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# IN-SERVICE PERFORMANCE EVALUATION OF POST-AND-BEAM GUARDRAILS IN CONNECTICUT, IOWA AND NORTH CAROLINA


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**ABSTRACT**
This paper presents results of an in-service performance evaluation of four guardrail systems: the G1 cable guardrail, G2 weak-post W-beam guardrail and the G4(1S) and G4(1W) strong-post W-beam guardrails. The data were collected in portions of Connecticut, Iowa and North Carolina during a 24-month data collection effort in 1997 to 1999. The collision performance was measured in terms of collision characteristics, occupant injury and barrier damage.

**KEYWORD**
Roadside safety, in-service performance evaluation, guardrails.

# INTRODUCTION

Guardrails are a fundamental component of the roadside safety system in place on roadways in the United States. Many types of guardrails have been developed and used over the past five decades but the number of different types of guardrails commonly used has decreased in recent decades as States have chosen the systems with the greatest degree of design flexibility. Guardrails can be categorized into three broad types: weak-post guardrails, strong-post guardrails and rigid barriers. Weak-post systems are intended to experience large lateral deflections that slowly bring the vehicle to rest. These large lateral deflections result in less abrupt redirection but they require lateral clear-zones as large as four or five meters. Strong-post barriers usually require less than a meter of lateral clear space but they tend to redirect vehicles more sharply. Rigid barriers are designed to experience no lateral deflection and they redirect vehicles very abruptly.

The purpose of this paper is to examine the in-service performance of the G1, G2, G4(1S), and G4(1W) guardrails in portions of three States: Connecticut, Iowa and North Carolina. All collisions involving these guardrail types were investigated in one-half of Hartford County in Connecticut, a four-county area of Iowa and a three-county area in North Carolina. The data collection began on 1 July 1997 and continued until 30 June 1999. Bullnose median barrier installations in Iowa, which incorporate the G4(1W) guardrail system, were excluded from this analysis.

The G1 cable guardrail, SGR01a in the AASHTO *Roadside Design Guide*, is used in all three states.*(1)* It consists of S75x8.5 steel posts with 5000-mm spacing and three 19-mm diameter steel cables.*(1)* The 3-cable guardrail has been used for at least 30 years. Today cable guardrails are used extensively in upper midwestern states like Nebraska, North Dakota, South Dakota and Minnesota.*(2)* Cable guardrails are also common in the northeastern states like New York, Connecticut, Vermont and Maine and mid-Atlantic States like Virginia and North Carolina.*(2)* Cable guardrails are the most commonly used weak-post barrier system in use today. The standard G1 3-cable guardrail has successfully passed the NCHRP Report 350 crash tests.*(1)*

The G2, or SGR02, is a weak-post W-beam guardrail used in Connecticut. It also uses S75x8.5 steel posts spaced at 3810 mm and a 2.67-mm thick steel “W” section.*(1)* While weak-post w-beam guardrails were once very common, they are now used almost exclusively in east-coast states like Connecticut, New York, Pennsylvania, Virginia and North Carolina.*(2)* The system has not passed the crash test requirements of NCHRP Report 350 although efforts are underway to modify the system such that it does pass the required tests.*(3)*

The G4(1W) in Iowa and the G4(1S) in North Carolina are two versions of a blocked-out strong-post W-beam guardrail using a 2.67-mm thick steel “W” section and posts spaced at 1905 mm.*(1)* The strong-post W-beam guardrails are by far the most common type of guardrails in use today.*(2)* While there are a number of varieties of this system using different combinations of posts and blockouts, every state uses some type of strong post w-beam guardrail.*(2)* The G4(1W), a modified SGR04b shown in Iowa DOT’s Standard Road Plan as RE-12A, uses 200x200mm wood posts with wood blocks, whereas the G4(1S), or SGR04a, uses W150x13 steel posts with steel blocks.*(1)(4)*

The data collection teams were notified about collisions from police and highway maintenance agencies in their respective data collection areas. Information from the police accident reports and maintenance cost-recovery reports were collected for each case where available. In addition to these official sources of information, the collision sites were visited and the damage to the guardrail was measured and documented with photographs. The following sections will address a review of previous studies; installation characteristics of the different guardrail systems; and their performance with respect to collision characteristics, occupant injury and barrier damage.

# LITERATURE REVIEW

A number of studies have been conducted on the performance of cable and W-beam barriers. The reports summarized in this section describe these studies and their findings.

**NEW YORK - 1977**

A 1977 report described an in-service evaluation performed on light-post and heavy-post guardrail systems in the State of New York.*(5)* The purpose of the study was to determine the performance of the newer light-post and older heavy-post barriers based on actual collision experience and to expose problems associated with the field use of the light-post barriers. The heavy-post barriers studied consisted mainly of strong-post W-beam guardrail, while the light-post barriers included cable, W-beam, and box-beam systems.

Data were collected over a period of two years for each of the barrier systems, although the study period for all systems was not concurrent. Reports and site visits by New York DOT maintenance personnel provided the bulk of the data, supplemented by forms filled out by police officers at the scene. Occupant injury was the primary means of determining the barrier's performance, as well as vehicle characteristics and behavior. Maintenance performance was determined from the number of posts reset and replaced, rail length re-erected or replaced, and the length of barrier damaged.

The data collected included 717 light-post collisions and 3496 heavy-post collisions. The number of police-reported collisions was not known since the primary data source was maintenance personnel rather than police agencies. Statistical differences between barrier types were analyzed using the Chi-squared contingency test. Tables 1 and 2 summarize some of the relevant results of the study.

Table 1 shows the occupant injury rates for some of the barriers studied. Fatality/serious injury rates were lower for light-post barriers than for heavy-post barriers on the roadside; rates for median barriers were nearly identical. The fatality/hospitalization rate for the cable light-post barrier was five percent; for cable heavy-post, nine percent; for

W-beam light-post, 13 percent; and for W-beam heavy-post, 19 percent. End-section impacts resulted in higher injury rates than mid-section impacts.

*Table 1. Severity of injury for different barrier types, New York, 1977.(5)*

| | Fatal | | Hospitalized | | Other | | Total | |
|---|---|---|---|---|---|---|---|---|
| | No. | % | No. | % | No. | % | No. | % |
| Cable light-post | 4 | 1 | 15 | 4 | 356 | 95 | 375 | 100 |
| Cable heavy-post | 35 | 2 | 177 | 8 | 2094 | 90 | 2306 | 100 |
| W-beam light-post | 4 | 2 | 23 | 11 | 185 | 87 | 212 | 100 |
| W-beam heavy-post | 34 | 3 | 165 | 16 | 846 | 81 | 1045 | 100 |

Table 2 shows the number of barrier penetrations for mid-section impacts with the same four barrier types. "Penetrations" include vehicles traveling over, under, or through the barrier. In general, the light-post cable barriers were penetrated less often than the heavy-post barriers. There was also a correlation between penetration and the seriousness of a collision. Field investigations during the study showed that the low mounting height of the light-post barriers could have contributed to vehicle penetrations, but data to confirm this were not available at the time of the report.

*Table 2. Mid-section penetration for different barrier types, New York, 1977.(5)*

| | Penetrated | | Contained | | Total | |
|---|---|---|---|---|---|---|
| | No. | % | No. | % | No. | % |
| Cable light-post | 37 | 17 | 180 | 83 | 217 | 100 |
| Cable heavy-post | 317 | 31 | 709 | 69 | 1026 | 100 |
| W-beam light-post | 29 | 27 | 77 | 73 | 106 | 100 |
| W-beam heavy-post | 116 | 26 | 336 | 74 | 452 | 100 |

**NEW YORK - 1977**

Another report in 1977 described a study to document field performance of light-post barriers at New York's newer mounting height and to investigate the field performance of slip-base sign posts, frangible luminaire supports, and impact attenuation devices.*(6)* Data were collected for the light-post barriers over a four-year period (1971-75) for all barriers constructed between 1969 and 1971 on state roads. It was assumed that these barriers would have the newer New York standard height of 27 inches to the center of the rail. Data were also collected on the New York State Thruway during a six-month period in 1973.

Maintenance personnel and police officers provided most of the data for this study. The performance of the barrier was based on the severity of injuries, the vehicle reaction (e.g., whether penetration of the barrier occurred), and the required repairs and maintenance.

A total of 392 collisions occurred involving the roadside and median barriers. Tables 3 and 4 summarize the performance of the cable and W-beam barriers.

Table 3 shows that over 80 percent of collisions with cable and W-beam barriers resulted in only property damage. Table 4 summarizes the proportion of mid-section barrier penetrations for each guardrail type. “Penetrations” include vehicles traveling over, under, or through the barrier.

