An Analysis of the Risk of Occupant Injury in Second Collisions

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One of the most potentially injurious phases of a redirectional collision with a longitudinal barrier often occurs during the vehicle's post-impact trajectory. Though a longitudinal barrier system may be well designed and crash test experience shown to be good, data presented in this paper suggest that occupants often suffer severe injury in a second collision after their vehicle has been successfully redirected from a longitudinal barrier. In this paper current NCHRP Report 230 guidelines for the postimpact trajectory of test vehicles are briefly discussed, data from two states—North Carolina and New York—are examined to determine increased risk associated with second collisions, and the risk of suffering fatal or severe injury in various types of redirectional collisions is quantified. The postimpact trajectory will be shown to be an important feature of redirectional collisions, and the increased risk to occupants associated with secondary collisions will be demonstrated.

The importance of achieving a controlled postimpact trajectory has been presumed at least since the publication of NCHRP Report 230 *(1)* in 1981. The specifications for evaluating the postimpact trajectory in this report are

- Minimum intrusion into the traveled way, and
- When intrusion does occur, a change in velocity of less than 15 mph and an exit angle less than 60 percent of the impact angle.

These two specifications represent a commonsense approach to defining a controlled postimpact trajectory. An ideal postimpact trajectory, according to NCHRP Report 230, is one in which the vehicle is redirected nearly parallel with the guardrail system, coming to a stop without striking any other roadside objects. The conventional wisdom at the time Report 230 was written was that a vehicle that rebounded across the roadway *(a)* would be a serious risk to other traffic and *(b)* could possibly strike another fixed object and result in an even more serious collision than the initial longitudinal barrier impact. As later sections of this paper will show, these assumptions appear to be well founded.

Several earlier papers by the authors and others began to refocus attention on postcollision performance *(2)*. Ray and Michie *(3, 4)* determined that the majority of severe and fatal accidents that occur when the vehicle is smoothly redirected appear to be a result of second collisions rather than poor barrier performance per se. This paper presents further data that confirm the hypothesis that secondary collisions represent one of the most serious risks to vehicle occupants in redirectional collisions.

This paper is not an attempt to assess the causes of redirection problems; the data are not detailed enough to extract precise information about barrier types, the correctness of barrier installations, and the proper warranting of particular systems. For example, Figure 1 shows an approach guardrail that, because of its flexibility, geometry, and incompatibility with the bridge rail, redirected the errant vehicle into the bridge rail on the opposite side of the roadway. This probably represents a problem with poor approach guardrail selection and design. Another, quite different scenario is shown in Figure 2. A vehicle struck a guardrail system, was redirected nearly parallel to the rail, and then collided with a tree located on the same side of the road just past the guardrail end. This probably

