vehicle rollovers in the in-depth study is probably mainly a reflection of differences in topography.

Table 9.
Types of vehicle in single vehicle rollover crashes compared to vehicles in all other crash types: In-depth and TARS data

Type of Vehicle	Rollover	Other	% Rollover	% Rollover TARS[1]
Car	28	247	10.2	3.6
SUV	9[2]	25[3]	26.5	10.7
Semi trailer	4	13	23.5	-
Rigid truck	1	14	6.7	-
Van	1	15	6.3	4.5
Total	43	314	12.0	4.15
All trucks	5[4]	27[4]	15.6[4]	9.5

Notes: [1] See note to Table 3; [2] Two towing a trailer; [3] One towing a trailer; [4] Included above

Driver Characteristics

The age distribution of the drivers involved in single vehicle rollover crashes was very similar to that for all other drivers in this sample of crashes. There were eight drivers under 20 years of age and they were all on Provisional licences. They represented 18.6 per cent of all of these 43 drivers, slightly more than the 14.4 per cent of those drivers in this age group involved in the other types of crash in this study sample. Overall, however the percentage of drivers under 30 years of age was almost exactly the same in both groups of drivers (37.2% for those in single vehicle rollovers and 37.7% for the remainder). This is consistent with the results from the TARS data, which showed little difference in the age distribution of these two groups of drivers apart from an apparent over representation of drivers in the 16 to 18 year age range.

There were more male than female drivers involved in single vehicle rollover crashes but the difference was small (55.8% were male) and less than for the other types of crash in the in-depth study sample (62.6%). There was some statistically insignificant difference (p=0.389, Chi square=0.74) in the percentage of male drivers in this sample who were involved in single vehicle rollover crashes compared with other types of crash (10.9%) and the corresponding percentage for female drivers (14.0%). (Table 10) The corresponding percentages for State-wide single vehicle crash data were males 4.2 and females 4.1.

Table 10.
Sex of drivers involved in single vehicle rollover crashes compared to all other crash types

Sex of Driver	Rollover	Other	% Rollover
Male	24	196	10.9
Female	19	117	14.0
Total	43	313	12.1

Drivers operating on a Provisional licence had a higher rate of involvement in single vehicle crashes than in other types of crash but not to a statistically significant degree (Table 11). However, a slightly larger difference was observed in the TARS data and it was statistically significant, as would be expected with the much larger number of cases.

Table 11.
Licence status of drivers involved in single vehicle rollover crashes compared to all other crash types and TARS data

Licence Status	Rollover	Other	% Rollover	% Roll TARS
Learner	-	-	-	8.2
Provisional	8	45	15.1	5.0
Full	35	275	11.3	3.1
Unlicensed	-	-	-	8.6
Total	43	313[1]	12.1	4.1

Note: [1] Excludes 3 Learners and 8 unlicensed drivers

Blood alcohol levels were obtained for 36 of the 43 drivers. Twenty eight were sober (78% of the known BAC cases), probably reflecting the bias towards daytime crashes in the sample (but see the following case description), two were below the legal blood alcohol limit of 0.05 g/100mL, another two were above the limit but below 0.10 and four were above 0.116, with the highest being 0.256.

The crash involving the driver who had a blood alcohol level of 0.256 occurred at 4.30 pm on a Saturday. The driver allowed the car to drift across onto the left unsealed shoulder for some considerable distance before overcorrecting to the right. The car, a 1978 HZ Holden Kingswood, then yawed across the road and rolled three quarters of a turn on striking a low bank. (Figures 1, 2 and 3) The uninjured 49 year old male driver was probably wearing a seat belt.

