Risk of Rollover in Ran-Off-Road Crashes

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Linked Illinois state accident and roadway data files were used to explore the nature and importance of vehicle rollovers in "ran-off-road" crashes. Rollovers are known to be a major roadside safety problem—the Illinois data examined in this study indicate that rollovers are involved in one-half of rural roadside crash driver fatalities. The risks of rollover in ran-off-road crashes are compared by land use, road type, and object struck. Side slopes and ditches were found to be the dominant vehicle tripping mechanism involved in rollovers. The findings support the need for closer attention to rollover risks on side slopes and ditches. In particular, the risk of rollover on specific slope and ditch configurations needs to be defined.

Rollover crashes are known to be severe, with most occurring on the roadside. Nationwide data from 1985 indicate that vehicle overturns account for 11 percent of the total harm resulting from police reported crashes, that is, in all traffic crash types (*1*). Further, these data indicate that three-fourths of the first harmful events in all rollover crashes occur outside the shoulder, and that overturns are the cause of one-third of "ran-off-road" crash fatalities. It is estimated from General Estimating System data that 115,000 single-vehicle passenger car off-road rollover crashes occurred in 1989, according for 83 percent of all single-vehicle passenger car rollovers (*2*).

Griffin (*3*) found that the probability of rollover in single-vehicle passenger car crashes (1980 Texas data) was highly dependent on vehicle curb weight and influenced by road type. For example, the 1980 Texas data indicated the risk of rollover in single-vehicle crashes of a 1,450-kg (3,200-lb) car to vary from 20 percent for county roads to 4 percent for city streets. The data indicated rollover risk to vary for Interstate highways from 3 percent for 2,350-kg (5,200-lb) cars to 30 percent for 730-kg (1,600-lb) cars.

Examination of similar data from 1981 Texas files showed risk of driver fatality to be 1.9 times higher in rollovers than nonrollovers (*4*). This study also found the risk of driver fatality or incapacitating injury (K + A injuries) in overturned vehicles to be independent of curb weight. K = killed, A = incapacitating injury, B = nonincapacitating evident injury, C = possible injury, and 0 = no injury; from ANSI D20.1, "Data Element Dictionary for Traffic Record Systems.")

Klein (*5*) examined rollover rates of passenger cars and light trucks using data from five state accident files. The percentage of single-vehicle crashes that resulted in rollover varied by body type from 40 percent for sport utility vehicles to 15 percent for passenger cars.

Hinch et al. (*6*) found that land use produced the largest difference in rollover risk in single-vehicle accidents involving cars, light trucks, and vans: 25 percent in rural accidents compared with 6 percent in urban cases. Malliaris and DeBlois (*7*) found higher police estimated speeds in rollover car crashes compared with all other crashes from both the GES and Fatal Accident Reporting System.

Overturns are the outcome of some tripping mechanism in the crash sequence. It is necessary to identify these mechanisms in any effort aimed at reducing rollovers. This in turn requires information on the sequence of crash events and object struck. A bilevel investigation of police-reported accidents by Harwin and Emery (*8*) is the only study known to the author that contains this needed information.

Harwin and Emery reported the vehicle tripping mechanisms found in a data collection effort involving all Maryland police-reported, single-vehicle rollovers involving cars, light trucks, and vans from August 1987 through December 1988. The data collected were verified by trained accident reconstructionists. Taken together, side slopes and ditches were found to be the predominant cause of rollover in these crashes. Side slopes (including "flat") and ditches were found to be the vehicle tripping mechanism in 50 percent of urban and 70 percent of rural rollovers.

In terms of fixed objects, "curb/wall" was the leading cause of rollover in urban areas, accounting for about 17 percent of urban rollovers compared with 4 percent of rural rollovers in this Maryland study (*8*). "Guardrail/barrier" was the leading fixed object cause of rollover for rural areas, accounting for about 7 percent of rural and 10 percent of urban rollovers. These combined definitions of object types clearly limit the utility of these findings. For example, the Maryland data did not contain a code for median barriers, thus, shaped concrete median barrier cases could be coded as either curb/wall or guardrail/barrier impacts.