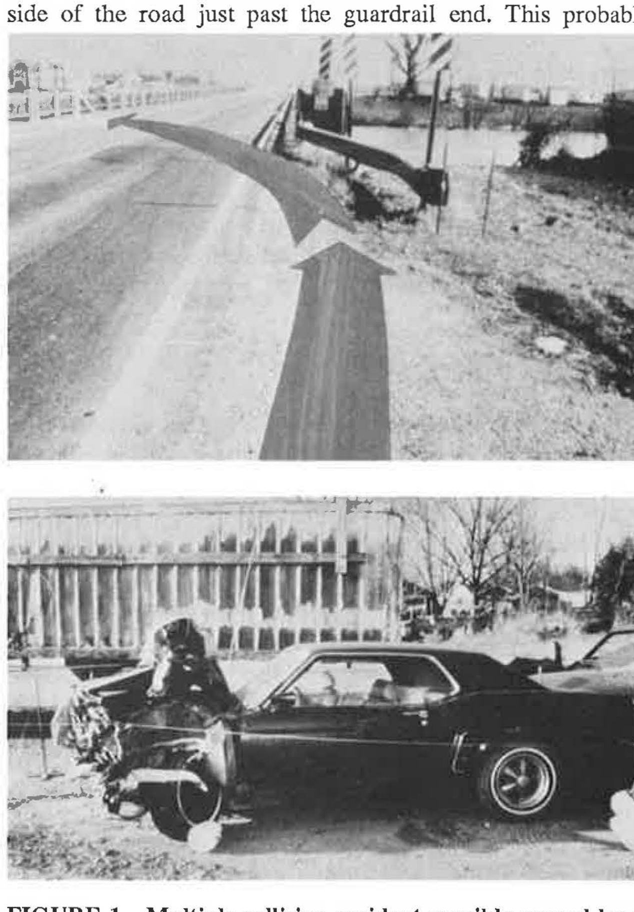

FIGURE 1 Multiple-collision accident possibly caused by a poor transition design.

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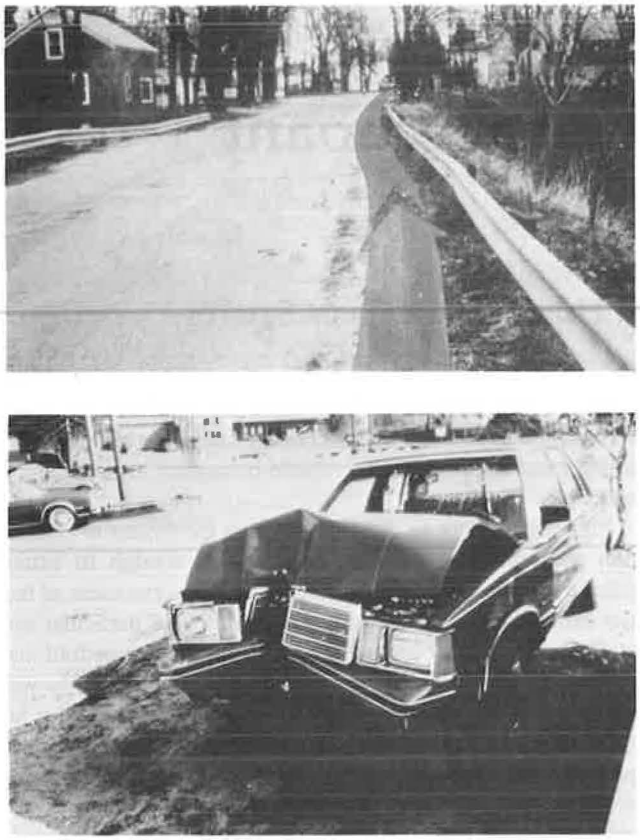

FIGURE 2 Multiple-collision accident possibly caused by poor warranting.

represents a warranting problem. Thus, second impacts may have a variety of causes, including improper selection, warranting, and design.

The objectives of this paper are to illustrate that second events, whatever their cause, present a major hazard to vehicle occupants, and to illustrate to those responsible for selecting, locating, and designing longitudinal barrier systems that they should seek ways to improve the postimpact trajectory of vehicles.

ACCIDENT DATA

Two accident data bases were used in this analysis of the second-impact problem. The first data base was developed by Hunter and Stutts *(5)* from police accident reports filed in North Carolina in 1980 and 1981. Hunter and Stutts obtained their data by utilizing coded information provided by the reporting police officer and his sketch of the vehicle trajectories. This data base was composed of 325 accidents that involved collisions with longitudinal barrier systems. The second source of accident data was a study performed by Bryden and Fortuniwicz *(6)* of 3,302 single-vehicle longitudinal barrier accidents in New York State. As in the data base developed by Hunter and Stutts, the primary source of information in the New York data was the police accident report for each case. These two independently obtained data bases were analyzed by using similar techniques so that comparisons between the data bases would be reasonably valid.

Both data bases are, of course, limited by the quality of the reporting police officer's observations. In addition, the officer's often vague description must be translated into crisp definitions such as "smooth," "stopped," or "sharp." There is, then, a degree of variability in skill and education between officers as well as a degree of uncertainty in categorizing the officer's observations. This variability is certainly retained in the data bases.