*Table 3. Severity of injury for different barrier types, New York, 1977.(6)*

| | Major Injury | | Minor Injury | | No Injury | | Total | |
|---|---|---|---|---|---|---|---|---|
| | No. | % | No. | % | No. | % | No. | % |
| Cable | 0 | 0 | 2 | 9 | 21 | 91 | 23 | 100 |
| W-beam | 2 | 4 | 8 | 15 | 42 | 81 | 52 | 100 |
| W-beam median | 2 | 2 | 14 | 16 | 73 | 82 | 89 | 100 |

*Table 4. Mid-section penetration for different barrier types, New York, 1977.(6)*

| | Penetrated | | Contained | | Unknown | | Total | |
|---|---|---|---|---|---|---|---|---|
| | No. | % | No. | % | No. | % | No. | % |
| Cable | 4 | 33 | 5 | 43 | 3 | 33 | 12 | 100 |
| W-beam | 4 | 8 | 40 | 80 | 6 | 12 | 50 | 100 |

Using the Chi-squared technique, differences between barrier types were determined at a 95 percent confidence level. Only the difference between the W-beam and box-beam median barriers was statistically significant. In general, the low number of serious injuries (e.g., three percent for W-beam barriers and none for cable barriers) and the complete absence of fatalities indicated good performance of the barriers in terms of injury severity. The collisions were also classified by whether penetration (over, under, or through) occurred, yielding relatively low penetration rates. For the mid-section collisions, the W-beam barriers had a penetration rate of six percent; the cable barriers had a rate of 33 percent, but this was limited by a sample size of only 12 collisions. Lastly, collision damage and repair costs were examined, which showed that the length of rail damaged tended to decrease as the stiffness of the rail increased. Cable guardrail therefore had the highest average length of damaged barrier. The difference of repair costs among the rail systems was nevertheless very minor.

**IOWA - 1979**

A 1979 report described a study to determine the performance of the light-post cable guardrail in the State of Iowa using collision data.*(7)* Data collection for this study included state maintenance property damage reports, the Accident Location and Analysis System (ALAS) database, and police motor vehicle accident reports. The guardrail's performance was determined by whether the barrier redirected the vehicle, if it kept the vehicle from entering the hazardous area, and if it was economical to construct and maintain.

A total of 60 maintenance reports were examined from the two-year data collection period, of which 31 were matched with a police report from the ALAS database. From these, it was observed that the average property damage and collision severity were lowest for the cable guardrail system. The fatality/injury rate for the cable barriers was 16 percent (e.g., one fatality and four injuries), compared to an overall rate for all the barriers of 32 percent. Approximately 32 percent of the vehicles impacting the barrier penetrated it.

**NEW YORK - 1989**

A 1989 report described an in-service evaluation of cable median guardrail on the Palisades Interstate Parkway in the State of New York.*(8)* Data were collected for police-reported collisions at the 15 sites under investigation. Examination of photolog files verified that the collisions involved one of the cable barriers. Collisions were then classified according to the most severe injury, the occurrence of a secondary collision, and the interaction of the vehicle with the barrier (i.e., contained, penetrated, snagged, etc.). It is important to note that only passenger vehicles are allowed on the parkway.

A total of 99 police-reported collisions occurred with the barriers during the three-year evaluation period. Injuries were reported in 24 of the collisions (e.g., 24 percent). In four cases, the impacting vehicle was not contained by the barrier. Two of these were attributed to the height of the barriers, which were constructed before the standard height of cable barriers was lowered. In the other two cases, the vehicles impacted trees; it is uncertain if the vehicles penetrated the barrier or if the barrier deflected to allow the vehicles to impact the trees. Due to the performance data and the costs associated with the use of the system, it was determined that the cable median barrier's performance was satisfactory.

**NEW YORK - 1992**

A report in 1992 summarized an in-service evaluation of light-post barriers in the State of New York that examined the performance of these devices and related collision severity to barrier mounting height.*(9)* Data were collected over a one-year period from July 1, 1982 to June 30, 1983, primarily from police accident reports. On-site investigations were also conducted after repair of the barrier. Cable, W-beam and box-beam barriers on the roadside and in the median were included in the study.

Table 5 summarizes the occupant injury severity for the cable and W-beam roadside and W-beam median barriers. The distribution of injury severity is similar for each type of barrier.

*Table 5. Severity of injury for different barrier types, New York, 1992.(9)*

| | A+K | | B+C | | PDO | | Total | |
|---|---|---|---|---|---|---|---|---|
| | No. | % | No. | % | No. | % | No. | % |
| Cable | 38 | 9 | 178 | 42 | 211 | 49 | 427 | 100 |
| W-beam | 36 | 12 | 140 | 46 | 130 | 42 | 306 | 100 |
| W-beam median | 5 | 11 | 18 | 39 | 23 | 50 | 46 | 100 |

W-beam injury rates were greater for barrier heights below 30 inches, and the chance of a secondary event was greater for barrier heights below 27 inches.  Redirection rates were high for W-beam barrier heights above 23 inches.

For cable barriers, vehicle trajectories and frequency of secondary collisions were best in the 24 to 29 inch height range, and more adverse vehicle trajectories were noted for barrier heights exceeding 29 inches.  Based on this evaluation, a recommendation was made to set the standard center-of-rail height to 24 inches.

# INSTALLATION CHARACTERISTICS

The first step in delivering good performance of a roadside feature in the field is to ensure that it is installed correctly. Installation characteristics can be categorized as function, location or hardware-related. Installation data were collected for 403 guardrail cases, including both control section and collision cases, of the 499 total cases included in this evaluation.

## FUNCTION

In Connecticut, concrete median barriers rather than guardrails are generally used in the median of divided highways. This is reflected in Table 6, which shows that all the G1 and G2 guardrails were located on the roadside shoulder. Guardrails are also not often used in medians in Iowa, where bullnose median treatments are used on divided roadways. In contrast, guardrails are frequently used in the median in North Carolina. Almost all the G1 barriers and 21 percent of the G4(1S) installations were in medians.

*Table 6. Placement of barriers in 403 guardrail cases.*

| | G1 | | | | | | | | G2 | | G4 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CT | | IA | | NC | | All | | CT | | IA G4(1W) | | NC G4(1S) | | Total | |
| | No. | % | No. | % | No. | % | No. | % | No. | % | No. | % | No. | % | No. | % |
| Median | 0 | 0 | 0 | 0 | 73 | 96 | 73 | 58 | 0 | 0 | 12 | 55 | 42 | 21 | 127 | 32 |
| Right Shoulder | 10 | 100 | 37 | 95 | 0 | 0 | 47 | 38 | 55 | 100 | 10 | 45 | 142 | 71 | 254 | 63 |
| Left Shoulder | 0 | 0 | 2 | 5 | 3 | 4 | 5 | 4 | 0 | 0 | 0 | 0 | 17 | 8 | 22 | 5 |
| Total # Known | 10 | 100 | 39 | 100 | 76 | 100 | 125 | 100 | 55 | 100 | 22 | 100 | 201 | 100 | 403 | 100 |

The purpose of the guardrail installation was categorized as shielding errant vehicles from a fixed object, steep slope, cross-median traffic or some other hazard. As shown in Table 7, cable guardrails are usually used in Connecticut and Iowa only if the hazard is a steep side slope, while they are most commonly used in North Carolina as median barriers. Most of the G2 barriers in Connecticut and G4(1S) in North Carolina were also used to shield steep slopes.

*Table 7. Hazards shielded by barriers in 402 guardrail cases.*

| | G1 | | | | | | | | G2 | | G4 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CT | | IA | | NC | | All | | CT | | IA G4(1W) | | NC G4(1S) | | Total | |
| | No. | % | No. | % | No. | % | No. | % | No. | % | No. | % | No. | % | No. | % |
| Fixed Object | 0 | 0 | 3 | 8 | 0 | 0 | 3 | 2 | 6 | 11 | 11 | 52 | 28 | 14 | 48 | 12 |
| Steep Side Slope | 10 | 100 | 35 | 90 | 1 | 1 | 46 | 37 | 44 | 80 | 5 | 24 | 128 | 64 | 223 | 55 |
| Cross-Median Traffic | 0 | 0 | 0 | 0 | 72 | 95 | 72 | 58 | 0 | 0 | 3 | 14 | 27 | 13 | 102 | 25 |
| Other | 0 | 0 | 1 | 2 | 3 | 4 | 4 | 3 | 5 | 9 | 2 | 10 | 18 | 9 | 29 | 8 |
| Total # Known | 10 | 100 | 39 | 100 | 76 | 100 | 125 | 100 | 55 | 100 | 21 | 100 | 201 | 100 | 402 | 100 |

Table 8 summarizes the slopes for 162 of the cases where the hazard was a steep side slope. Slope measurements were not available for the Connecticut cases and a few of the Iowa and North Carolina cases. In Iowa, ten of the G1 installations shielded uphill slopes, while 23 shielded downhill slopes. All the G4 guardrails in Iowa and North Carolina that were installed due to steep side slopes shielded downhill slopes. Slopes in Iowa were between 1:4.0 and 1:2.2, and North Carolina had a wide range of slopes, from 1:8.0 to 1:0.6. In general, the guardrails in the study area are being used to shield slopes steeper than 1:3 as recommended by the AASHTO *Roadside Design Guide*.*(1)*

*Table 8. Typical steep slopes shielded by guardrail installations in 163 cases, in meters.*

| | G1 | G4 | | |
|---|---|---|---|---|
| | IA | IA G4(1W) | NC G4(1S) | Total |
| Uphill slopes | | | | |
| No. of cases | 10 | 0 | 0 | 10 |
| Mean | 1:2.5 | - | - | 1:2.5 |
| Minimum | 1:4.0 | - | - | 1:4.0 |
| Maximum | 1:1.5 | - | - | 1:1.5 |
| Downhill slopes | | | | |
| No. of cases | 23 | 5 | 126 | 152 |
| Mean | 1:2.8 | 1:3.9 | 1:1.6 | 1:1.9 |
| Minimum | 1:4.0 | 1:8.0 | 1:8.0 | 1:8.0 |
| Maximum | 1:2.2 | 1:2.2 | 1:0.6 | 1:0.6 |

## LOCATION

The specific location of a guardrail refers to its position on the roadside or median. Typical site characteristics of these types of installations are shown in Tables 9 through 12. The length of a guardrail installation was defined as the distance from the end of the guardrail terminal to either the end of the downstream terminal or the beginning of a bridge rail. The G1 cable guardrails on Connecticut and Iowa roadsides tended to be about 190 meters long, while the two roadside G1 installations in North Carolina averaged 449 meters long. The lengths of roadside guardrail installations differed significantly from the lengths of median installations. Table 9 summarizes the roadside guardrail lengths and Table 10 summarizes the lengths of median guardrail installations.