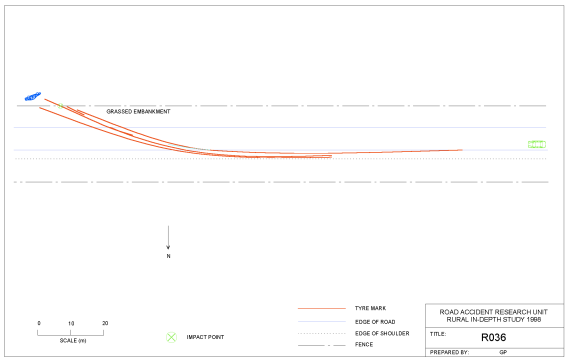

Figure 1. Site diagram showing tyre marks from initial off road excursion and overcorrection back to the right.

Figure 2. Yaw marks leading to the point of rollover.

Figure 3. Car rolled to the left 3/4 of a turn. Shown here after being rolled back onto its wheels.

Injury Severity

Injury severity is expressed here in terms of the level of treatment required or, for fatal cases, the outcome. The distribution of the maximum injury severity in each of these single vehicle rollover crashes is shown in Table 12. (AIS ratings of injuries are available but are not included in this paper.)

The percentage of fatal crashes is larger than would be expected in a representative sample of all crashes to which an ambulance is called for the reason noted earlier in this paper.

Table 12.
Maximum injury severity in single vehicle rollover crashes

Maximum Injury Severity	Number of Crashes	% of Crashes
Property damage only*	9	20.9
Treatment at hospital	18	27.9
Admission to hospital	14	32.6
Fatal	8	18.6
Total	43	100.0

* Note: Includes some cases involving injuries treated by private doctor

The comparison of the distribution of injury severities between single vehicle rollover crashes and other crashes shown in Table 13 provides a more meaningful assessment of the importance of single vehicle rollover crashes.

Bearing in mind that the criterion for entry into this sample of crashes of all types was that an ambulance be called, it is notable that over one third of all of the occupants involved did not require ambulance transport (36.3% of the 571 occupants). However less than 20 per cent of the occupants in single vehicle rollover crashes were in that category compared with 38 per cent of vehicle occupants in other types of crash (p=0.004, Chi square=8.12). This difference was accounted for mainly by a higher percentage of the rollover cases requiring treatment at hospital, but not admission, and a higher percentage who were fatally injured.

In other words, occupants in a single vehicle rollover were more likely than occupants of vehicles in other types of crash to be injured to a degree requiring transport to hospital by ambulance but no more likely to be admitted to hospital. The higher percentage of rollover cases resulting in a fatal injury was within the bounds of chance variation, and partially due to the method of inclusion of such cases.

Table 13.
Injury severity of occupants in single vehicle rollover crashes compared to occupants involved in all other crash types

Injury Severity	Rollover	Other	Column % Rollover	Column % Other
Property damage only*	12	195	19.7	38.2
Treatment at hospital	22	127	36.1	24.9
Admission to hospital	18	138	29.5	27.1
Fatal	9*	50	14.8	9.8
Total	61	510	100.0	100.0

* Note: Includes some cases involving injuries treated by private doctor and two occupants of one car were fatally injured

There was no meaningful difference in the maximum injury severity distributions between single vehicle rollover crashes with and without a collision with a fixed object but the number of cases was small in each group.

Seat Belt Use, Injury Severity and Ejection

Eighty per cent of the most severely injured occupants (the most severely injured in each of the single vehicle rollover crashes) were wearing a seat belt in the crash, based on the 40 out of 43 crashes for which this information was available. There appears to be a clear negative association between belt use and injury severity, as listed in Table 14. However, the very small number of "belt not worn" cases means that comparing "admission to hospital and fatal" with "treatment and no injury" cases with respect to belt use fails to yield a statistically different difference.

Table 14.
Maximum injury severity of occupants in single vehicle rollover crashes by seat belt use

Maximum Injury Severity	Belt Worn	Belt Not Worn	Belt Use Unknown	% Worn (Known)
Property damage only*	9	-	-	100.0
Treatment at hospital	11	1	-	91.7
Admission to hospital	19	4	1	69.2
Fatal	3	3	2	50.0
Total	32	8	3	80.0

* Note: Includes some cases involving injuries treated by private doctor

Similarly, four of the eight most severely injured occupants per vehicle who were not wearing a seat belt were ejected in the crash, compared with none of the 31 who were wearing a seat belt (Table 15).