In addition to the variation in quality of police-reported data, the reader should also recognize that most researchers believe that reported accidents make up perhaps as little as 10 percent *(7)* of the real-world collisions. Reported accident data are generally considered to have a bias toward more severe accidents, those involving personal injury or undrivable vehicles. Thus, the following presentation will appear to be overly pessimistic; that is, it will overestimate the magnitude of the problem, because more severe accident cases will be overrepresented in the data base.

A screening procedure similar to that used by Ray and Michie *(4)* was used to filter out accident cases that were not of interest in this study. Cases that met the following criteria were retained for further analysis:

- A longitudinal barrier was the first object struck.
- Only passenger vehicles were involved.
- The guardrail impact was in the midsection of the longitudinal barrier system (end-on impacts with terminals and end treatments were discarded).
- The impact angle was oblique.

One further screening criterion was applied only to the North Carolina data: vehicles that exhibited nontracking characteristics were eliminated. This information was elucidated from the reporting officer's trajectory sketch. Examples of nontracking characteristics are

- A vehicle that slides laterally into a barrier and
- A vehicle that is spinning (yawing) before impact.

If the foregoing characteristics were present, the case was eliminated. Because there was no information in the New York data to determine whether a vehicle was tracking or not, no attempt was made to screen out nontracking impacts.

After the two data bases had been screened, 2,332 cases were identified in the New York data base and 103 cases in the North Carolina data base. The reasons and frequency for excluding cases are shown in Table 1. Because the police accident reports, coding forms, and definitions used to build these two data bases are not identical, the excluded cases do not show a meaningful pattern. For example, the New York data base was assembled from accident cases in which the first harmful event was a barrier collision. The North Carolina data used all accidents in which a barrier was involved; therefore, there are fewer improper-sequence cases (cases in which the barrier collision was not the first harmful event) in the New York data and relatively more in the North Carolina data. In addition, the North Carolina cases were ones that were thought to have a barrier performance "problem," where a performance problem is defined as a penetration, second impact event, vehicle overturning, or vehicle snagging. The New York data did not segregate cases on the basis of performance. Thus, the two data bases are not comparable in terms of equivalent exposure, but rather they can be compared in terms of occupant severity for various accident and collision types.

TABLE 1 CASES EXCLUDED FROM DATA BASES *(5, 6)*

	New York (N = 3,302)		North Carolina (N = 325)	
Criterion	No.	Percent	No.	Percent
Not tracking before impact	–	–	44	13.5
Improper sequence	12	0.4	19	8.9
Not passenger car	487	14.7	55	16.9
Impact not at barrier midspan	389	11.8	9	2.8
Other				
Icy roads				
Angle not oblique				
Nonstandard barriers	82	2.5	85	26.2
Total	970	29.4	222	68.3
Total eligible	2,332	70.6	103	43.8

FAULT-TREE ANALYSIS

Once the eligible cases were identified, a fault tree (Figure 3) was developed that described the possible barrier-performance scenarios. Each cell in the tree describes a particular barrier function, such as penetration or redirection. The penetration cell describes any event that resulted in the vehicle's going under, over, or through the barrier. Penetration events clearly represent poor performance in terms of the NCHRP Report 230 evaluation criteria. The alternative to the penetration event is the redirectional event, in which the vehicle remains on the correct side of the barrier. There are basically two types of redirected behavior: smooth and sharp. Smooth redirection, where the vehicle remains upright and stable and does not snag or pocket, is the most desirable type of barrier performance according to Report 230. Sharp redirection is generally associated with vehicle snagging or pocketing and is unacceptable by Report 230 standards. The next possible outcome in the smooth-redirection subtree is the possibility of experiencing a second event such as a collision with a fixed object or with following or opposing traffic, or a noncollision second event such as a rollover.