Extensions of the Harwin and Emery study (*8*) are needed to more clearly define the ran-off-road rollover problem. In particular, the Maryland data base used did not contain information on nonrollovers, thus the likelihood of a rollover in a crash with any specific object of interest is not known. For example, although curb/walls were found to be the leading urban fixed object tripping mechanism, the risk of overturn in curb/wall impacts could actually be relatively low if there were large numbers of nonrollover curb/wall involvements. Also, the Maryland data base lacked information on roadway type, had a relatively limited description of objects struck, and was limited to cars and light trucks.

Further, in safety problem identification studies, it is useful to examine more than one state due to differences between states in roadway and traffic conditions. Findings of similar results from more than one state, especially states with somewhat different topographies and roadside characteristics, make it more probable that the results will be useful nationwide.

The purpose of this study was to expand on the work of Harwin and Emery in examining the risk of overturn in police-reported roadside crashes in terms of potential tripping mechanisms and other highway variables and to examine the risk of death or serious injury in these crashes.

DATA

Illinois files from the Highway Safety Information System were selected for use in this study. HSIS contains linked accident, road-

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way, and traffic data from eight states. Linking the Illinois accident and roadway data permitted examination of road type, land use, number of lanes, and speed limit. Illinois files were selected for this study because they contain information on both object struck and relation to the roadway for the first three "involvements" in the crash sequence. Furthermore, the Illinois accident data contains a more detailed list of objects struck than most state accident files.

The data used were on all vehicle crashes in which either the first, second, or third involvement in the crash sequence occurred outside the shoulder. Data were for all vehicle types except motorcycles and covered the years 1985 to 1989. The resulting file contained 115,858 cases: 16,453 rollovers and 99,405 nonrollovers.

It was originally thought that the Illinois file would produce information on the first, second, and third harmful events in these crashes from the data in the first, second, and third involvement variables. It was found, however, that the involvement variables contained a code for "ran off road" and that the first involvement was given this code in essentially all of the cases of this subject file. In practice, this means that the second involvement variable in the data of this study was really the first harmful event (FHE) in the crash sequence, and the third involvement variable was the second harmful event. The analyses that follow interpret the variables in this way.

RESULTS

Risk of Rollover in Roadside Crashes

Rollover and nonrollover outcomes by land use and road type are shown in Table 1. Rural ran-off-road vehicle crashes were 3.5 times as likely to result in rollover as urban crashes (26.3 percent versus 7.3 percent). Rural Interstates and rural two-lane roads had comparable rollover rates (28.9 percent and 28 percent, respectively). Urban Interstates had higher rollover rates than did other urban roads (9.1 percent versus 6.5 percent).

The very large number of case vehicles in this study (115,858) meant that differences reported were statistically significant. For example, a chi-square value of 154 was found for the comparison of percent of overturned vehicles between urban Interstates (9.1 percent) and other urban roads (6.5 percent) as previously noted. This was much higher than the critical chi-square value of 6.6 required to demonstrate a 99% chance ($P < .01$) that this difference is statistically significant.

TABLE 1 Involved Vehicles by Road Type

ROAD TYPE	ROLLOVER	NONROLLOVER	PERCENT ROLLOVER
	RURAL		
INTERSTATE	3,156	7,746	28.9%
2–LANE	6,623	17,041	28.0%
OTHER	1,262	6,159	17.0%
RURAL TOTALS	11,041	30,946	26.3%
	URBAN		
INTERSTATE/FREEWAY	2,108	21,090	9.1%
OTHER	3,302	47,327	6.5%
URBAN TOTALS	5,410	68,417	7.3%

As a second example, a chi-square value of 3.35 was found for the comparison of the seemingly equal rollover rates between rural Interstates (28.9 percent) and rural two-lane roads (28 percent). This result indicates that there is a 90 percent chance ($P < .10$) that the Interstate value is really higher. From a practical point of view, it is difficult to imagine anyone taking an action on the basis of such small differences between rollover percentages. This is simply another illustration of the statistical significance of meaningful differences found from the data.