Table 15.
Occupant ejection from the vehicle in single vehicle rollover crashes by seat belt use

Ejection	Belt Worn	Belt Not Worn	Belt Use Unknown	% Worn (Known)
Yes	-	4	1	0.0
No	31	4	-	88.6
Unknown	1	-	2	-
Total	32	8	3	80.0

Finally, the five ejected occupants included three of the seven fatalities for whom ejection status could be determined (Table 16).

Table 16.
Maximum injury severity of occupants in single vehicle rollover crashes by ejection from the vehicle

Maximum Injury Severity	Ejected	Not Ejected	Ejection Unknown	% Ejected (Known)
Property damage only*	-	9	-	0.0
Treatment at hospital	1	10	1	9.1
Admission to hospital	1	12	1	7.7
Fatal	3	4	1	42.9
Total	5	35	3	12.5

* Note: Includes some cases involving injuries treated by private doctor

Vehicle Movements Preceding Rollover

Most of the cars involved in single vehicle rollovers in this sample of crashes were travelling on a straight road (Table 17). Two crashes were not relevant to this consideration of vehicle movements preceding rollover. One simply involved a car running off the road and along an embankment for no apparent reason. The elderly driver ceased driving following that crash. Another crash was thought probably to have been intentional.

Table 17.
Cars in single vehicle rollover casualty crashes by road alignment and initial and final off road excursion

Road Alignment	Initial Off Road Excursion on:		Final Off Road Excursion on:	
	Left	Right	Left	Right
Straight	12 (4)[1]	2 (1)	5	4
Right curve	6 (2)	2 (2)	3	1
Left curve	3 (2)	1	1	1
Total[2]	21(8)	5 (3)	9	6

Notes:
[1] Number in parentheses indicates that the initial off road excursion was also the final one
[2] Two cases have been omitted (see text)

In almost every case the car that rolled over yawed out of control before rolling. The typical vehicle movement that precipitated the loss of control was running gradually across to the left until the left hand wheels ran onto the unsealed gravel shoulder. The driver then swerved back to the right and overcorrected to the left, as shown in one such crash. (Figures 4, 5 and 6) The 17 year old female driver had held a licence for less than a year. She was wearing a seat belt and sustained only a minor laceration (AIS 1) to her head. The car was a 1975 Datsun 120Y which had low pressures in the rear tyres. While this may have increased the difficulty in controlling the car, the vehicle motions following the initial off road excursion were very similar to those in other crashes where tyre pressures were at the recommended levels.

There were more single car rollovers on right hand rather than left hand curves, but together they still accounted for fewer crashes than the single car rollovers on straight sections of road (Table 17).

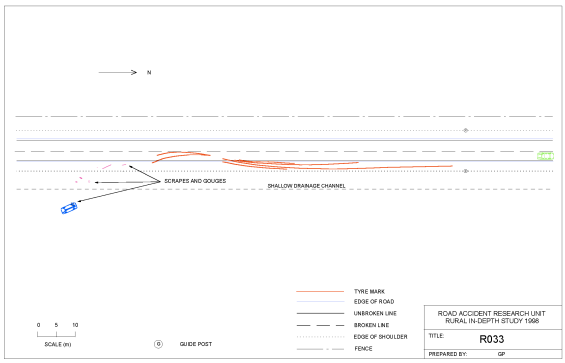

Figure 4. Site diagram showing tyre marks in initial off road excursion and followed by yaw marks to the right and back to the left.

Figure 5. Yaw marks at the point of rollover and final location of car (rolled back onto its wheels).

Figure 6. Roof damage following rollover.

SUVs in Single Vehicle Rollovers

There were nine single vehicle rollovers involving a SUV. In one of these the vehicle rolled on a winding downhill section of a divided highway but, despite multiple rolls, remained on the two lanes for traffic in its direction of travel. There were also two cases in which the initial loss of control was either precipitated by, or strongly influenced by, a trailer which was being towed by the SUV. One of these two crashes occurred on a straight road when the trailer began to oscillate behind the short wheelbase SUV and the other on a gradual left hand curve during an overtaking manoeuvre.

