IN-SERVICE CRASH EVALUATION OF THREE-STRAND CABLE MEDIAN BARRIER IN NORTH CAROLINA

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Introduction

In December 1993 the segment of I-40 between Davis Drive in the Research Triangle and Wade Avenue in Raleigh, NC was identified as a high hazard location by the Traffic Engineering Branch of the NCDOT. The segment was also ranked as the highest priority in a listing of 24 high hazard locations across NC. The primary crash problem was cross-median head-on events. From February-November of 1994 the NCDOT installed a 3-strand cable system as a median barrier on this hazardous roadway section (Figure 1). The NCDOT prepared an interim report of the cable barrier installation that focused on maintenance of the system and associated costs (Mustafa, 1997). The current report is an evaluation of the crash effectiveness of this cable median barrier.

Figure 1. View of the cable median barrier.

Literature Review of Crash Studies

The literature contains a wealth of information pertaining to roadside barriers, and many of the reports deal with crash test and computer simulation findings. Since the current study is an evaluation of the crash performance of cable barrier, the literature review presented below focuses on crash studies of different types of barriers. These are typically before-and-after studies, in which crash data are analyzed to determine whether, and by how much, crashes, injuries, and fatalities were reduced after the devices were installed. Some studies compare one type of barrier with another.

General Median and Median Barrier Crash Study Results

The NCDOT Traffic Engineering Branch conducted a study of crashes on the interstate system in the state where a vehicle crossed the median and entered the opposing traffic lane. Between April 1, 1988 and October 31, 1999, a total of 751 of these across-median crashes took place, resulting in 105 fatalities. These crashes represented 3 percent of all interstate crashes but 32 percent of the interstate fatalities during the study period. Average injury severity was also much greater for these events. A recommendation was made to construct median barriers at 24 sections of interstate highway in NC.

A review of 32 studies found that median barriers increased crash rates by 30 percent but reduced crash severity: the chance of being killed was reduced by 20 percent and the chance of being injured by 10 percent. Guardrails reduced both crash rates and crash severity: the chance of being killed was 45 percent lower and the chance of being injured was reduced 50 percent (Elvik, 1995).

Watts (1988) reported results from a feasibility before/after study involving the installation of median barriers along 32 km (20 mi) of divided highway in the United Kingdom. The fatal casualty rate was reduced 85 percent for crashes involving the median. Serious injury rates were also reduced by 58 percent.

Knuiman *et al.* (1993) used HSIS data from Illinois and Utah to examine the relationship between median width and crash rates. Log-linear modeling was used, and effects were estimated assuming a negative binomial variance for the crash count per roadway section. When no barriers were present (*i.e.*, the medians were traversable), total crash rates in the two states declined with increasing median width for medians between 8-18 m (25-60 ft) wide. Also, median width had a slightly stronger effect on injury crashes than on property-damage-only crashes in Utah, but not in Illinois. The study surmises that drivers may view the median area as an escape area or clearzone, in that for wider medians the data showed decreases in multi-vehicle crashes of all types, including rear-ends, and perhaps increases or no change in single-vehicle crashes.

Concrete Median Barrier Studies

Boutlier and Whiteman (1995) examined median-related collisions and evaluated the performance of concrete median barrier. In the data base were 4,540 collisions occurring in

1991-1993 on 380 km (236 mi) of Highway 401 in eastern Ontario. A concrete median barrier installed along 40 km (25 mi) of Highway 401 in Ontario reduced the injury crash rate by 28 percent. Median-related fatalities dropped from 27 in the four years before installation to one in the two years after installation.

Quincy and Vulin (1988) used before data from 1981-1982 and after data from 1983-1985 to evaluate the effect of replacing a standard barrier with a concrete barrier along 14 km (9 mi) of highway in France. The total number of accidents increased by 33 percent, primarily due to increases in median barrier impacts. The concrete barrier was more likely to redirect errant vehicles than the standard barrier (77 versus 56 percent, respectively).

Using both police data and NASS Longitudinal Barrier Special Study (LBSS) cases, Mak and Sicking (1989) performed a comprehensive analysis of rollover crashes to: (1) identify the root causes of vehicle rollover in impacts with concrete safety shaped barriers, (2) determine the extent and severity of overturn collisions with concrete safety shaped barriers, and (3) identify potential countermeasures to reduce concrete safety shaped barrier rollovers. Overall, rollover occurred in 8.5 percent of the crashes involving concrete safety shaped barriers, a lesser rate than had been reported in previous studies. F-shape, constant slope, and vertical wall barriers were examined as potential countermeasures. Rollover potential was lower with constant slope and vertical wall concrete barriers than with concrete safety shaped barriers, but the vertical wall was associated with the greatest increase in lateral acceleration.