*Table 9. Typical length of roadside guardrail installations in 220 cases, in meters.*

| | G1 | | | | G2 | G4 | | |
|---|---|---|---|---|---|---|---|---|
| | CT | IA | NC | All | CT | IA G4(1W) | NC G4(1S) | Total |
| No. of cases | 9 | 38 | 2 | 49 | 30 | 10 | 131 | 220 |
| Mean | 186 | 198 | 449 | 206 | 258 | 301 | 283 | 263 |
| Minimum | 10 | 19 | 378 | 10 | 3 | 19 | 27 | 3 |
| Maximum | 532 | 595 | 520 | 595 | 747 | 1931 | 988 | 1931 |

*Table 10. Typical length of median guardrail installations in 106 cases, in meters.*

| | G1 | | | | G2 | G4 | | |
|---|---|---|---|---|---|---|---|---|
| | CT | IA | NC | All | CT | IA G4(1W) | NC G4(1S) | Total |
| No. of cases | 0 | 0 | 57 | 57 | 0 | 12 | 37 | 106 |
| Mean | - | - | 575 | 575 | - | 36 | 650 | 540 |
| Minimum | - | - | 188 | 188 | - | 10 | 29 | 10 |
| Maximum | - | - | 1810 | 1810 | - | 76 | 3000 | 3000 |

The hazard offsets at the guardrail installations are summarized in Table 11. The hazard offset is the distance from the back of the guardrail to the face of the hazard measured perpendicular to the roadway. Objects like small breakaway signs and delineators were not considered hazards. If the only hazard was the bridge railing end then the distance to the hazard was coded as missing and if the hazard was a steep slope the distance refers to the beginning of the steep slope hazard. In general, the guardrails were placed consistent with the recommendations in the AASHTO *Roadside Design Guide*.*(1)* The beginning of the slope was always greater than 610 mm from the back of the guardrail and the lateral distance to fixed objects was always greater than the expected design dynamic deflection.

*Table 11. Typical hazard offsets at guardrail installations in 101 cases, in mm.*

| | G1 | | | | G2 | G4 | | |
|---|---|---|---|---|---|---|---|---|
| | CT | IA | NC | All | CT | IA G4(1W) | NC G4(1S) | Total |
| Fixed Objects | | | | | | | | |
| No. of cases | 0 | 1 | 0 | 1 | 6 | 8 | 27 | 43 |
| Mean | 0 | 7150 | 0 | 7150 | 2483 | 1848 | 2172 | 2220 |
| Minimum | 0 | 7150 | 0 | 7150 | 360 | 1425 | 630 | 360 |
| Maximum | 0 | 7150 | 0 | 7150 | 3400 | 2100 | 7150 | 7150 |
| Steep Side Slopes | | | | | | | | |
| No. of cases | 5 | 9 | 0 | 14 | 33 | 1 | 4 | 52 |
| Mean | 1625 | 2298 | 0 | 1522 | 1493 | 1370 | 2333 | 1153 |
| Minimum | 914 | 855 | 0 | 855 | 610 | 1370 | 920 | 610 |
| Maximum | 2300 | 6180 | 0 | 6180 | 5000 | 1370 | 3680 | 6180 |
| All Hazards | | | | | | | | |
| No. of cases | 5 | 11 | 0 | 16 | 44 | 10 | 31 | 101 |
| Mean | 1625 | 2882 | 0 | 1981 | 1782 | 1995 | 2193 | 1962 |

AASHTO recommends a maximum approach slope of 1:6 and preferably no steeper than 1:10.*(1)* Slopes were measured inside the guardrails at several points and the maximum slope was tabulated in 403 cases as shown in Table 12. Negative slopes (e.g., uphill from the road to the guardrail) were found only in two Iowa cases in which the guardrail was installed above a low curb. Positive slopes (e.g., downhill from the road to the guardrail) were found in both Iowa and North Carolina, with slopes as steep as 1:4.8 in North Carolina G1 cases and 1:6 in North Carolina G4(1S) cases. Only one case in North Carolina with a slope of 1:4.8 exceeds the allowable steepness of 1:6, but a number of cases in both states do exceed the recommended 1:10 steepness. It is probable that the sites with steep approach slopes reflect poor maintenance where an approach slope has eroded or subsided due to normal cross-drainage.

*Table 12. Maximum approach slope in 402 guardrail installations.*

| | G1 | | | | G2 | G4 | | |
|---|---|---|---|---|---|---|---|---|
| | CT | IA | NC | All | CT | IA G4(1W) | NC G4(1S) | Total |
| No. of cases | 10 | 38 | 76 | 124 | 55 | 22 | 201 | 402 |
| No. of negative slopes | 0 | 2 | 0 | 2 | 0 | 0 | 0 | 2 |
| Max negative slope | - | 1:12 | - | 1:12 | - | - | - | 1:12 |
| No. of positive slopes | 0 | 9 | 42 | 51 | 0 | 11 | 71 | 133 |
| Max positive slope | - | 1:8 | 1:4.8 | 1:4.8 | - | 1:6 | 1:8 | 1:4.8 |

**HARDWARE**

As discussed in the literature review, rail height has been identified as a factor in the collision performance of guardrail systems.*(8,9)* The height of the undamaged rail was determined for 399 of the 499 guardrail collisions, as shown in Tables 13 and 14. Rail heights for the other 100 collision cases were not available, usually because they could not be determined due to guardrail damage. The nominal height to the top of the rail given in the design specifications is 685 mm for the G1, 836 mm for the G2, and 706 mm for the G4(1W) and G4(1S).*(1)* AASHTO's *Roadside Design Guide* recommends a tolerance of ±75mm from the nominal value. The quality of installation as measured by guardrail mounting height varied among the states for the G1, with most of the incorrect rail heights being too high. In the ten Connecticut cases, 70 percent of the rail heights were acceptable; in the 76 North Carolina cases, 67 percent of the rail heights were acceptable; and in the 37 Iowa cases, only 38 percent of the rail heights were acceptable. Eighty-seven percent of the unacceptable G1 rail heights in Iowa and 96 percent of those in North Carolina were too high, with maximums far exceeding the acceptable values. Eighty-six percent of the G4(1W) guardrails in Iowa were installed at the correct height, while 23 percent of the G4(1S) roadside installations in North Carolina were too low and about one-third of the G2 guardrails in Connecticut were too high or too low. Altogether, about 68 percent of roadside guardrails and 76 percent of median guardrails were found to be installed at an acceptable height. The effects of rail height on guardrail performance are further discussed later in this report.

*Table 13. Height of undamaged rail in 272 roadside guardrail installations.*

| | G1 | | | | G2 | G4 | | |
|---|---|---|---|---|---|---|---|---|
| | CT | IA | NC | All | CT | IA G4(1W) | NC G4(1S) | Total |
| No. of cases | 10 | 37 | 3 | 50 | 55 | 9 | 158 | 272 |
| Design height (mm) | 685 | 685 | 685 | 685 | 836 | 706 | 706 | --- |
| Mean height | 739 | 769 | 723 | 760 | 828 | 715 | 678 | --- |
| Minimum height | 635 | 500 | 650 | 500 | 680 | 610 | 530 | --- |
| Maximum height | 945 | 970 | 830 | 970 | 975 | 785 | 1010 | --- |
| # acceptable (±75mm) | 7 | 14 | 2 | 23 | 37 | 7 | 117 | 184 |
| # too high | 3 | 20 | 1 | 24 | 9 | 1 | 5 | 39 |
| # too low | 0 | 3 | 0 | 3 | 9 | 1 | 36 | 49 |

*Table 14. Height of undamaged rail in 127 median guardrail installations.*

| | G1 | | | | G2 | G4 | | |
|---|---|---|---|---|---|---|---|---|
| | CT | IA | NC | All | CT | IA G4(1W) | NC G4(1S) | Total |
| No. of cases | 0 | 0 | 73 | 73 | 0 | 12 | 42 | 127 |
| Design height (mm) | 685 | 685 | 685 | 685 | 836 | 706 | 706 | --- |
| Mean height | - | - | 744 | 744 | - | 695 | 679 | --- |
| Minimum height | - | - | 230 | 230 | - | 640 | 120 | --- |
| Maximum height | - | - | 1300 | 1300 | - | 790 | 810 | --- |
| # acceptable (±75mm) | - | - | 49 | 49 | - | 11 | 36 | 96 |
| # too high | - | - | 23 | 23 | - | 1 | 2 | 26 |
| # too low | - | - | 1 | 1 | - | 0 | 4 | 5 |

Post spacing is only an issue for the G1 systems since W-beam rail sections have bolt holes punched in them at post locations. This virtually eliminates the possibility of incorrectly spacing the posts. Average post spacing was determined for 124 G1 cases. The maximum nominal spacing in the design specifications is 5000 mm for the G1. The installations were almost all acceptable in terms of post spacing, with the G1 systems in Iowa being the worst at 95 percent acceptable, as shown in Table 15.