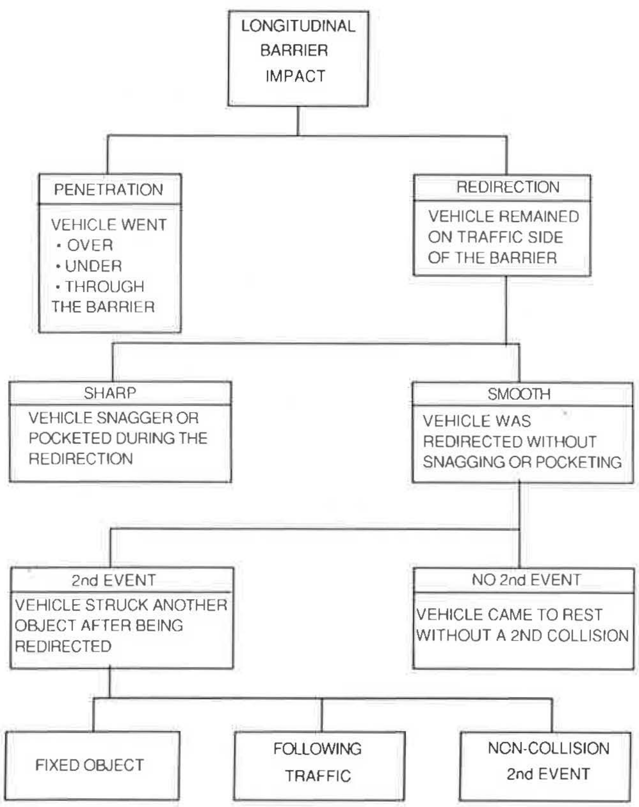

FIGURE 3 Fault-tree schematic of possible longitudinal-barrier collision scenarios.

Currently the Report 230 evaluation criteria require barrier performance to fall in the smooth-redirection cell of Figure 3. The eligible cases in each data base were searched to determine the frequency of each type of barrier function and the number of fatal and severe (A + K) injury outcomes associated with each type of barrier performance. Figures 4 and 5 show the fault trees for the New York and North Carolina data, respectively.

New York Data

Figure 4 shows that of the 2,332 eligible New York accidents, 1,882 were characterized by smooth redirection. The most serious injury was a fatality or severe injury (A + K) in 141 of the 1,882 cases. Thus, 7.5 percent of the accident cases characterized by a smoothly redirected vehicle resulted in an A + K injury. As should be expected, smooth-redirection events had a lower percentage of A + K injuries than the sharp-redirection, stopped-along-barrier or penetration events. Of these 1,882 smooth-redirection collisions, Figure 4 indicates that 337 experienced second-collision events and 1,545 experienced no second-collision events.

The stopped category is placed between the sharply and the smoothly redirected categories in the New York data because it was impossible to discriminate between which stopped events belonged to each category. "Stopped" may refer to a severe snag where the vehicle remains in contact with the barrier or it may represent a low-energy collision where the barrier dissipated all the kinetic energy before the vehicle separated from the barrier.

North Carolina Data

In North Carolina data, all two-vehicle accidents were sampled, whereas, because of the large number, only one-third of the single-vehicle cases were sampled. The data discussed below and shown in Figure 5, then, include a weight of 3 for the single-vehicle cases.

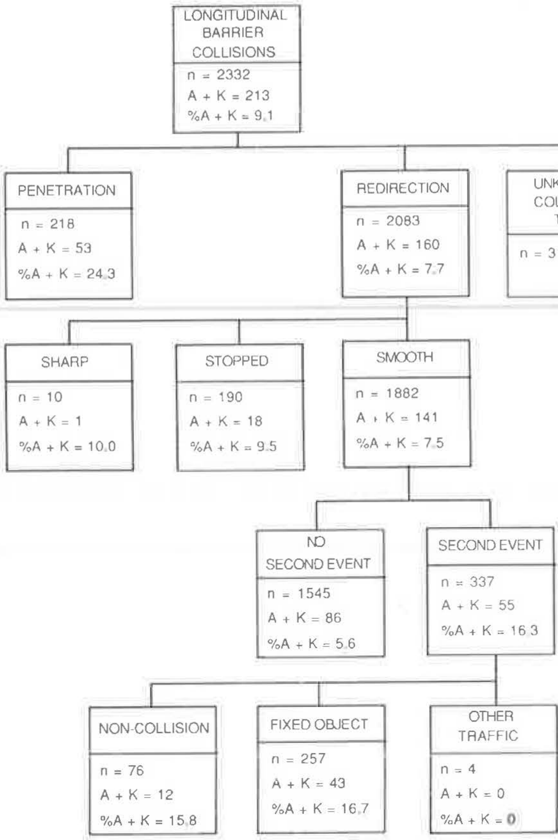

FIGURE 4 Fault tree for New York accident data.