Table 1 shows that two-thirds of the Illinois ran-off-road rollovers occurred on rural roads. Because the risk of rollover in a rural roadside crash was similar to that for two-lane roads and Interstates (28 percent versus 28.9 percent), the difference in the total counts of rollover vehicles between these road types was essentially caused by differences in the number of reported roadside crashes.

FHEs in rollover crashes by land use are listed in Table 2. In general these FHEs represent the probable cause of rollover. Likely exceptions would be objects such as delineator posts in which contact forces during a collision are relatively minor. In such collisions, some event after object contact such as a ditch or steep slope could well be the true vehicle tripping mechanism.

The dominant cause of overturns was "tire-soil forces" on side slopes and ditches, which caused 80.6 percent of rural and 72 percent of urban rollovers. By comparison, ditches and embankments accounted for 2.2 percent of rural and 1.0 percent of urban rollovers.

Tire-soil forces on side slopes and ditches are not a listed sequence of event variable in the Illinois file. Rather, they are deduced as being the most probable vehicle tripping mechanism for the very large number of cases in which the sequence of events was "ran-off-road" then "overturn." The event location variable in the file indicated that in 98 percent of these cases the rollover occurred on the roadside; thus, the tires were interacting with some roadside surface, generally soil, at the point of vehicle tripping. In the other 2 percent of these cases, the vehicle returned to the roadway and overturned, thus tire-pavement forces generated the tripping forces.

As noted previously, "ditch/embankment" is another sequence of event variable the police officer could have selected as preceding rollover. The surprisingly small number of ditch/embankment rollovers compared with "tire-soil force" rollovers suggests that relatively flat slopes and gently rounded ditches may have been involved in most of these tire-soil cases.

Conceptually at least, hard cornering in loss of control maneuvers could result in tires being rolled off the rim and contribute to rollover propensity on side slopes and ditches. However, Emery was able to locate and examine about 1,500 rollover vehicles, about one-half of the number of vehicles in the Maryland study (8), and not one such case was observed (unpublished data). Thus, this mechanism cannot explain these results.

Rollover caused by either an impact with a fixed object such as a small drainage structure or rock outcropping; or a pavement edge dropoff are probably included in the tire-soil force rollovers in Table 2. Data from a special study by Terhune (*9*) of 1,000 car and light truck single-vehicle crashes in the National Accident Sampling System were examined to obtain an estimate of the importance of these tripping mechanisms.

Terhune (*9*) identified rollover type by examining case slides, scene diagrams, and narratives. Of the 159 slope or ditch rollover cases in the file, 21 involved impact with ditch backslopes, which could have included vehicle body contact as well as tire-ditch interaction forces, and 7 were complex cases involving more than one tripping mechanism. Tipping on extremely steep slopes (vehicle

TABLE 2 Rollovers by First Harmful Event

FIRST HARMFUL EVENT	RURAL NUMBER	RURAL PERCENT	URBAN NUMBER	URBAN PERCENT
	OTHER THAN FIXED OBJECT			
"TIRE-SOIL FORCES" (1)	8,886	80.6%	3,885	72.0%
SNOW BANK	43	0.4%	26	0.5%
VEHICLE	40	0.4%	34	0.6%
OTHER NONCOLLISION	2	0.0%	1	0.0%
OTHER - SUBTOTAL	8,971	81.3%	3,946	73.1%
	FIXED OBJECT			
OTHER OBJECT	456	4.1%	401	7.4%
GUARDRAIL	409	3.7%	306	5.7%
DITCH/EMBANK	248	2.2%	53	1.0%
HIGHWAY SIGN	200	1.8%	110	2.0%
FENCE OTHER	165	1.5%	56	1.0%
DELINEATOR POST	123	1.1%	33	0.6%
TREE	123	1.1%	87	1.6%
UTILITY POLE	104	0.9%	80	1.5%
BRIDGE RAIL/END	85	0.8%	38	0.7%
MAILBOX	52	0.5%	22	0.4%
CULVERT HEADWALL	24	0.2%	4	0.1%
CONC. MEDIAN BARRIER	19	0.2%	80	1.5%
LIGHT STANDARD	15	0.1%	82	1.5%
BARRICADE	10	0.1%	15	0.3%
TRAFFIC SIGNAL	6	0.1%	22	0.4%
UNDERPASS STRUCT	3	0.0%	9	0.2%
BRIDGE ABUTMENT	3	0.0%	2	0.0%
BUILDING	3	0.0%	5	0.1%
IMPACT ATTENUATOR	3	0.0%	0	0.0%
CURB/ISLAND CUR	3	0.0%	28	0.5%
ADVERTISING SIGN	2	0.0%	6	0.1%
MEDIAN FENCE	2	0.0%	3	0.1%
RR SIGNAL	1	0.0%	1	0.0%
WATER HYDRANT	1	0.0%	10	0.2%
FIXED OBJECT - SUBTOTAL	2,060	18.7%	1,453	26.9%
TOTALS	11,031	100.0%	5,399	100.0%