Statewide crash data were used to examine the effect of New Jersey barrier installations in California. Fatal crashes decreased by 36 percent and injury crashes decreased by 13 percent. Cross-median crashes were virtually eliminated. The benefits in terms of fewer fatal and injury crashes outweighed the installation costs by two-to-one (TR News, 1992).

An innovative use of median Jersey barrier took place along 6 km (4 mi) of a *two-lane*, access-controlled highway serving seasonal traffic to beaches in Rhode Island. Following the installation, both the total and the injury plus fatal crash rates were lower than before. This barrier was installed in this setting because of a number of fatalities and public pressure and served to prevent faster vehicles from overtaking slower vehicles (Murthy, 1992).

Light- and Heavy-Post Barriers

Van Zweden and Bryden (1977) found that the combined fatality-serious injury rate was lower for light-post barriers than for heavy-post barriers in New York State. For both light- and heavy-post systems, cable barriers had lower severity rates than other median barrier types. Across all barrier types, light-post barriers were usually penetrated less often than heavy-post barriers. For impacts at mid-section, light-post cable barrier was penetrated in 17 percent of the crashes, compared to 31 percent for heavy-post cable. Penetrations of the cable were much more likely when a truck was the impacting vehicle.

Hunter *et al.* (1993) used the NASS LBSS crash data to examine the performance of various types of guardrail, median barriers, and end treatments, as well as the risk to the driver when striking a barrier length of need versus and end section. This study also found weak-post barriers to be less associated with driver injury than other barrier types.

A study of 3,300 crashes in New York State found no single optimum mounting height for any barrier type, but recommended that the center-of-rail height be lowered from 69 to 61 cm (27 to 24 in) for light-post barriers (Hiss and Bryden, 1992).

Schneider (1979) examined a total of 31 crashes involving light-post cable guardrail in 1977 and 1978 and compared these with 1,082 crashes involving all other types of guardrail in Iowa. Although sample size was small, average property damage and average crash severity were lower with the cable guardrail than with other guardrail types.

Cable Barrier Systems

Single-strand cable median barriers were discontinued in 1978 in California because they were associated with more penetrations, more vehicle damage, and higher maintenance costs than other types of barriers. Instead, concrete barriers were recommended for median widths of 11 m (36 ft) or less, and thrie beam for median widths over 11 m (36 feet) (Seamons and Smith, 1991).

In contrast, 8 km (5 mi) of cable median barrier along New York's Palisades Interstate Parkway performed favorably compared to other types of barriers in terms of injury rate, vehicle containment, and post-impact vehicle trajectory. Only one cross-median crash was reported after the installation (Tyrell and Bryden, 1989).

An evaluation of 15 km (9 mi) of cable barrier in Oregon found a decrease in the fatality rate. Injury crashes increased fivefold, the result of vehicles striking the barrier after they entered the median, whereas errant vehicles could re-enter the roadway before the barrier was installed. Out of 53 barrier impacts, the cable barrier prevented 21 potential crossovers (Sposito and Johnson, 1999).

Other Barrier Types

Some information is available for other types of barriers from the performance of in-service evaluations. The International Barrier Corporation's (IBC) sheet metal barrier performed well in Iowa but was not as cost-effective as concrete barrier (Marks, 1990). Woodham (1989) also found good performance from the IBC barrier in Colorado. However, it was not recommended as a standard because of its costs. Both the self-restoring barrier guardrail and the modified thrie beam guardrail performed well in Colorado (Woodham, 1988).

Leonin and Powers (1986) reported on a variety of in-service evaluations. For example, the IBC sand-filled median barrier was found to be comparable to the standard concrete safety shape. Other installations of self-restoring barrier guardrail performed better than concrete safety shape for high-angle impacts. Better performance was noted for the modified thrie beam when compared with the standard thrie beam.

Method

While median barrier is traditionally metal guardrail or concrete barrier, North Carolina was one of the first states to use cable guardrail to try to decrease the number of serious and fatal cross-median crashes. The cable barrier is quite forgiving compared to traditional steel and concrete designs; thus, a wider median is needed to allow for increased deflection. The first sets of cable barriers were installed at the high hazard location identified above on I-40 between Raleigh and Durham. Barrier in any median has two effects – the desired effect of reducing the severe or often fatal cross-median crash into opposing vehicles, and the undesired effect of increasing less severe crashes due to reducing the clear zone (or recovery zone) for errant vehicles. Thus, it is important to look at both effects in an evaluation.