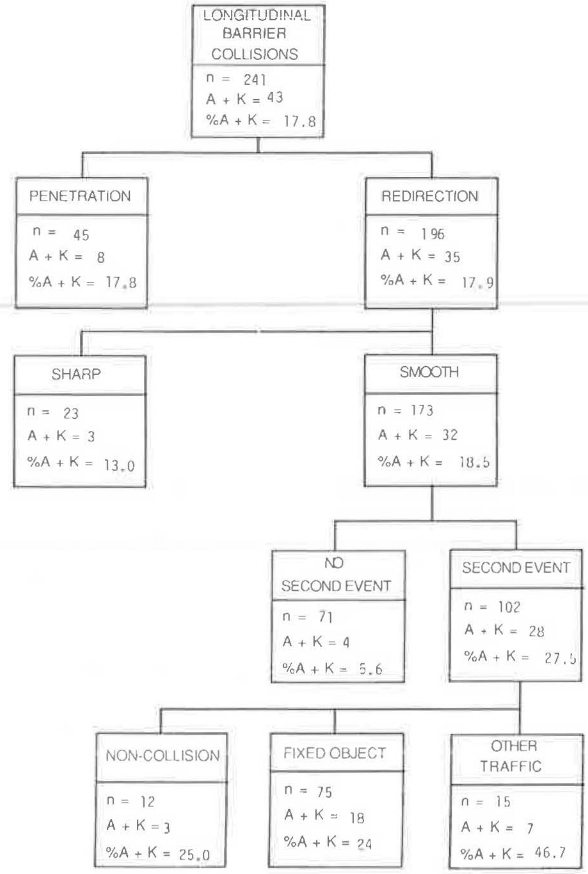

FIGURE 5 Fault tree for weighted North Carolina accident data.

After the eligible cases were isolated, there were 34 two-vehicle cases and 69 single-vehicle cases, yielding a weighted sample of 241 cases. Figure 5 shows the fault tree for the 241 North Carolina cases. The data indicate nearly equal severities for redirectional and penetration collisions. Again, the subtree under the smooth redirection cell proved to be very informative. A + K injuries resulted in only 5.6 percent of the accident cases in which no second event was experienced after a smooth redirection. In contrast, cases in which a second event did occur after a smooth redirection resulted in A + K injuries in 27.5 percent of the cases. As with the New York data, A + K injuries were much more likely in multiple-impact collisions. Striking other vehicles after redirection appeared to be the most serious type of second-collision accident in the North Carolina data, resulting in A + K injuries in 46.7 percent of the cases. Fixed-object and noncollision second events resulted in A + K injuries in approximately 25 percent of the cases. The North Carolina data imply, on the basis of police-reported data, that an A + K injury is likely in one out of four cases in which a second event occurs and that an occupant's chance of serious or fatal injury is nearly five times greater than in an accident in which the vehicle is smoothly redirected and there is no second event.

Severity of Second Events

An examination of Figures 4 and 5 provides interesting insight into the risk associated with second-event collisions. Because the North Carolina data used accident cases in which a problem with barrier performance was suspected, it is not surprising that the percentage of A + K injuries is much higher than in the New York data. The New York data are probably more realistic in terms of exposure to a variety of different barrier-function scenarios. The New York data suggest that penetration-type accidents are four times as likely to produce A + K injuries as redirectional collisions. This illustrates why penetrations are deemed unacceptable in Report 230.