(1) SEE TEXT

center of gravity outboard of wheels) accounted for another 15 cases. In addition to these 159 cases, another 3 cases involved pavement edge dropoff-induced rollovers. Tire-soil forces were the tripping mechanism for the remaining 72 percent of these slope/ditch rollovers. Thus, the Terhune data support the view that tire-soil forces are the tripping mechanism for most of the Illinois "ran-off-road" then "overturn" cases.

Guardrail impacts accounted for the largest number of fixed object impact rollovers: 3.7 percent of all rural and 5.7 percent of all urban rollovers. No other specific fixed object accounted for as much as 3 percent of either the rural or urban rollover totals.

For rural fixed object impacts, the average rollover rate was 8.1 percent. Figure 1 shows the rural and urban rollover rates for each object that had a rural rollover rate greater than 8.1 percent. Rural overturn rates were higher than urban for each object, and culvert headwalls posed the greatest overturn risk.

As discussed previously, overturns subsequent to a delineator, as well as many highway sign and mail box impacts, may not be due to contact forces with these objects because they tend to be relatively minor in nature. Guardrail end impacts may be the cause of the higher than average fixed object rollover rate found for guardrails.

For urban fixed object impacts, the average rollover rate was 3.0 percent. The leading urban fixed object rollover rates not shown in Figure 1 were curb/channelizing island, 8.4 percent; median fence, 7.3 percent; and concrete median barrier, 5.1 percent.

Figure 2 shows the combined effects of vehicle type and land use on rollover rates. Each bar shown in this figure is based on at least 1,000 observations. Vans, straight trucks, and pickup trucks had the highest rollover rates, and large cars had the lowest rollover rate. Rollover was more probable on rural than urban roads for each vehicle type, ranging from 2.4 times for pickup trucks to 3.9 for large cars.

Vehicles in single-vehicle ran-off-road crashes were much more likely to overturn than vehicles that left the road in multivehicle

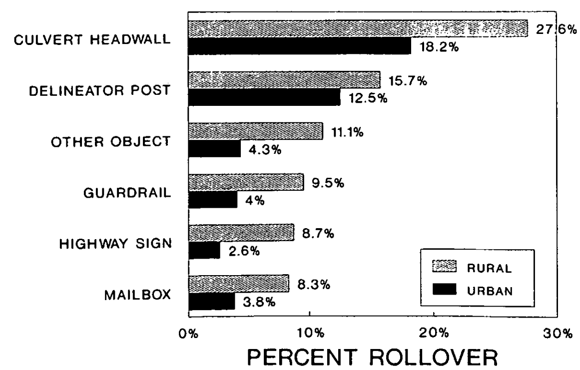

FIGURE 1 Percent rollover by object struck.

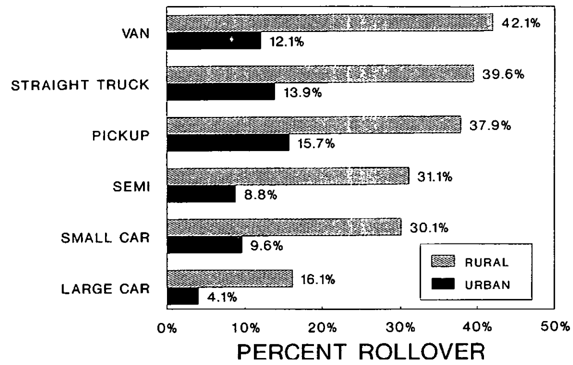

FIGURE 2 Percent rollover by vehicle type.