Before/after and comparison site crash data were gathered for the evaluation. Computerized crash data were obtained from the Highway Safety Information System (HSIS). The HSIS is operated by the University of North Carolina Highway Safety Research Center (HSRC), under contract with the Federal Highway Administration (FHWA). The HSRC staff conducts research with the HSIS and provides guidance to users on the application of the HSIS for the study of highway safety problems. HSRC is also responsible for the operation of the HSIS Laboratory at the FHWA Turner-Fairbank Highway Research Center in McLean, Virginia.

In 1987 five States where chosen to be included in the HSIS: Illinois, Maine, Michigan, Minnesota, and Utah. The primary criteria used in selecting the states were the data availability (the range of data variables collected), quantity, and quality. All of the selected States maintain basic crash files, roadway inventory files, and traffic files. In 1995, California, North Carolina, and Washington were added to increase the amount of data available and provide better geographic coverage. The first year of available data for NC is 1990; thus, there were several years of both before and after computerized data available for this cable barrier study.

Additional data were available from follow-up crash investigations in Wake, Durham, and Orange counties from July 1, 1997 through June 30, 1999 (24 months) as part of a National Cooperative Highway Research Program (NCHRP) contract. Crash notification came from the screening and collection of crash report hard copies from State Highway Patrol, local police, and sheriff's offices in the three-county area. Crashes were documented after-the-fact at the actual site and supplemented with the standard NC crash report form. The crash investigations pertained to roadside hardware and focused on cable median barrier, steel beam guardrail (G4-1S), and BCT and MELT terminals associated with steel beam guardrail.

Background

The segment of I-40 described above covers a distance of 13.7 km (8.5 mi). Figure 2 is a map of the area similar to the map used in Mustafa (1997). At the time of installation, all but an 0.8 km (0.5 mi) section at the eastern end of the section was a six-lane median-divided freeway with 3.7 m (12 ft) outside usable shoulders, including 3.0 m (10 ft) paved shoulders. The median width ranged from 13.4-19.5 m (44-64 ft) and included 3.0 m (10 ft) inside paved shoulders. Mustafa (1997) describes the median sections as:

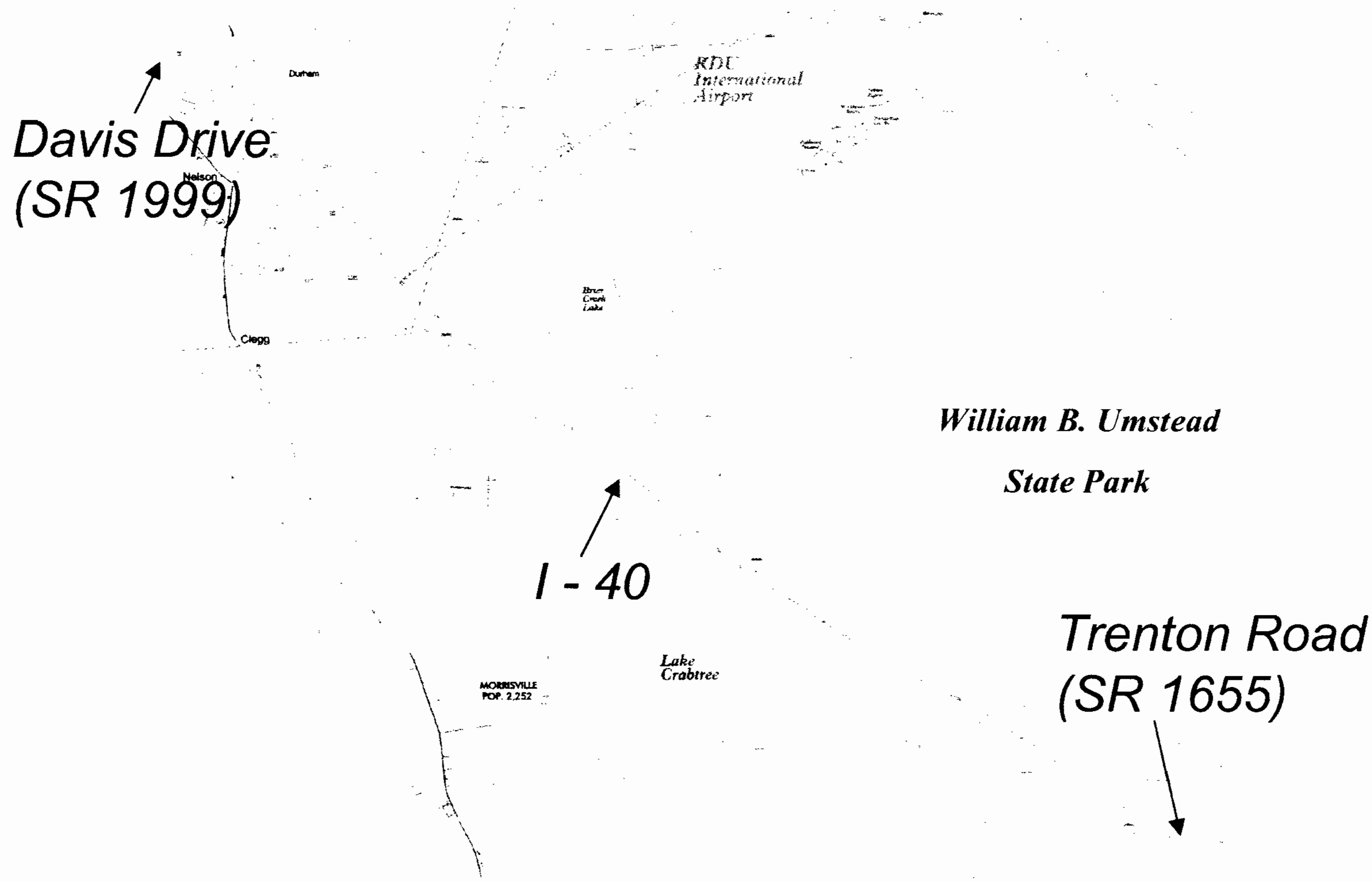

Figure 2. Segment of Interstate 40 where cable median barrier was installed in 1994.

- The median width of the 2.7 km (1.7 mi) segment between SR 1959 (Miami Boulevard) to the Wake County line is 13.4 m (44 ft) with cable median barrier along both sides of the grassed median.
- The median width of the 7.5 km (4.7 mi) segment between the Durham County line and SR 1652 (Harrison Avenue) is 13.4 m (44 ft) with cable median barrier along both sides of the grassed median.
- The median width of the 2.3 km (1.4 mi) segment between SR 1652 (Harrison Avenue) and SR 1655 (Trenton Road) is 19.5 m (64 ft) with a cable median barrier along both sides of the grassed median on the 0.6 km (0.4 mi) segment nearest the SR 1652 (Harrison Avenue) interchange, and with a single line of cable median barrier installed along the center of the median on the remainder of this segment.

Figures 3 shows the cable median barrier along both sides of the grassed median (i.e., double run), while Figure 4 shows the center-of-the-median installation (i.e, single run). The NCDOT recommended that the single run in the center of the median not be used in narrow medians or medians with maximum cross-slopes greater than 6:1.