*Table 15. Post spacing in 124 G1 cases.*

| | G1 | | | |
|---|---|---|---|---|
| | CT | IA | NC | All |
| No. of cases | 10 | 38 | 76 | 124 |
| Design spacing (mm) | 5000 | 5000 | 5000 | 5000 |
| Mean spacing | 4909 | 4854 | 4603 | 4704 |
| Maximum spacing | 5000 | 7860 | 5180 | 7860 |
| # acceptable (≤5000mm) | 10 | 36 | 75 | 121 |
| # unacceptable | 0 | 2 | 1 | 3 |

# IN-SERVICE PERFORMANCE

## COLLISION CHARACTERISTICS

Data from a total of 471 guardrail collisions were collected in the Connecticut study area for 12 months and in the Iowa and North Carolina study areas during the entire 24-month data collection period, including 127 G1 collisions, 126 G2 collisions, 201 G4(1S) collisions, and 15 G4(1W) collisions. Of these, 401 were reported to the police. Impact scenarios were determined based on physical evidence observed at the scene, like skid marks on the pavement, ruts in the soil and scraps on the guardrail. When the collision was reported to the police, the officer's sketch of the impact was also useful in determining the collision scenario. All the police-reported collisions in Connecticut and Iowa involved a guardrail on the roadside, while 98 of the police-reported collisions in North Carolina (38 percent) involved an impact with a guardrail in the median. Altogether about half of the police-reported collisions (53 percent) involved a guardrail on the roadside (22 on the left shoulder and 191 on the right).

The type of vehicle involved in the collision could only be determined in the 401 collisions that were reported to the police. More than 80 percent of the police-reported guardrail cases in Connecticut and North Carolina and almost 50 percent of the guardrail cases in Iowa involved collisions by passenger cars, as shown in Table 16.

*Table 16. Vehicle types involved in 401 police-reported guardrail collisions.*

| | G1 | | | | | | | | G2 | | G4 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CT | | IA | | NC | | All | | CT | | IA G4(1W) | | NC G4(1S) | | Total | |
| | No. | % | No. | % | No. | % | No. | % | No. | % | No. | % | No. | % | No. | % |
| Passenger car | 11 | 79 | 7 | 50 | 53 | 90 | 71 | 82 | 87 | 83 | 4 | 40 | 176 | 87 | 338 | 84 |
| Pickup truck | 1 | 7 | 1 | 7 | 2 | 3 | 4 | 5 | 2 | 2 | 2 | 20 | 15 | 7 | 23 | 6 |
| Sport utility vehicle | 1 | 7 | 1 | 7 | 1 | 2 | 3 | 3 | 8 | 8 | 1 | 10 | 1 | 0 | 13 | 3 |
| Van | 0 | 0 | 1 | 7 | 1 | 2 | 2 | 2 | 0 | 0 | 0 | 0 | 4 | 2 | 6 | 1 |
| Bus | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Tractor-trailer truck | 0 | 0 | 3 | 21 | 2 | 3 | 5 | 6 | 5 | 5 | 3 | 30 | 5 | 2 | 18 | 4 |
| Other | 1 | 7 | 1 | 7 | 0 | 0 | 2 | 2 | 1 | 2 | 0 | 0 | 0 | 0 | 3 | 1 |
| Total # of Cases | 14 | 100 | 14 | 100 | 59 | 100 | 87 | 100 | 103 | 100 | 10 | 100 | 201 | 100 | 401 | 100 |

The primary difference between the data collection areas is the percentage of pickups and tractor trailer trucks. The Iowa data collection area is bisected by a major east-west cross-country truck route (Interstate 80) which results in a relatively high proportion of truck collisions (e.g., 25 percent compared to four percent in the other two states).

Pickup trucks were involved in approximately 13 percent of cases in Iowa, compared to only three percent in Connecticut and seven percent in North Carolina. Overall, pickups, SUVs, and vans make up 10 percent of the collisions. The proportion of pickup, SUV and van vehicles is lower than might be expected given recent indications of the popularity of these types of vehicles.*(10)* Possible reasons for the relatively small proportion of pickup trucks, sport utilities and vans may be regional, or they may reflect the fact that the vehicle population is dominated by older vehicles. In any case, there are clearly differences in the vehicle types among the areas and this is likely the result of different population mixes in those areas.

The events that preceded and followed the guardrail impact in 400 police-reported cases are shown in Table 17. The errant vehicle interacted with no other vehicles or objects prior to striking the guardrail in about 80 percent of the cases in all three States for all types of guardrails. The errant vehicle interacted with another vehicle in the traffic stream prior to striking the guardrail in about 15 percent of the cases and with a tree, pole or other roadside object in the remainder of the cases. In general it appears that most guardrail collisions are the first impact in the sequence of collision events.

*Table 17. Events in 400 police-reported guardrail collisions.*

| | G1 | | | | | | | | G2 | | G4 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CT | | IA | | NC | | All | | CT | | IA G4(1W) | | NC G4(1S) | | Total | |
| | No. | % | No. | % | No. | % | No. | % | No. | % | No. | % | No. | % | No. | % |
| Events prior to impact | | | | | | | | | | | | | | | | |
| None | 11 | 79 | 12 | 86 | 49 | 83 | 72 | 83 | 90 | 88 | 8 | 80 | 162 | 81 | 332 | 83 |
| Tree or pole | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 |
| Other vehicle | 2 | 14 | 1 | 7 | 9 | 15 | 12 | 14 | 10 | 10 | 2 | 20 | 38 | 19 | 62 | 16 |
| Other roadside object | 1 | 7 | 0 | 0 | 1 | 2 | 2 | 2 | 1 | 1 | 0 | 0 | 1 | 0 | 4 | 1 |
| Unknown | 0 | 0 | 1 | 7 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| Events following impact | | | | | | | | | | | | | | | | |
| None | 12 | 86 | 10 | 71 | 56 | 95 | 78 | 90 | 86 | 84 | 10 | 100 | 181 | 90 | 355 | 89 |
| Tree or pole | 0 | 0 | 1 | 7 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 3 | 1 |
| Other vehicle | 1 | 7 | 1 | 7 | 1 | 2 | 3 | 3 | 2 | 2 | 0 | 0 | 5 | 2 | 10 | 3 |
| Other roadside object | 0 | 0 | 1 | 7 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 2 | 1 |
| Unknown | 1 | 7 | 1 | 7 | 2 | 3 | 4 | 5 | 12 | 12 | 0 | 0 | 14 | 7 | 30 | 8 |

The collision with the barrier was the last event in nearly 90 percent of the cases as shown in the bottom portion of

Table 17. There were three cases where the vehicle subsequently struck a tree after being redirected, two cases where it struck another roadside object, ten cases (two percent) where it struck another vehicle and 30 cases where the subsequent event could not be determined. The data show that guardrail collisions are most typically single-event run-off-road collisions where the impact with the guardrail is the only hazardous event.

The result of the impact with the guardrail is shown in Table 18. The vehicle was redirected in about half the collisions (e.g., 53 percent), and the vehicle stopped while still in contact with the guardrail in 25 percent of the collisions. There were 29 cases where the vehicle snagged and spun out, 12 cases where it penetrated the rail, and 44 cases (11 percent) where it overrode or underrode the barrier. The result of the collision was acceptable in at least 309 of the 400 collisions (77 percent). There was no significant difference between the performance of the roadside guardrails and the median guardrails.

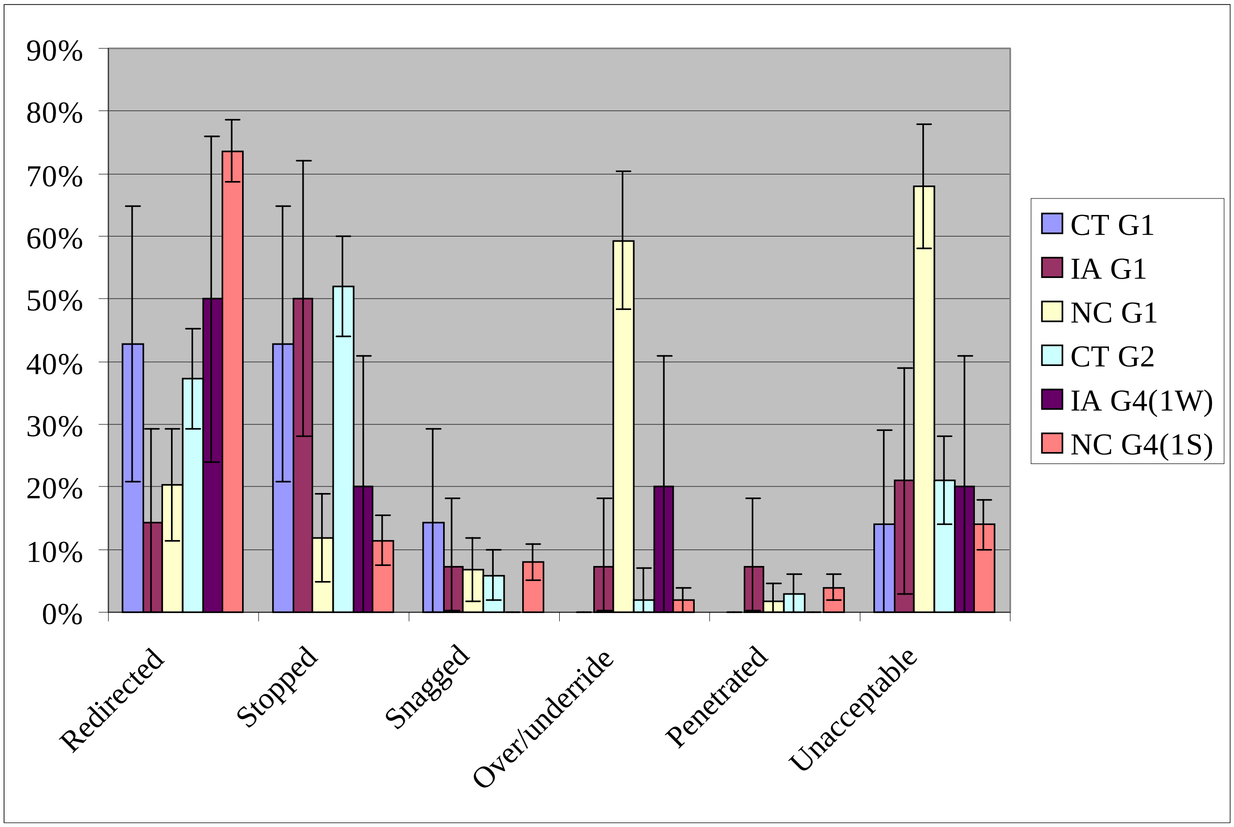
*Table 18. Resulting events in 400 police-reported guardrail collisions.*