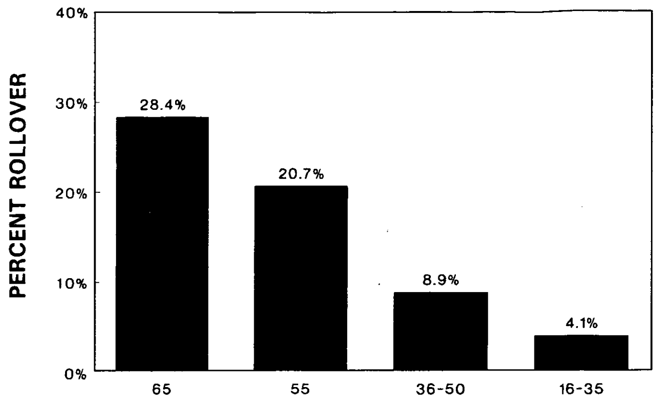

FIGURE 4 Percent rollover by speed limit.

crashes as shown in Figure 3. Further, if three or more vehicles were involved, the rollover risk to a vehicle leaving the road was less than if two vehicles were involved.

The probable explanation for rollover risk decreasing as the number of involved vehicles increases is that rollover is dependent on speed at impact with potential tripping mechanisms. Collision with another vehicle reduces speed and thus overturn risk in subsequent collision events.

Figures 4 and 5 reinforce the notion that roadside rollovers increase with speed. Figure 4 shows a consistent increase in percent of rollovers with increasing speed limit. Figure 5 shows a higher percent of rollovers on dry pavements, which, on average, have higher operating speeds than wet or snow-covered surfaces. Further, higher rural rollover risk than urban rollover risk was found for every comparison made in this study. Higher operating speeds were associated with higher posted speed limits and less speed constraint from traffic volumes on most rural roads.

Figure 6 compares the effect of the location of the FHE on the percentage of vehicles that rolled over for rural Interstates and two-lane roads. Median crashes on Interstates were more likely to result in rollovers than ran-off-road right departures (35.5 percent versus 25.8 percent). Differences in obstacle-free recovery areas and slopes and ditches may account for these median-roadside rollover risk differences.

No difference was seen between ran-off-road left and right departures for rural two-lane roads. Recovery areas, obstacles, and slopes and ditches encountered for left-side departures were similar to right-side departures on two-lane roads. Differences in average speed and angle at departure may have occurred, however. These results indicate that the effects of differences in left or right departure conditions on rollover risk on rural two-lane roads may be minor.

The cases in which the first event was on the road represent 9 percent of the Interstate and 11 percent of the two-lane road cases. A relatively large number of these cases were probably multivehicle, thus explaining the lower rollover risk found.

Risk of Death or Injury in Roadside Crashes

The main reason for concern about rollover risk in roadside crashes is the large known increase in severity of these crashes. The percent of the total number of driver injuries associated with vehicles that overturned at each level of the KABCO injury scale is shown in Figure 7 for rural roads and Figure 8 for urban roads. Illinois KABCO injury definitions are consistent with ANSI D20.1.

Clearly, in Illinois rollover was the predominant cause of death or serious injury on rural roads. On rural roads, rollovers accounted for nearly one-half of the ran-off-road fatalities (47.8 percent) and 41 percent of the A injuries. For nonrollovers, the cause of death or serious injury was impact with some object in essentially all cases. Thus, for nonrollovers, the cause of death or injury was split among impacts with the objects listed in Table 2.

On urban roads, rollover caused a very significant but smaller percent of total serious driver injuries: 22.8 percent of ran-off-road fatalities and 15 percent of A injuries.