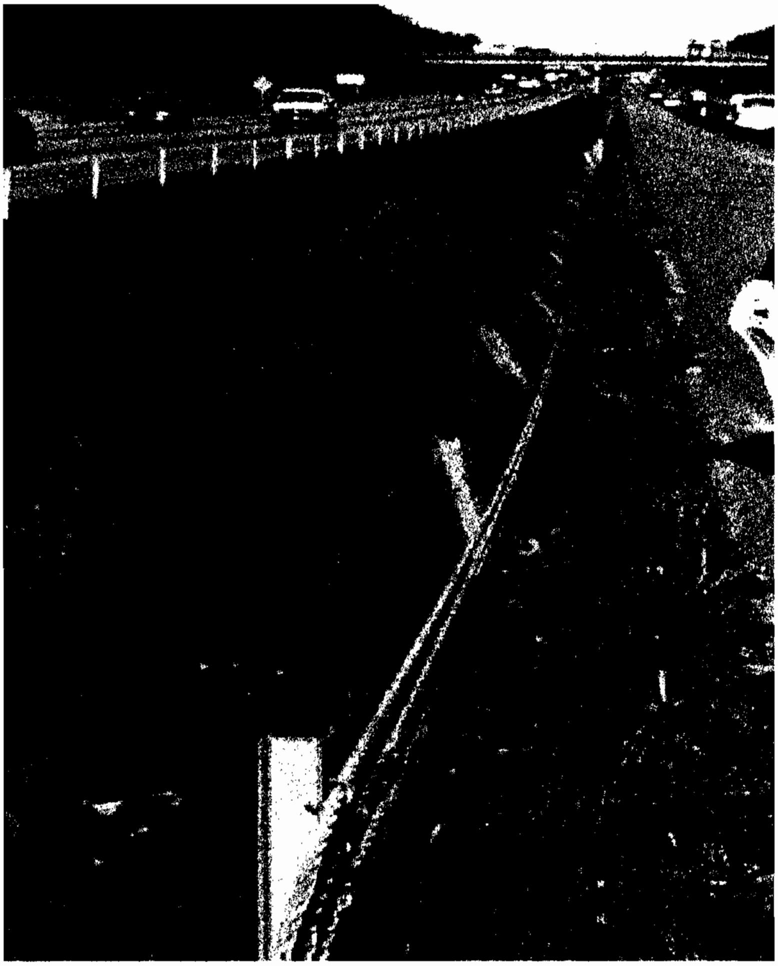

Figure 3. View of the double run section.

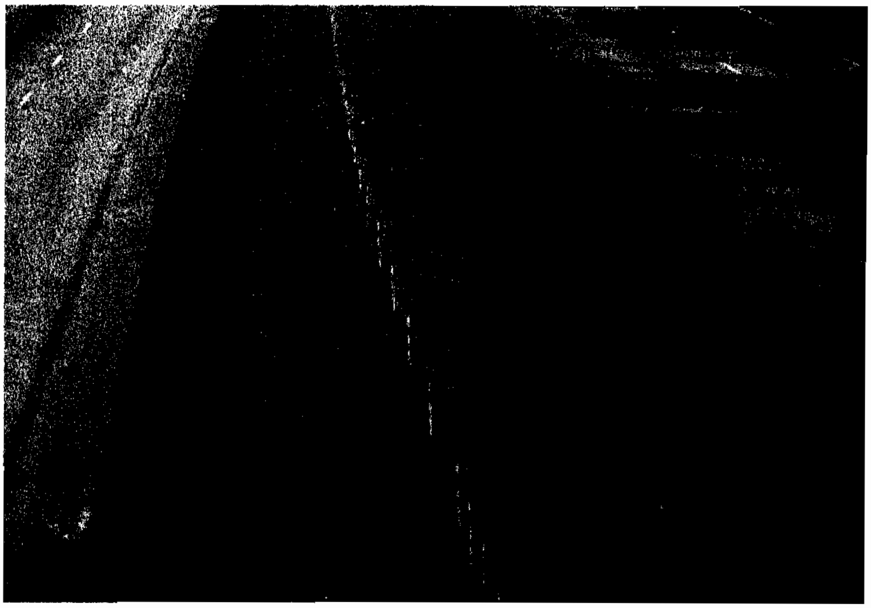

Figure 4. View of the single run section.

At the time of installation, the posted speed limit on the section was 105km/h (65 mph), and the average annual daily traffic (AADT) ranged from 106,000 vehicles per day near the western end to 119,000 vehicles per day near the eastern end. In addition to the cable barrier, the median section included some sections of steel beam guardrail placed around bridge piers and large sign supports.

Cable Barrier Description

Mustafa (1997) describes the cable barrier in the following way:

> This is a flexible barrier system consisting of three 19 mm (0.75 in) diameter stranded steel cables spaced 77 mm (3 in) apart and mounted on weak metal posts. The top cable is mounted to the post at a nominal height of 0.7 m (27 in) above the ground. The posts are installed with a 4.9 m (16 ft) spacing. The three cables are mounted on the side of the post facing the roadway. An exception is where a single length of cable barrier is used in the median, as installed on portions of the subject segment of I-40 where the median is greater than 13.4 m (44 ft). In these locations the middle cable is installed on the opposite side of each post from the other two cables. The cables are terminated at anchorage units that allow tensioning them.
>
> The system is designed to flex and absorb some of the impact energy, and to redirect impacting vehicles after sufficient tension is imparted to the cables. The maximum lateral deflection of the cables upon impact is estimated at 3.5 m (11.5 ft). Therefore, this system cannot be used in medians narrower than 6.7 m (22 ft)

or where a minimum lateral clearance of 3.5 m (11.5 ft) behind each length of cable barrier is unavailable.