The most interesting feature in both Figures 4 and 5 is the subtree under the smooth-redirection cell. For both data sets, accidents that were characterized by the occurrence of a second event were three times more likely to result in A + K injuries than an accident with no second event. If the New York data are taken as a lower bound and the North Carolina data are assumed to be an upper bound, the probability of being fatally or severely injured in a second collision after a successful vehicle redirection is between 13 and 33 percent. In comparison, the probability of being fatally or severely injured in a redirected vehicle when no second event occurs is between 4 and 9 percent. The occurrence of a second collision event clearly puts vehicle occupants at a much higher risk.

As discussed earlier, these data, because they are composed only of reported accidents, tend to overestimate the magnitude of the record impact problem. If it is assumed that unreported accidents never experience second collisions and that only 10 percent of all accidents are reported, these data indicate that between 1 and 3 percent of all accidents in which a vehicle is redirected from a longitudinal barrier result in severe or fatal occupant injuries.

Collisions with Following and Opposing Traffic

The North Carolina data indicate that the risk of sustaining A + K injuries when other traffic is present is very high. The New York data were compiled using single-vehicle accidents, whereas the North Carolina data contained both single- and two-vehicle cases. Using only single-vehicle cases may have biased the New York data against observations of following-traffic collisions because many single-vehicle accidents occur as a result of driver inattention and fatigue in rural areas on high-speed low-volume Interstates. Other-traffic collisions may not appear to be a problem in the New York data because when single-vehicle accidents are used, conditions are likely to be such that there are fewer vehicles to interact with. In contrast, many of the two-vehicle cases from the North Carolina data involved one vehicle's leaving the road in order to avoid a collision with another. This sort of behavior may be more likely on higher-volume roadways, which would, of course, increase the probability of collisions with following or opposing traffic.

Although rebound data were not available from New York, Hunter and Stutts *(5)* investigated the rebound characteristics of redirected vehicles in the North Carolina accident data. Rebound was used as a measure of the potential for becoming involved in collisions with other traffic. Agent *(8)* investigated the rebound characteristics of vehicles redirected from longitudinal barriers by using police-reported accident data from Kentucky. A summary of Agent's data along with the data obtained in North Carolina by Hunter and Stutts *(5)* is as follows:

	North Carolina		*Kentucky* (8)	
Vehicle Rebound	*No.*	*Percent*	*No.*	*Percent*
Not onto roadway	8	5	78	23
Onto roadway	59	36	136	39
Across roadway	97	59	131	38
	164		345	

If the values shown above are taken as an estimate of the range of values, Figure 6 can be assembled.

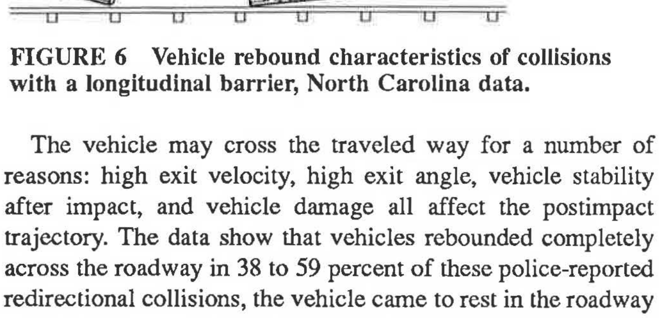

FIGURE 6 Vehicle rebound characteristics of collisions with a longitudinal barrier, North Carolina data.

The vehicle may cross the traveled way for a number of reasons: high exit velocity, high exit angle, vehicle stability after impact, and vehicle damage all affect the postimpact trajectory. The data show that vehicles rebounded completely across the roadway in 38 to 59 percent of these police-reported redirectional collisions, the vehicle came to rest in the roadway in 36 to 39 percent of the collisions, and the vehicle remained off the roadway in 5 to 23 percent of the redirectional collisions. Therefore, on the basis of reported accidents in Kentucky and North Carolina, there was potential for becoming involved in a subsequent collision with other traffic in more than 74 percent of the police-reported redirectional collisions.