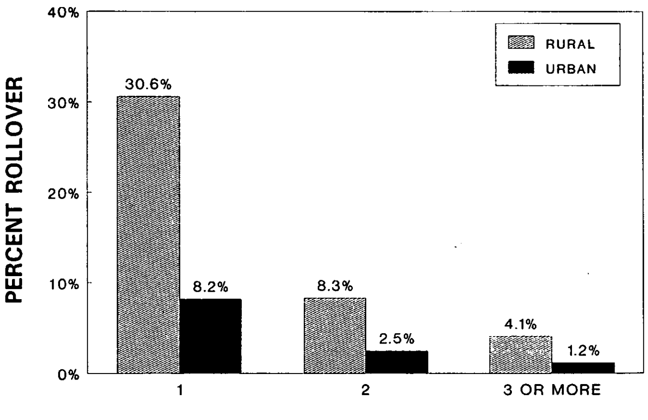

FIGURE 3 Percent rollover by number of involved vehicles.

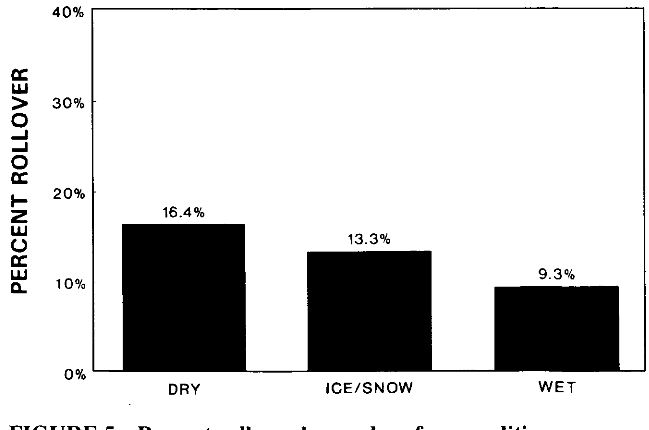

FIGURE 5 Percent rollover by road surface condition.

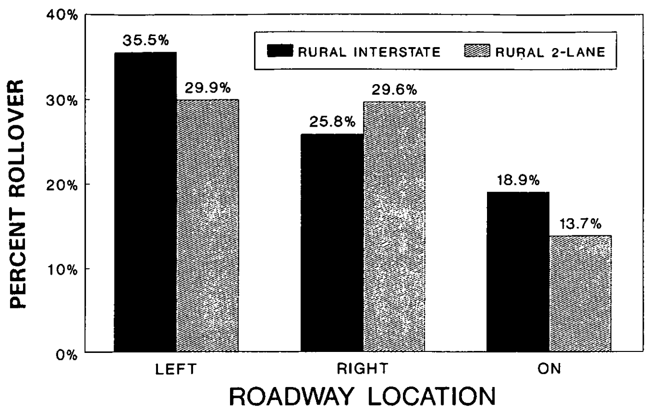

FIGURE 6 Percent rollover by first involvement location, rural interstate versus rural two-lane road.

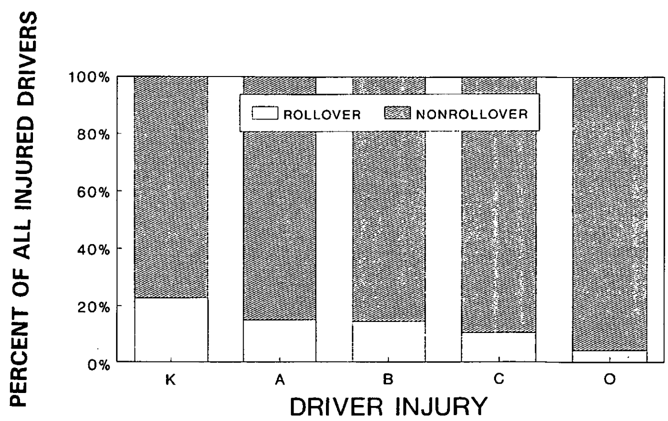

FIGURE 8 Percent of urban ran-off-road driver injuries in rollovers by injury severity.

The percent of the total number of driver fatalities and A injuries due to rollovers on rural Interstates and two-lane roads are shown in Figure 9. Rollovers accounted for a similar fraction of the total fatalities occurring on both rural interstates and two-lane roads. The percent of the total number of A injuries due to rollover was higher on rural interstate (46.3 percent) than on two-lane roads (41.3 percent).