Installation of the Cable Barrier

The installation methodology procedure is described in Mustafa (1997) as:

Installation of the cable barrier includes setting out the anchor blocks (one at each end of a segment of barrier) and weak posts, then the cable, which is wound in 609.8-m (2000-foot) reels, is dispensed from a reel stand on the back of a flatbed truck. One end of the cable is attached to a spring turnbuckle which is fastened to one of the anchor blocks (see Figure 5). The other end of the cable is attached to a hand winch (come-along) with a wire rope grip. The cable is then mounted to the posts using J-hook bolts beginning at the end already attached to the anchor unit and proceeds towards the hand winch end. The hand winch is used to take up [slack] in the cable as it is attached to the posts. After the cable is mounted to all posts, it is attached to the second spring turnbuckle and anchor unit. The spring turnbuckle is used to tension the cable to the required force depending on the expected ambient temperature.

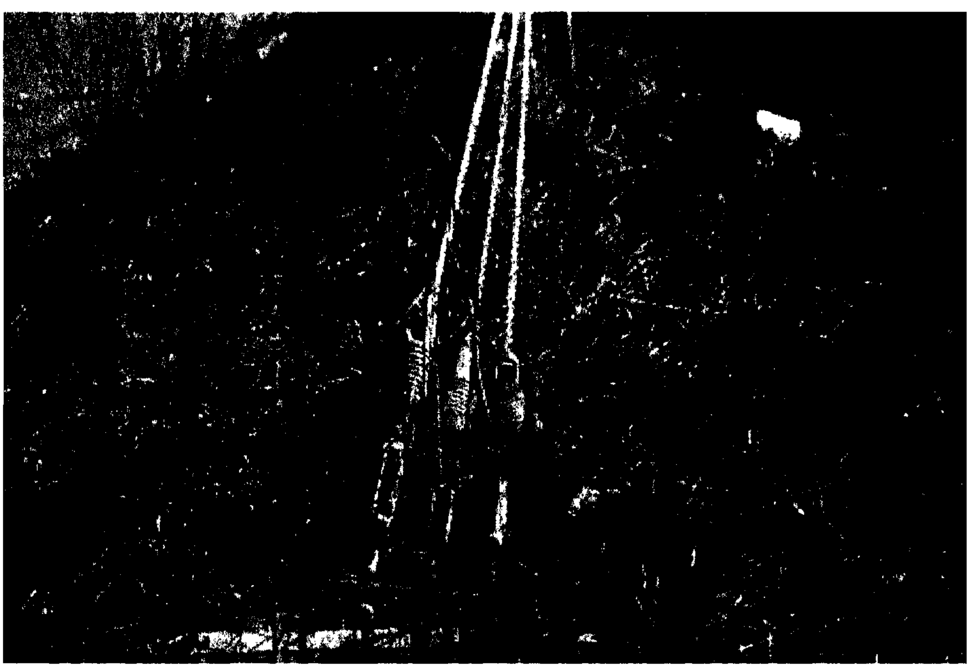

Figure 5. View of end anchor with springs and turnbuckle.

The NCDOT has been continuing to install cable median barrier on divided roadways, with installation usually performed by a private contractor. Besides the cable section in the Research Triangle area that is the focus of this report, cable median barrier has been installed in Wake

County on another section of I-40 east of Raleigh, on US1 south of Raleigh, and on US 64 east of Raleigh. Durham County has approximately 18 miles of cable barrier on I-40.

There are no written installation procedures besides what is written for standard traffic control and the standard NCDOT maintenance and construction facilities specifications. The rolls of cable are only 610 m (2000 ft) feet long, so splicing is often necessary. The splice is detailed in the specifications. Currently, the installation depends on how the job is staged for equipment and traffic control. Often, the cable is installed in a moving operation in stages. In stage installation, the crew would go through and complete each step of the installation for the whole length. The equipment is lined up in a single file so that the whole operation can work in a width of 3 m (10 ft). Lane closures vary based on the median width and the operation width of the construction. The NCDOT requires a lane closure if the work is within 3 m (10 ft) of the travel lane.

Installation can be done rather quickly. A recent eight-mile project on I-40 just east of Raleigh was finished in three weeks by an eight-member crew. The crew consisted of two men placing the anchors, two men driving the posts, three men stringing the rail, and one superintendent. The cable barrier installation required an excavator, a dump truck, a lowboy on a flatbed, a truck that carried the cable, and a truck to drive the posts. The crew worked in a space that was less than two truck widths.