Again, if it is assumed that in unreported accident cases the vehicle never rebounds onto the roadway, a very conservative assumption, and that the reported accident cases represent 10 percent of all cases, then the proportion of all accident cases in which a vehicle rebounds onto the roadway appears to be about 7 percent. This is clearly not the outcome preferred by NCHRP Report 230. Impact speed and angle are doubtless contributing factors to the rebound performance of redirected vehicles and are difficult to estimate in real-world accident data. There are a variety of possible scenarios by which the vehicle may reenter the roadway. The important point, however, is that many vehicles apparently intrude back into the traveled way after redirection.

DISCUSSION

The occurrence of occupant injury in longitudinal barrier collisions that can be characterized by smooth redirection of the vehicle appears to be largely a function of chance. Because almost 75 percent of the redirected vehicles in the data bases rebounded onto or across the roadway, a significant number of real-world vehicles (perhaps greater than 7 percent) appear to have the potential for becoming involved in a collision with other traffic or with fixed objects. Fortunately, there is often no following traffic to interact with and no objects to strike, but the potential for serious secondary events is present nonetheless.

The two data bases show that vehicle involvement in a second collision after being smoothly redirected from a longitudinal barrier greatly increases the chance of fatal and severe occupant injuries. Cases in which a second impact occurred appeared to be three times as likely to result in severe or fatal injury as those in which there was no second event.

Although NCHRP Report 230 specifies that test articles should minimize vehicle intrusion into the roadway, it appears that intrusion into the roadway is not an uncommon outcome of a redirectional collision. Using the most optimistic figures from the previous section, in only 23 percent of the reported North Carolina accidents did the vehicle not intrude onto the traveled way. For those collisions that rebounded into the traveled way, the rebound distance may or may not have satisfied the Report 230 criteria, but clearly the 38 to 59 percent of vehicles that rebounded completely across the roadway did not.

Some factors that influence the postimpact trajectory are very difficult both to predict and control on the basis of the evaluation of full-scale vehicle crash tests or computer simulations. Driver reactions to the barrier impact are erratic and the effect is impossible to predict; the effect of vehicle damage on the postimpact trajectory is highly dependent on vehicle type. Added to these unpredictable parameters are the effects of impact and exit conditions.

Although it is difficult to assess the magnitude of the vehicle-rebound problems by extrapolating these police-reported accident data to all reported and unreported accidents, it appears that redirection back into or across the traveled way is a typical scenario. It is generally believed that the majority of accidents, especially minor single-vehicle collisions with longitudinal barriers, are not reported. Thus, reported accident data, like the data used in this study, often are biased toward those accidents in which there was personal injury, vehicle damage that required towing, or substantial property damage. The data appear to suggest, though, that vehicle rebound is worthy of attention by designers and installers of longitudinal barrier systems.

CONCLUSIONS

There are a variety of reasons for which vehicles become involved in second collisions—improper construction of a barrier system, incorrect warranting, extreme impact conditions, and poor design details, to name several. Unfortunately, none of the data bases presented in this paper can yield precise information about the cause of a second impact, and it is likely that all the reasons listed earlier play some role in most real-world collisions. The purpose of this paper is simply to focus attention on the second-impact problem and to suggest that those responsible for barrier design, warranting, and installation be made aware that the postimpact trajectory of the vehicle can be as important as shielding a vehicle from a roadside hazard.

This research has illustrated a need for devising methods to minimize roadway intrusions from the postimpact trajectory. Such methods must include careful design, warranting, and construction of barrier systems. The data have shown that designing systems that smoothly redirect errant vehicles does not ensure that occupants of these vehicles will not be seriously injured. A vehicle may be smoothly redirected from a longitudinal barrier, successfully shielding the occupants from injury in the first collision, only to experience a postimpact trajectory that is potentially more hazardous than the original collision.

To some, it may appear to be a statement of the obvious to suggest that occupants of vehicles are subjected to more risk as the number of collision events increases. Although NCHRP Report 230 specifies some postimpact trajectory requirements, the authors believe that the postimpact trajectory specifications are seldom used to evaluate appurtenance performance. The central purpose of this paper is to demonstrate the importance of the postimpact trajectory and to encourage the highway safety community to refocus its attention on this important aspect of longitudinal barrier collisions.

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