Roadside obstacle-free zones, terrain, and predominant obstacle type varies between states. These differences affect the percentage of total ran-off-road driver fatalities and injuries associated with rollover crashes. For example, a state with large areas of rural woodlands might well show a larger percent of rural driver fatalities and injuries due to tree impacts than in a prairie state like Illinois. In a state with rural woodland, the percentage of total rural fatalities and injuries would be expected to be lower than the losses found in Illinois, as shown in Figures 8 and 9.

Table 3 provides insight on the risk of driver death or serious injury (K + A injuries) by roadside crash type. Rollover is the most severe crash type shown; almost one-fourth of drivers in these crashes suffered fatal or A injuries (24.7 percent). Of the nonrollovers, the most severe crash type found was drivers in vehicle-vehicle collisions in which some second crash impact occurred (22.5 percent K + A).

Driver fatalities or A injuries occurred in 10.6 percent of all nonrollover fixed-object collisions. The risk of driver fatality or A injury in overturn crashes (22.5 percent) was 2.3 times greater than this fixed-object crash risk.

The risk of driver fatality or A injury increased if there was a second reported crash impact for each of the nonrollover crash types shown. Crashes with more than one impact event were likely to have been at a higher speed, on average, than single event crashes; this could be the primary reason for the difference in risk.

CONCLUSIONS

The findings of this study on the general nature of the roadside rollover problem are consistent with the literature; crash severity, rural roads, and vehicle type are factors strongly associated with ran-off-road rollovers. This study also found, as did Harwin and Emery (*8*) from Maryland data, that ditches and slopes were the dominant ran-off-road tripping mechanism. Rollover risks on rural Interstates and two-lane roads were found to be similar.

The findings of this study offer insight on the nature of this problem. Specifically, this analysis of all ran-off-road vehicle crashes in Illinois, motorcycles excluded, resulted in the following principal findings.

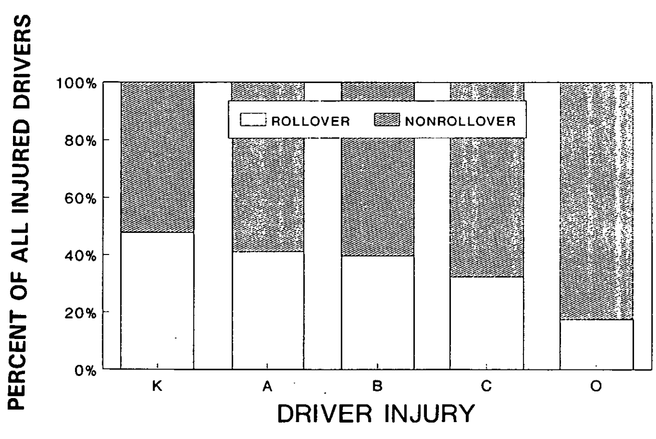

FIGURE 7 Percent of rural ran-off-road driver injuries in rollovers by injury severity.

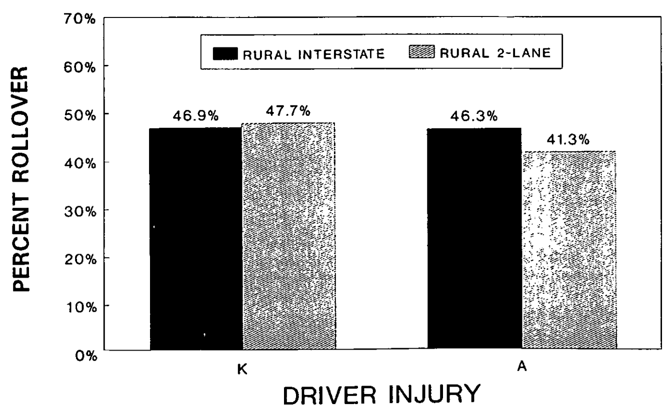

FIGURE 9 Percent of ran-off-road (K + A) severe driver injuries in rollovers, rural interstate versus rural two-lane roads.