The total cost for this 8-mile segment on I-40 was $431,217. The cost was not broken down per post, but amounts to approximately $10/ft. The cost of a segment is based on the span length and the anchor units. The maximum span for the cable is 610 m (2000 ft) plus the anchor area. The anchor area is approximately 12 m (40 ft). Therefore, the maximum span is about 634 m (2080 ft). The minimum length is about 30 m (100 ft); however, most spans are over 300 m (1000 ft). The anchors are concrete, 122 cm (48 in) square and 1.5 m (5 ft) high, weigh 1,816 kg (4000 lb), and cost approximately $800 each.

Maintenance Practices

The basic maintenance methodology procedure is described in Mustafa (1997) as:

> In addition to periodic adjustments of the turnbuckles at the anchorage units to set the proper tension in the cables, maintenance activities include the same elements involved in installation as necessitated by crashes. The

replacement of damaged portions of the cable barrier involves the following sequence of tasks, usually during a two or three-day maintenance period. It should be noted that these tasks are carried out in the median and the inside paved shoulders without the need for lane closures:

- Removal (pulling out) of damaged posts with a backhoe. This is generally accomplished on the first day of the maintenance period.
- Setting out the new posts. The new posts are usually set out using a truck-mounted post driver during night work on the first or second day of the maintenance period.
- Replacement and/or retensioning the cables, tamping and backfilling. This is generally carried out on the second or third day of the maintenance period.

A maintenance crew is generally able to replace 50 to 75 posts in two to two and a half hours. The average crew size needed to set out posts is usually eight workers as listed below: Two workers to set posts, one post driver operator, one worker to align post driver, two workers to install j-hooks (used to hold the cables) to the posts, one worker to backfill and tamp sand around posts, one worker to assist where needed.

In recent conversations, NCDOT engineers for Wake and Durham counties concurred that this was the procedure still employed; however, the maintenance may require a lane closure or a shoulder closure based on the size of the available area in the median. Additionally, the amount of time required at any location is based on the amount of damage. Figure 6 shows severe damage to a double run section. At most crashes, the cable needs to be rehung on the posts

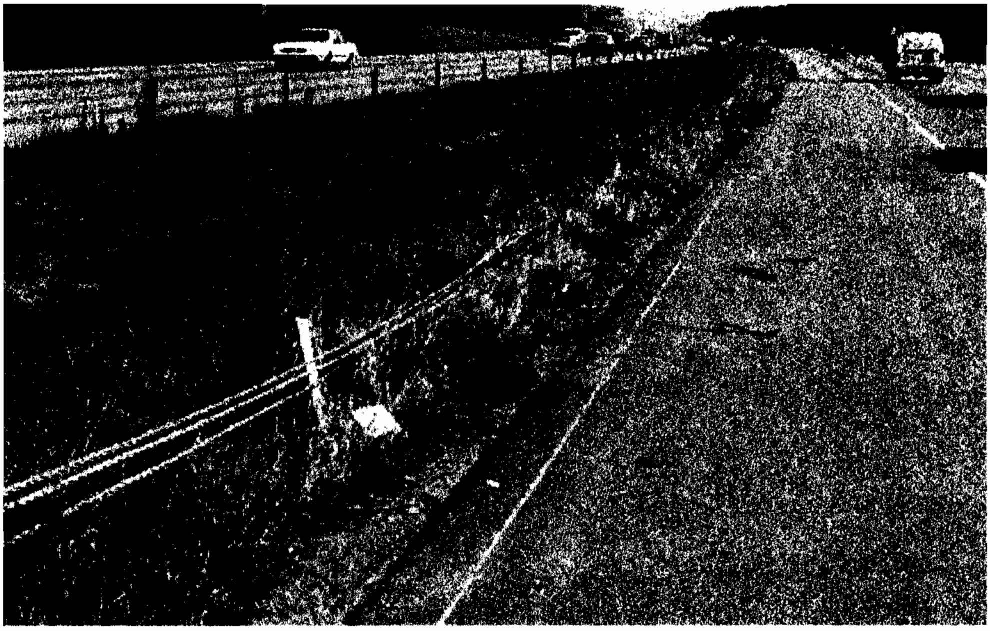

Figure 6. Severe crash damage to double run section.

and set. When needed, retensioning involves cutting slack out of the cable and stretching the cable to the appropriate tension. The average maintenance period in Durham County is four to five hours. Both the crew and equipment requirements are the same as the installation requirements.

Maintenance responsibilities have changed over time. When the cable barrier was first installed and until recently, crews from the Wake County NCDOT office handled the repairs necessitated by crashes. The Wake County area is now handled under a maintenance contract, and the Durham County maintenance contract is out for bid.