| Result of impact | G1 | | | | | | | | G2 | | G4 | | | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CT | | IA | | NC | | All | | CT | | IA G4(1W) | | NC G4(1S) | | | |
| | No. | % | No. | % | No. | % | No. | % | No. | % | No. | % | No. | % | No. | % |
| Redirected | 6 | 43 | 2 | 14 | 12 | 20 | 20 | 23 | 38 | 37 | 5 | 50 | 148 | 74 | 211 | 53 |
| Stopped in contact | 6 | 43 | 7 | 50 | 7 | 12 | 20 | 23 | 53 | 51 | 2 | 20 | 23 | 11 | 98 | 25 |
| Snagged/spun out | 2 | 14 | 1 | 7 | 4 | 7 | 7 | 8 | 6 | 6 | 0 | 0 | 16 | 8 | 29 | 7 |
| Over/underride | 0 | 0 | 1 | 7 | 35 | 59 | 36 | 41 | 2 | 12 | 2 | 20 | 4 | 2 | 44 | 11 |
| Penetrated | 0 | 0 | 1 | 7 | 1 | 2 | 2 | 2 | 3 | 3 | 0 | 0 | 8 | 4 | 13 | 3 |
| Hit from behind | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 |
| Unknown | 0 | 0 | 2 | 14 | 0 | 0 | 2 | 2 | 0 | 0 | 1 | 10 | 1 | 0 | 4 | 1 |
| *Acceptable* | *12* | *86* | *9* | *64* | *19* | *32* | *40* | *46* | *91* | *88* | *7* | *70* | *171* | *85* | *309* | *78* |

While there were no penetrations, overrides, or underrides involving G1 cable guardrails in Iowa or Connecticut, almost 60 percent of the cable guardrail collisions in North Carolina involved overriding or underriding the barrier and 2 percent of the collisions involved penetration. Eighteen of the 35 cases in which a G1 guardrail was overridden or underridden in North Carolina involved a guardrail that was too high. Interestingly, this represents 18 of the 22 North Carolina cases in which a G1 guardrail was too high.

Some of the differences among the States and among the various types of guardrail are statistically significant at the 90 percent confidence level, as shown in Figure 1.

**Figure 1: Result of impact in 400 police-reported guardrail collisions, with 90% confidence intervals.**




All the possible resulting events are shown in Figure 1 except "hit from behind," which occurred only once in the 400 cases, and "unknown." The North Carolina G4(1S) had the highest proportion of redirections (between 69 and 79 percent). Only about 12 percent (between five and 19 percent) of G1 collisions resulted in the vehicle being stopped in contact with the guardrail in North Carolina, compared to between 28 and 65 percent in the other two States. The G1 cable guardrail used in all three States had only one instance of overriding or underriding in Connecticut or Iowa (between zero and 18 percent in Iowa), but between 48 and 70 percent of G1 collisions in North Carolina resulted in overriding or underriding. The G1 in North Carolina had by far the highest proportion of over/underrides, followed by the Iowa G4(1W) and then the Connecticut G2. The Iowa G1, Connecticut G2, and the North Carolina G1 and G4(1S) all had instances of penetrations. A vehicle response is usually considered acceptable if the guardrail is not penetrated, overridden or underridden, or snagged and spun out. In general, collisions with the G1 in North Carolina most frequently had an unacceptable result (between 58 and 78 percent), with the rest having no statistically significant differences.

The proportions of police-reported collisions and maintenance-only reported collisions are very different among the States, as shown in Table 19.

*Table 19. Police-reported and maintenance-only-reported guardrail collisions.*

| | G1 | | | | | | | | G2 | | G4 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CT | | IA | | NC | | All | | CT | | IA G4(1W) | | NC G4(1S) | | Total | |
| | No. | % | No. | % | No. | % | No. | % | No. | % | No. | % | No. | % | No. | % |
| Police-reported | 14 | 100 | 18 | 78 | 59 | 77 | 91 | 81 | 96 | 99 | 12 | 86 | 201 | 100 | 400 | 94 |
| Maintenance-reported | 0 | 0 | 5 | 22 | 17 | 23 | 22 | 19 | 1 | 1 | 2 | 14 | 0 | 0 | 25 | 6 |
| Total | 14 | 100 | 23 | 100 | 76 | 100 | 113 | 100 | 97 | 100 | 14 | 100 | 201 | 100 | 425 | 100 |

The reason for this is that State DOT workers perform repairs to guardrails in Iowa and are therefore notified by the police whenever a barrier is struck. In North Carolina, repair and maintenance are generally contracted out such that DOT is not notified unless the damage itself poses a hazard to traffic. In Connecticut, the police reports are not released to the public, including the DOT, for a period of time after they are completed, so it is difficult to match collision data to repair data. The actual number of unreported collisions, of course, is probably much higher than any of the estimates indicate.

**UNREPORTED COLLISIONS**

Portions of interstate highways in the three data collection areas were closely monitored during the 24 months of data collection, or 12 months in Connecticut. The Connecticut control segment contained 3.6 kilometers of G1 installations and 25.2 kilometers of G2 installations, and it experienced average daily traffic (ADT) volumes of about 84,000 vehicles per day each direction. The Iowa control segment contained 1.5 kilometers of G1 installations and 0.4 kilometers of G4(1W) installations, and it experienced average daily traffic (ADT) volumes of about 16,000 vehicles per day one way.*(11)* The North Carolina control segment contained 1.4 kilometers of G1 installations and

2.9 kilometers of G4(1S) installations, and it experienced average daily traffic (ADT) volumes of about 50,000 vehicles per day each direction past the G1 median installations and 45,000 vehicles per day each direction past the G4(1S) roadside and median installations. In addition to collecting information about all collisions reported to the police or maintenance agencies, the data collection team surveyed every guardrail installation on the control segments approximately once every month in order to record any minor damage. Such damage generally consisted of dents in the guardrail, collapsed end sections, or slightly bent posts.

There was evidence of about 30 collision events per year with G1 installations and 145 collision events per year with all guardrail installations on the control segments as shown in Table 20. Of these presumed collision events, about 16 (52 percent) of the G1 events and 74 (51 percent) of all events were reported to police or maintenance agencies. The data suggest that on average, about 50 percent of the collisions with guardrails in the States of Connecticut, Iowa, and North Carolina are not reported to the police or DOT. Presumably, if no one was injured and the vehicle was still operable after the collision, the driver left the scene without a police report being filed or maintenance personnel being notified. These collisions represent guardrail successes, since they shielded an errant vehicle from some more hazardous roadside feature without causing occupant injuries or serious property damage.

*Table 20. Reported and unreported guardrail collisions per year on control segments in data collection areas.*

| | G1 | | | | G2 | G4 | | | |
|---|---|---|---|---|---|---|---|---|---|
| Collision Type | CT No. | IA No. | NC No. | All No. | CT No. | IA G4(1W) No. | NC G4(1S) No. | All No. | Total No. |
| Unreported | 4 | 5 | 5 | 14 | 13 | 0.5 | 42.5 | 43 | 70 |
| Maintenance-only-reported | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| Police-reported | 10 | 1 | 5.5 | 16.5 | 54 | 1.5 | 2 | 3.5 | 74 |
| Total | 14 | 6 | 10.5 | 30.5 | 68 | 2 | 44.5 | 46.5 | 145 |

Where both inventory and collision information are available, it is possible to calculate expected average collision rates based on the number of vehicles passing guardrail installations. The control sections were inventoried and the locations and lengths of guardrail systems were recorded. Nearly one billion vehicle-kilometers are traveled past a guardrail installation each year on these three segments of interstate highways combined, as shown in Table 21.