The number of cases involving SUVs is too small to provide a reliable basis for comparison with single vehicle rollovers involving cars but in five of the eight SUV cases the initial was also the final excursion (Table 18), as illustrated in Figures 7, 8 and 9. We were not able to determine why the vehicle went out of control in this crash, which occurred on a wet road. The unrestrained 51 year old driver, who remained inside the vehicle, sustained multiple fractures, including neck of femur and four ribs.

Table 18.
SUVs in single vehicle rollover casualty crashes by road alignment and initial and final off road excursion

Road Alignment	Initial Off Road Excursion on:		Final Off Road Excursion on:	
	Left	Right	Left	Right
Straight	2 (1)[1]	1 (1)	1	-
Right curve	1 (1)	-	-	-
Left curve[2]	3 (2)	1	1	1
Total	6 (4)	2 (1)	2	1

Notes: [1] Number in parentheses indicates that the initial was also the final off road excursion

[2] There was one case, not listed here, in which the vehicle rolled on a winding road without leaving the paved roadway

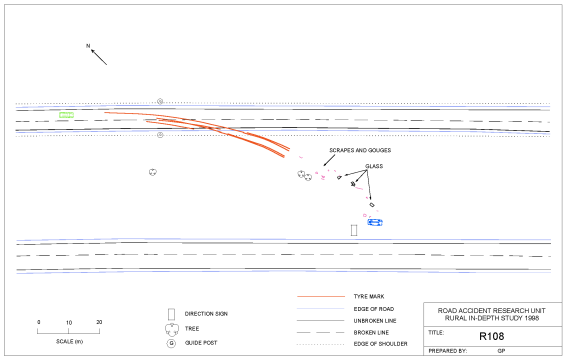

Figure 7. Site diagram showing yaw marks and final position of vehicle.

Figure 8. Yaw marks after leaving the sealed road surface.

Figure 9. 1988 Toyota Land Cruiser in final position (doors cut away by emergency service).

DISCUSSION

The United States New Car Assessment Program (NCAP) rollover resistance rating is primarily based on the Static Stability Factor (measured as a function of the track of the vehicle in relation to the height of its centre of gravity) for the following reason:

> "About 95% of rollovers are tripped - meaning the vehicle struck something low, such as a curb or shallow ditch, causing it to tip over. The Static Stability Factor (SSF) is specifically designed to measure this more common type of rollover and thus plays a significantly larger role in a vehicle's star rating" .... "than the results of the dynamic maneuvering test." (www.safercar.gov)

However, the "dynamic maneuvering test" measures whether a vehicle tips up in a "fishhook" or Road Edge Recovery manoeuvre which, as its name indicates, is very similar to the motion which results from a driver allowing a vehicle to run off onto the unsealed shoulder and swerve abruptly back onto the road, often then overcorrecting back to the left, as was commonly the case in the rollover crashes reviewed here, which occurred mainly on straight roads in the State-wide data.

Furthermore, electronic stability control would appear to have the potential to prevent the loss of control consequent on most of the road edge recovery manoeuvres seen in this study. Eighty per cent of the single car rollover crashes in this in-depth study sample were initiated by the car running at least partially onto the left unsealed shoulder.

Vehicle-based lane deviation detectors may reduce the frequency of such initial off road excursions, at least in those cases where edge lines are provided on the roadway. Similarly, countermeasures such as audio-tactile edge lining and sealing the shoulder could be expected to reduce the frequency of out of lane excursions and the loss of control in those excursions that do occur.

The risk of a casualty crash being a single vehicle rollover increases markedly at higher travelling speeds, as indicated by the speed limit of the road on which the crash occurred. This adds strong support to the case for reductions in the higher speed limits in rural areas in Australia and elsewhere.

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