TABLE 3 Percent of Driver (K + A) Injuries, Rollover Versus Nonrollover

FIRST HARMFUL EVENT	SECOND HARMFUL EVENT YES	SECOND HARMFUL EVENT NONE	TOTALS
ALL ROLLOVER VEHICLES			24.7%
ALL NONROLLOVER VEHICLES			
VEHICLE COLLISION	22.5%	12.7%	15.3%
OTHER/UNKNOWN	14.2%	4.5%	10.9%
FIXED OBJECT	15.1%	9.7%	10.6%
ALL NONROLLOVERS	14.9%	9.3%	10.9%

Nature of the Ran-Off-Road Rollover Problem

1. The risk of driver fatality or A injury was greater in rollover crashes than in any nonrollover crash type examined.
2. Roadside rollover risks were much higher in rural areas: 26 percent of involved vehicles on rural roads overturned, compared with 7 percent on urban roads.
3. Rollovers were the dominant rural roadside safety problem. In Illinois, 48 percent of all rural ran-off-road driver fatalities occurred in rollovers. The remaining fatalities were split among a long list of struck objects.
4. Rollover rate was highly dependent on vehicle type. In rural crashes the percent of overturn vehicles varied from 42 percent for vans to 16 percent for large cars.
5. Rollover risk appeared to be strongly dependent on crash speed.

Cause of Vehicle Tripping

6. Slopes and ditches were the principal cause of ran-off-road rollovers, associated with 83 percent of rural and 73 percent of urban rollovers (Table 2). Tire-soil forces were the probable tripping mechanism in most slope/ditch rollovers. Mechanisms contributing to tire-soil forces included: rate of slope, slope changes, soil cover, and tire plowing in soft soil. Police-reported accident files, such as the Illinois data used in this study, do not provide the level of detail required to sort out the relative importance and interaction of these variables as tripping mechanisms.
7. The average overturn rate in rural fixed-object impacts was 8.1 percent. Two objects that exceeded this rate are worthy of note, culvert headwalls (27.6 percent) and guardrails (9.5 percent). The rate for culverts points out the severe nature of impacts with these structures. Guardrail end impacts may be the cause of the higher-than-average guardrail overturn rate.
8. In urban areas, the average overturn rate in fixed-object impacts was 3.0 percent. Culvert headwalls had the highest rate at 18.2 percent, curb/channelizing islands had a rate of 8.4 percent, and concrete median barriers a rate of 5.1 percent.

Road Type: Comparison of Rural Interstates and Two-Lane Roads

9. The risk of overturn, given a ran-off-road crash, was similar for rural Interstates and rural two-lane roads (28.9 percent versus 28.0 percent).
10. Left roadway departures resulted in the same rollover risk as right roadway departures on two-lane roads. For interstates, left-side (median) events had higher rollover rates than right-side events (35.5 percent versus 25.8 percent).
11. Overturns accounted for about the same fraction of total ran-off-road driver fatalities on both rural roadway types (46.9 percent on Interstates versus 47.7 percent on two-lane roads).
12. Overturns accounted for more of the total driver A injuries on Interstate (46.3 percent) than two-lane roads (41.3 percent).

RECOMMENDATIONS

As noted previously the dominance of slopes and ditches found as the probable vehicle tripping mechanism is in general agreement with the findings of the Maryland study (*8*). Further problem identification studies of rollovers on slopes and ditches are recommended, specifically:

1. National accident data bases should be examined to study further the nature and importance of slopes and ditches as a tripping mechanism.
2. The importance of specific slope and ditch configurations as potential tripping mechanisms also should be studied further. Additional field data will be required to conduct accident analyses on this issue because needed data for these analyses are not contained in existing data bases. Computer simulation studies will require refined information on vehicle conditions as they leave the roadway. The literature suggests that lateral skidding occurs at tripping in many rollovers (*8,9*).
3. Issues such as the effects of soft soil and terrain irregularities on overturn risk also need to be examined.

These studies are needed to develop specific cost-effective recommendations to reduce rollover risk on slopes and ditches. Recommendations that might result from these investigations include the following:

- Identification of areas of roadways, such as the outside of horizontal curves, that might justify special attention.
- Revised severity indices for slope and ditch configurations resulting in changes in barrier warrants.
- Recommendations to maintenance personnel about maintaining relatively flat roadsides.
- Defining the importance of countermeasures that would reduce the likelihood of loss of control such as antilock brakes or higher pavement surface friction.

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