*Table 21. Collision rates for guardrails on the control segments.*

| Characteristics | G1 CT | G1 IA | G1 NC | G1 All | G2 CT | G4 IA G4(1W) | G4 NC G4(1S) | G4 All | Total |
|---|---|---|---|---|---|---|---|---|---|
| No. of installations | 18 | 13 | 3 | 34 | 106 | 8 | 20 | 28 | 168 |
| Length of installations (km) | 3.59 | 1.48 | 1.37 | 5.01 | 25.28 | 0.37 | 2.94 | 3.31 | 33.61 |
| Million vehicle-km per year | 107.4 | 8.4 | 48.7 | 164.5 | 756.0 | 2.1 | 52.4 | 54.5 | 975.0 |
| Collision events in one year | | | | | | | | | |
| All collisions | 14 | 6 | 10.5 | 30.5 | 68 | 2 | 44.5 | 46.5 | 145 |
| All reported collisions[§] | 10 | 1 | 5.5 | 16.5 | 55 | 1.5 | 2 | 3.5 | 74 |
| Million vehicle-km passing for one collision | | | | | | | | | |
| All collisions | 7.7 | 1.4 | 4.6 | 5.4 | 11.1 | 1.1 | 1.2 | 1.2 | 6.7 |
| All reported collisions | 10.7 | 8.4 | 8.9 | 10.0 | 13.7 | 1.4 | 26.2 | 15.6 | 13.0 |

§ Reported collisions are those that are reported to either a police agency or a maintenance agency.

Using the data in Table 20, the collision rates shown in Table 21 can be calculated. One collision event (e.g., reported and unreported) occurred for every 6.7 million vehicle-kilometers traveled past a guardrail. As shown earlier, 50 percent of these can be expected to be minor collisions that result in little property damage and no occupant injury. Collisions serious enough to be reported to the police will occur on average once for every 13 million vehicle-kilometers past a guardrail. This analysis, of course, is based on the average occurrence of guardrail collisions. Note that the collision rates vary among the guardrail systems studied. Collisions with G4 installations are the most common, but reported collisions with G4 installations are the least common, indicating either that more minor events occur with G4 guardrails or that minor damage is more apparent in these guardrails. Some sites will experience higher or lower rates because of traffic conditions or site characteristics at that specific location, and differing attention to detail in data collection will result in different estimates of unreported collision events. In any case, Tables 20 and 21 demonstrate that collisions with guardrails are rare events, and those serious enough to report to the police are exceptionally rare.

## OCCUPANT INJURY

The most important measure of roadside hardware performance is the amount of human trauma resulting from roadside hardware impacts. The reason for installing the hardware in the first place is to minimize the risk to vehicle occupants by shielding them from even more serious collisions with more hazardous roadside objects like poles, trees and steep side slopes. The severity of injuries to the vehicle occupants was assessed using the occupant injury codes listed on the police report (e.g., the KABCO scale). Each case was assigned the code for its most severe injury. Since the occupant injury information comes from the police report, the information was limited to the 401 police-reported collisions.

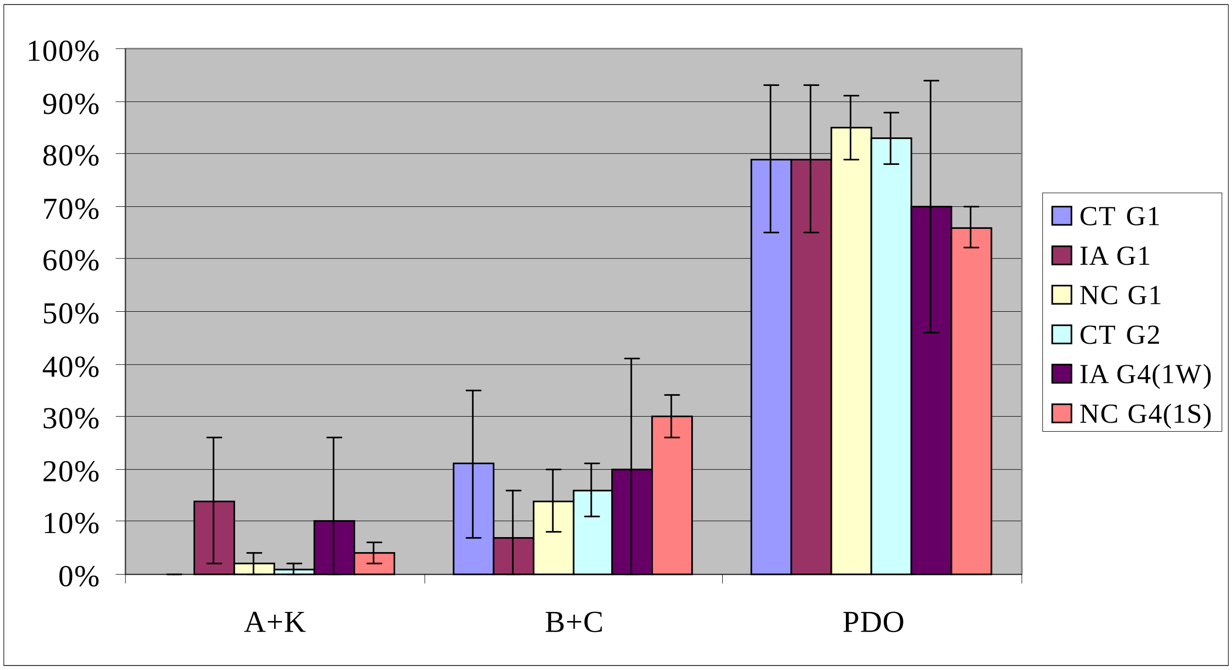
Table 22 summarizes the occupant injury severities of the police-reported collisions. Of the 117 police-reported collisions in Connecticut, about 80 percent of collisions with either the G1 or the G2 involved only property damage, and only one collision involved a fatality or severe injury (e.g., A+K severity). Of the 24 police-reported collisions in Iowa, about 80 percent of collisions with the G1 and 70 percent of collisions with the G4(1W) resulted in only property damage, and 13 percent of both involved fatalities or severe injuries (e.g., three cases). Of the 260 police-reported collisions in North Carolina, 85 percent of collisions with the G1 and 65 percent of collisions with the G4(1S) resulted in only property damage, and about three percent of both involved fatalities or severe injuries (e.g., ten cases). Although the majority of all police-reported collisions involved property damage only, in general the G1 and G2 guardrails (e.g., the weak-post systems) resulted in fewer injury collisions than the two types of G4 used.

*Table 22. Occupant injury severity in 400 police-reported guardrail collisions.*

| | G1 | | | | | | | | G2 | | G4 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Scenario | CT | | IA | | NC | | All | | CT | | IA G4(1W) | | NC G4(1S) | | Total | |
| | No. | % | No. | % | No. | % | No. | % | No. | % | No. | % | No. | % | No. | % |
| Severe or Fatal (A+K) | 0 | 0 | 2 | 14 | 1 | 2 | 3 | 3 | 1 | 1 | 1 | 10 | 8 | 4 | 13 | 3 |
| Moderate Injury (B+C) | 3 | 21 | 1 | 7 | 8 | 14 | 12 | 23 | 16 | 16 | 2 | 20 | 61 | 30 | 91 | 23 |
| Property damage only | 11 | 79 | 11 | 79 | 50 | 85 | 72 | 74 | 85 | 83 | 7 | 70 | 132 | 66 | 296 | 74 |
| Total | 14 | 100 | 14 | 100 | 59 | 100 | 87 | 100 | 102 | 100 | 10 | 100 | 201 | 100 | 400 | 100 |

The 90 [th] percentile precision ranges of the error rates were calculated where possible and are shown in Figure 2 (the range cannot be calculated for a category if there were no observations in that category).

**Figure 2: Occupant injury severity in 400 police-reported guardrail collisions, with 90% confidence intervals.**




For example, the probability that the true proportion of property-damage-only G1 collisions in Connecticut is 79 percent ±14 percent (e.g., between 65 and 93) is at least 0.90 (e.g., 90 percent confidence). The proportion of property-damage-only G1 collisions in Iowa is the same as in Connecticut, and the proportion in North Carolina is 85 percent ± 6 percent (e.g., between 79 and 91 percent) at the 90 percent confidence level. While the range of the estimates is relatively wide (e.g., 14 percent for Connecticut and Iowa and six percent for North Carolina), the estimates for all three data collection areas overlap, indicating that the G1 data are consistent with each other. The ranges for G1 performance in the three states overlap at all severity levels where a range could be calculated, indicating that there is no statistical difference among the performance of the G1 in the three states. There is also no statistical difference between the performance of the G1 and G2 in Connecticut or between the performance of the G1 and G4(1W) in Iowa. However, there is a statistical difference between the performance of the G1 and G4(1S) in North Carolina, showing that in general in North Carolina, a collision with a G1 results in less severe damage to vehicle occupants than does a collision with a G4(1S).

The aggregate level of occupant injury is summarized at the end of Table 22 for all guardrail collisions in the three data collection areas. In general, guardrail collisions result in severe and fatal occupant injuries in approximately three percent of the police-reported collisions. Some level of occupant injury occurs in about 26 percent of police-reported collisions. As noted above, since police-reported collisions represent only 50 percent of all collisions, it would appear that occupants are injured in about 13 percent of all collision events (i.e., reported and unreported).

Thirteen A+K cases were included in the data. Since these are the most serious collisions in terms of occupant injury, it may be helpful to examine the collision characteristics of this subset of cases. Three of the cases involved G1 guardrails, one involved a G2, and nine involved a type of G4. The vehicles included nine passenger cars, two pickups, and one tractor trailer. Ten of the 13 drivers were wearing seatbelts, and an airbag was deployed in three cases. All but three of the cases were single vehicle collisions, and the collision with the guardrail was the first impact in 12 of the 13 cases. Only four of the vehicles rolled over. Three were exceeding the speed limit, and five were slower than the speed limit. Ten of the collisions occurred in clear and dry weather, and seven occurred between 6:00 a.m. and 12:00 noon. Eight of the vehicles were redirected or stopped in contact with the guardrail; one overrode the guardrail, two underrode it, and two penetrated it. Of the G1 collisions, two passenger cars underrode the guardrail and one tractor-trailer penetrated it. In the one G2 collision, a car was redirected. Of the G4 collisions, one car and one pickup overrode the barriers, one car penetrated a barrier, and the rest of the vehicles were stopped or redirected. In seven of the cases, an impact with a slope, other vehicle, or other roadside object occurred before or after the collision with the guardrail, and in another case the driver was ejected from the vehicle and killed. Although no one characteristic seems to account for the severity of these collisions, speeding and not wearing a seatbelt were obviously factors that increased injury severity in several cases, and secondary impacts were a major problem as well.

Table 23 summarizes the occupant injury rates for the control sections in the three data collection areas. These rates are based on the unreported collision data and the police-reported collisions that occurred during the two-year data collection period. On average, one collision event (e.g., reported and unreported) occurred for every 6.7 million vehicle-kilometers traveled past a guardrail. Collisions that resulted in injuries occurred once for every 60.9 million vehicle-kilometers past a guardrail, with only one severe injury or fatality occurring in 650 million vehicle-kilometers. This analysis, of course, is based on the average occurrence of guardrail collisions. Some sites will experience higher or lower rates because of traffic conditions or site characteristics at that specific location.

*Table 23. Injury rates for guardrails on the control segments.*

| | G1 | | | | G2 | G4 | | | |
|---|---|---|---|---|---|---|---|---|---|
| Characteristics | CT | IA | NC | All | CT | IA G4(1W) | NC G4(1S) | All | Total |
| No. of installations | 18 | 13 | 3 | 34 | 106 | 8 | 20 | 28 | 168 |
| Length of installations (km) | 3.59 | 1.48 | 1.37 | 5.01 | 25.28 | 0.37 | 2.94 | 3.31 | 33.61 |
| Million vehicle-km per year | 107.4 | 8.4 | 48.7 | 164.5 | 756.0 | 2.1 | 52.4 | 54.5 | 975.0 |
| **Collision events in one year** | | | | | | | | | |
| A+K collisions | 0 | 0 | 0.5 | 0.5 | 1 | 0 | 0 | 0 | 1.5 |
| B+C collisions | 2 | 0 | 0.5 | 2.5 | 10 | 1 | 1 | 2 | 14.5 |
| PDO and unreported collisions§ | 12 | 6 | 9.5 | 27.5 | 57 | 1 | 43.5 | 44.5 | 129 |
| All collisions | 14 | 6 | 10.5 | 30.5 | 68 | 2 | 44.5 | 46.5 | 145 |
| **Million vehicle-km passing for one collision** | | | | | | | | | |
| A+K collisions | - | - | 97.4 | 329.0 | 756.0 | - | - | - | 650.0 |
| B+C collisions | 53.7 | - | 97.4 | 65.8 | 75.6 | 2.1 | 52.4 | 27.2 | 67.2 |
| PDO and unreported collisions§ | 9.0 | 1.4 | 5.1 | 6.0 | 13.3 | 2.1 | 1.2 | 1.2 | 7.6 |
| All collisions | 7.7 | 1.4 | 4.6 | 5.4 | 11.1 | 1.1 | 1.2 | 1.2 | 6.7 |

§ Unreported collisions are those that are not reported to either a police agency or a maintenance agency. They are assumed to have resulted in minor property damage only.

## GUARDRAIL DAMAGE

The amount and type of damage that a guardrail experiences can provide information about typical performance problems and the amount of resources required to repair the barrier. Damage characteristics were determined for 333 guardrail collisions in Connecticut, Iowa, and North Carolina and are shown in Tables 24, 25, and 26.

The number of posts broken or bent over is an indication of the length of barrier damage. For the G4(1W) in Iowa, which uses 200x200mm timber posts, posts may be either broken off or displaced in the soil. For the G1, G2, and

G4(1S), which use steel posts, the post is usually twisted and bent to the ground or displaced in the soil. The values shown in Table 24 are for posts that were either broken or bent sufficiently to require replacement. It was common to observe minor collisions that did not bend or break any posts. Conversely, sometimes as many as ten of the posts required replacement. The G2 in Connecticut, G4(1W) in Iowa, and G4(1S) performed similarly, whereas the G1 in Connecticut averaged much fewer posts bent or broken than in Iowa or North Carolina. This may be due in part to the lower speed limit on Connecticut highways (e.g., 55 mph rather than 65).

*Table 24. Typical number of posts broken or bent in 333 guardrail collisions.*

| | G1 | | | | G2 | G4 | | |
|---|---|---|---|---|---|---|---|---|
| | CT | IA | NC | All | CT | IA G4(1W) | NC G4(1S) | Total |
| No. of cases | 10 | 23 | 70 | 103 | 31 | 7 | 192 | 333 |
| Mean | 1.2 | 4.4 | 3.9 | 3.7 | 1.8 | 2.3 | 2.0 | 2.5 |
| Minimum | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Maximum | 5 | 10 | 8 | 10 | 8 | 9 | 8 | 10 |

The guardrail bolt should pull through the guardrail slot if the post is broken away or experiences large rotations. The purpose of this feature is to prevent the guardrail from being pulled to the ground when a post rotates in the soil. As shown in Table 25, the majority of cases did not result in the guardrail bolt pulling through the slot or failing. This is probably because the majority of collisions were relatively minor and did not involve large displacements of the post. One or more guardrail bolts did fail or pull through in about 20 percent of the cases, however.

*Table 25. Component failures in 333 guardrail collisions.*

| | G1 | | | | | | | | G2 | | G4 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Failed component | CT | | IA | | NC | | All | | CT | | IA G4(1W) | | NC G4(1S) | | Total | |
| | No. | % | No. | % | No. | % | No. | % | No. | % | No. | % | No. | % | No. | % |
| Guardrail bolt performance | | | | | | | | | | | | | | | | |
| Pulled through or failed | 3 | 30 | 0 | 0 | 36 | 51 | 39 | 38 | 8 | 26 | 2 | 29 | 29 | 15 | 78 | 23 |
| No failure | 7 | 70 | 23 | 100 | 34 | 49 | 64 | 62 | 23 | 74 | 5 | 71 | 163 | 85 | 255 | 77 |
| Guardrail performance | | | | | | | | | | | | | | | | |
| Tearing observed | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 14 | 7 | 15 | 5 |
| No tearing | 10 | 100 | 23 | 100 | 69 | 99 | 102 | 99 | 31 | 100 | 7 | 100 | 178 | 93 | 318 | 95 |

Tearing of the guardrail was not a common occurrence in the real-world guardrail collisions. Guardrail tearing was noted whenever any evidence of tearing was observed, such as when a tear initiated in a splice bolt hole or a cable was broken. There was some evidence of tearing in 15 cases in North Carolina (e.g., five percent of the cases), as shown in Table 25. Tearing was only observed in collisions with a G4(1S) guardrail, except for one G1 case where a cable was broken. Under typical in-service impact conditions, Table 25 indicates that at least one tear in the guardrail occurs in about one in 25 G4 cases and in North Carolina, as many as one in 14 G4(1S) cases.

Table 26 summarizes the average and maximum deflections of the guardrails at ground level and at rail height. Deflections at rail height could not be determined accurately for the G1 cable systems. In all three states, the mean ground-level deflections of the W-beam systems were larger than the mean deflections of the cable systems. For the G4 systems, AASHTO recommends allowing at least 907 mm of clearance for dynamic lateral deflection.*(1)* In 189 police-reported impacts between a passenger car, pickup, SUV, or van and a G4(1W) or G4(1S), the maximum lateral deflection measured at rail height was 730 mm. For these cases, AASHTO's recommendation would have been slightly conservative.

*Table 26. Guardrail deflections in 333 guardrail collisions.*

| | G1 | | | | G2 | G4 | | |
|---|---|---|---|---|---|---|---|---|
| | CT | IA | NC | All | CT | IA G4(1W) | NC G4(1S) | Total |
| No. of cases | 10 | 23 | 70 | 103 | 31 | 7 | 192 | 333 |
| Deflection at ground level | | | | | | | | |
| Mean (mm) | 61.7 | 136.2 | 1.7 | 37.6 | 96.9 | 348.3 | 198.4 | 142.4 |
| Maximum (mm) | 167.0 | 845.0 | 120.0 | 845.0 | 949.0 | 935.0 | 1640.0 | 1640.0 |
| Deflection at rail height | | | | | | | | |
| Mean (mm) | - | - | - | - | 400.0 | 835.7 | 364.6 | 318.7 |
| Maximum (mm) | - | - | - | - | 1950.0 | 1780.0 | 4720.0 | 4720.0 |

In summary, the G2 and G4 guardrails experienced similar types of damage, while the G1 guardrails generally suffered less damage. The overall performance of all four types of guardrails (e.g., G1, G2, G4(1S), and G4(1W)) was adequate.

## EFFECTS OF RAIL HEIGHT

In the past, there has been some concern over the detrimental effects of incorrect rail heights, particularly for the G1 cable barrier.*(5,6,8,9)* The data collected in this study contained 75 police-reported G1 cases that included information about rail height: three cases in Connecticut, 13 in Iowa, and 59 in North Carolina. Table 27 shows the distributions of injury severity and resulting event for the two G1 barriers under the correct height, 40 barriers at the correct height, and 33 barriers over the correct height.

*Table 27. Effect of rail height on G1 collision severity and vehicle behavior (police-reported)*

| | All G1, <610mm | | All G1, 610-760mm | | All G1, >760mm | | Total | |
|---|---|---|---|---|---|---|---|---|
| | # | % | # | % | # | % | # | % |
| Injury Severity | | | | | | | | |
| A+K | 0 | 0 | 1 | 3±4 | 2 | 6±7 | 3 | 4±4 |
| B+C | 0 | 0 | 4 | 10±8 | 5 | 15±10 | 9 | 12±6 |
| PDO | 2 | 100 | 35 | 88±8 | 23 | 79±12 | 63 | 84±7 |
| Resulting Event | | | | | | | | |
| Redirection | 0 | 0 | 14 | 35±12 | 2 | 6±7 | 16 | 21±8 |
| Stop in contact | 1 | 50±58 | 4 | 10±8 | 9 | 27±13 | 14 | 19±7 |
| Over/underride | 0 | 0 | 15 | 38±13 | 20 | 61±14 | 35 | 47±9 |
| Penetration | 0 | 0 | 1 | 3±4 | 0 | 0 | 1 | 1±2 |
| Snag/ spin-out | 1 | 50±58 | 3 | 8±7 | 1 | 3±5 | 4 | 5±4 |
| Unknown | 0 | 0 | 3 | 8±7 | 1 | 3±5 | 4 | 5±4 |
| Unacceptable | 1 | 50±58 | 19 | 48±13 | 21 | 64±14 | 40 | 53±9 |
| Total | 2 | 100 | 40 | 100 | 33 | 100 | 75 | 100 |

The distribution of the injury severity did not appear to be affected significantly by the height of the cable barrier. However, the frequency of the possible resulting events did differ between the correctly installed barriers and those that were too high. Many more cases of overriding or underriding the cables (probably underriding) occurred in barriers that were over 760 mm high, with a corresponding decrease in redirections. As a result, 64 percent of the barriers over 760 mm high caused an unacceptable result, compared to 48 percent of the barriers between 610 and 760 mm high. Most of the differences among height categories are not statistically significant at a 90 percent confidence level due to the small sample size.

During the data analysis, another trend appeared. All but one of the 59 police-reported G1 cases in North Carolina with rail height information also included the estimated speed of the impacting vehicle.  As shown in Table 28, for vehicle speeds of less than 80 kilometers per hour, there was no significant difference in terms of injury severity between barriers of correct height and those over 760 mm, although the resulting event distribution was somewhat different.  Unacceptable resulting events occurred in about 39 percent of all cases where the vehicle speed was less than 80 kilometers per hour.  The cable barrier was under the recommended height in only one case, so that category is not included in the table.  On the other hand, for vehicles impacting at 80 kilometers per hour or more, the frequency of unacceptable resulting events increased to 74 percent for barriers at the correct height and to 100 percent for those over 760 mm.  Every one of the fifteen cases in North Carolina in which a vehicle impacted a cable barrier over 760 mm high at a speed of 80 kilometers per hour or more resulted in the vehicle overriding or underriding the barrier.

*Table 28.  Effects of rail height and vehicle speed in 57 North Carolina G1 collision cases*

| | *Vehicle speed <80 km/h* | | | | | | *Vehicle speed ≥80 km/h* | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 610-760mm | | >760mm | | Total | | 610-760mm | | >760mm | | Total | |
| | # | % | # | % | # | % | # | % | # | % | # | % |
| Injury Severity | | | | | | | | | | | | |
| A+K | 0 | 0 | 1 | 13 | 1 | 4 | 0 | 0 | 0 | 0 | 0 | 0 |
| B+C | 3 | 20 | 1 | 13 | 4 | 17 | 1 | 5 | 3 | 20 | 4 | 12 |
| PDO | 12 | 80 | 6 | 75 | 18 | 79 | 18 | 95 | 12 | 80 | 30 | 88 |
| Resulting Event | | | | | | | | | | | | |
| Redirection | 8 | 53 | 0 | 0 | 8 | 35 | 4 | 21 | 0 | 0 | 4 | 12 |
| Stop in contact | 2 | 13 | 4 | 50 | 6 | 26 | 1 | 5 | 0 | 0 | 1 | 3 |
| Over/underride | 4 | 27 | 4 | 50 | 8 | 35 | 11 | 58 | 15 | 100 | 26 | 76 |
| Penetration | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 5 | 0 | 0 | 1 | 3 |
| Snag/ spin-out | 1 | 7 | 0 | 0 | 1 | 4 | 2 | 11 | 0 | 0 | 2 | 6 |
| Unacceptable | 5 | 33 | 4 | 50 | 9 | 39 | 14 | 74 | 15 | 100 | 29 | 85 |
| Total | 15 | 100 | 8 | 100 | 23 | 100 | 19 | 100 | 15 | 100 | 34 | 100 |

The analysis also showed that at speeds of 80 kilometers per hour or more, the one collision that occurred with a cable barrier under 610 mm high resulted in the guardrail snagging the vehicle.  These trends suggest that when installing cable guardrail on roadways with design speeds (or $85^{th}$ percentile speeds) of 80 kilometers per hour or more, careful attention should be paid to ensuring that the barrier is at the correct height, perhaps even within stricter tolerances than AASHTO recommends.

Of the G4(1S) collision cases in North Carolina, 199 police-reported cases included rail height information. Table 29 shows the same analysis summary for the G4(1S) as was conducted for all the G1 cases (eg., in Table 27). The distribution of resulting events was not significantly affected by rail height, but the injury severities were affected. At a 90 percent confidence level, between 46 and 72 percent of the collisions with barriers under 631mm high resulted in injuries (e.g., "A+K" or "B+C"), compared to only between 22 and 34 percent of the collisions with barriers at the correct height. Although the sample size of barriers over 781 mm high is small, about 43 percent of the collisions resulted in injuries. The proportions of property-damage-only collisions also reflect this difference. The results are relatively unaffected by the speed of the vehicles. This analysis suggests the importance of installing the G4(1S) barrier at the correct height in order to reduce injuries to vehicle occupants.

*Table 29. Effect of rail height on G4(1S) collision severity and vehicle behavior (police-reported)*

| | <631mm | | 631-781mm | | >781mm | | Total | |
|---|---|---|---|---|---|---|---|---|
| | # | % | # | % | # | % | # | % |
| Injury Severity | | | | | | | | |
| A+K | 2 | 5±6 | 5 | 3±2 | 1 | 14±22 | 8 | 4±2 |
| B+C | 21 | 54±13 | 38 | 25±6 | 2 | 29±28 | 61 | 31±5 |
| PDO | 16 | 41±13 | 110 | 72±6 | 4 | 57±31 | 130 | 65±6 |
| | | | | | | | | |
| Resulting Event | | | | | | | | |
| Redirection | 26 | 67±12 | 115 | 75±6 | 6 | 86±22 | 147 | 74±5 |
| Stop in contact | 6 | 15±9 | 17 | 11±4 | 0 | 0 | 23 | 12±4 |
| Over/underride | 2 | 5±6 | 2 | 1±1 | 0 | 0 | 4 | 2±2 |
| Penetration | 2 | 5±6 | 5 | 3±2 | 0 | 0 | 7 | 4±2 |
| Snag/ spin-out | 3 | 8±7 | 12 | 8±4 | 1 | 14±22 | 16 | 8±3 |
| Hit from behind | 0 | 0 | 1 | 1±1 | 0 | 0 | 1 | 1±1 |
| Unknown | 0 | 0 | 1 | 1±1 | 0 | 0 | 1 | 1±1 |
| | | | | | | | | |
| Unacceptable | 7 | 18±10 | 20 | 13±4 | 1 | 14±22 | 28 | 14±4 |
| Total | 39 | 100 | 153 | 100 | 7 | 100 | 199 | 100 |

**CONCLUSIONS**

The previous sections have described a preliminary analysis of the data collected in an in-service performance evaluation of the G1, G2, G4(1W), and G4(1S) guardrails in Connecticut, Iowa and North Carolina. Passenger cars dominated the in-service collision data, and there were significant differences between the data collection areas with respect to the percentage of large trucks involved in collisions.

Past studies have indicated some concern about the ability of the G2 guardrail to safely contain and redirect large vehicles.*(12)* Of the 15 cases included in this evaluation in which a pickup, SUV, or tractor-trailer impacted a G2 guardrail, there was one override and one penetration, neither resulting in occupant injuries. Overall, the G2 performed well.

Almost 75 percent of the police-reported guardrail collisions resulted in only property damage. Fourteen of the 402 police-reported collisions involved severe occupant injuries or fatalities. Within the limits of the data collected to date, there was no statistically significant difference between the performance of the guardrails in the three states, and there was no difference between the performance of the G1 and G2 or the G1 and G4(1W). However, occupant injuries were less common in collisions with a G1 guardrail than in collisions with the G4(1S) or both G4 types combined. Damage to the guardrail was also generally less severe in G1 collisions than in G4 collisions.

Past studies have also indicated a concern about the effects of rail height on barrier performance. This study confirmed that rail height is an important factor in the collision performance of G1 and G4(1S) guardrails.

The foregoing sections have indicated that the guardrails are performing reasonably well in Connecticut, Iowa and North Carolina. These analyses, however, are limited by a modest number of cases and the conclusions may require revision as more data are collected. It should also be noted that both Iowa and North Carolina have many years of experience in using these guardrails, and the proportion of properly installed guardrails was high. A state with a larger number of poorly installed and maintained guardrails cannot expect to replicate these results, since poorly installed systems may result in unsatisfactory performance.

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