Crash Performance Based on Recent Follow-Up Investigations

As mentioned earlier, HSRC performed follow-up crash investigations in Wake, Durham, and Orange counties from July 1, 1997 through June 30, 1999 (48 months) as part of a National Cooperative Highway Research Program (NCHRP) contract. The crash investigations focused on cable median barrier, steel beam guardrail (G4(1S)), and BCT and MELT terminals used with steel beam guardrail. The cable median barrier investigations were associated with:

- a 14.5 km (9 mi) section of I-40 in the Research Triangle area (the basic focus area of this evaluation) - mostly double run of cable
- a new section of I-40 about 6.4 km (4 mi) west of the Triangle area in Durham County - all single run of cable
- a 4.8 km (3 mi) section of US1 south of Raleigh - all double run of cable

The following section of the evaluation reports results from these follow-up investigations.

During the 48 months of monitoring there were 71 crashes into cable median barrier on the highway sections described above. This total includes 15 crashes that were noted during inspections of a control section of roadway to identify "hits" that were not reported by police. Key findings are the following:

- 92 percent of the crashes occurred on the Interstate sections and 8 percent on the US route.
- There were no fatalities and only one serious ("A") injury.
- One crash resulted in rollover.

- Nearly 90 percent of the vehicles involved were passenger cars, followed by pickup trucks (3.6 percent), and tractor-trailers (3.6 percent).
- 21 percent of the crashes resulted in redirection of the vehicle, 57 percent in overriding the cable, 12 percent stopping in contact with the cable, 7 percent snagging or spinning out, and 2 percent (1 crash) going under the cable.
- 82 percent of the crashes involved a vehicle striking only the cable barrier. Another vehicle and the cable were involved in 16 percent, and a fixed object and the cable in 2 percent.
- 72 percent of the crashes involved double run and 28 percent single run of cable.
- In 77 percent of the crashes the vehicle struck the "front" of the barrier, or the side facing the roadway.
- On sections with double run, 44 percent of the vehicles got past the first section of cable. Virtually all were overrides.

Table 1 shows more detail, when available, about the final resting position of the vehicles striking the cable barrier. When single run was struck, the majority (10 of 18 crashes) of the vehicles came to rest in the median. When double run was struck, 18 of 53 came to rest back on the approach shoulder.

Table 1. Final resting position for vehicles striking single and double runs of cable barrier.

Final Resting Position	Single Cable	Double Cable	Total
In Median	10	8	18
Redirected Back to Approach Shoulder	1	18	19
Redirected Back Across All Travel Lanes	0	1	1
Passed Through to Opposite Shoulder	0	1	1
Passed Through to Opposite Travel Lanes	1	0	1
Passed Through and Across Opposite Travel Lanes	2	1	3
Not Sure	4	21	25
Missing	0	3	3
Total	18	53	71

The tables below provide comparisons of cable barrier and steel beam guardrail crashes. Table 2 provides injury distributions for these barriers. There were no fatal crashes and one serious injury crash for the cable barrier, compared with three fatal crashes and five serious injury crashes for the steel beam guardrail. Both distributions show only property damage for two-thirds of the crashes. Table 3 examines barrier performance in crashes. As would be expected, slightly more than half of the cable crashes resulted in override, compared to two percent for steel beam guardrail. On the other hand, almost three-fourths of the steel beam guardrail crashes resulted in redirection, compared to about one-fifth of the cable cases. The percentages for snagging/ spinning out (7-8 percent) and stopping in contact (13 percent) were similar for both barriers.

Table 2. Injury distributions for cable and steel beam guardrail crashes.

Driver Injury Severity	Cable Barrier (G1)	Steel Guardrail (G4-1S)	Total
K (Fatal)	0 (0.0%)	3 (1.6%)	3
A (Incapacitating)	1 (1.8%)	5 (2.7%)	6
B (Non-Incapacitating)	1 (1.8%)	20 (10.6%)	21
C (Possible Injury)	7 (12.5%)	29 (15.3%)	36
O (Property damage only)	47 83.9%)	132 (69.8%)	179
Total*	56 (100%)	189 (100%)	245

*Missing totals excluded from percentage calculations. 15 of the cable guardrail crashes did not have a police report.

Table 3. Performance of the two barriers in crashes.

Result/ Performance	Cable Barrier (G1)	Steel Guardrail (G4-1S)	Total
Snagged/Spun out	4 (7.1%)	15 (8.0%)	19
Stopped In Contact	7 (12.5%)	24 (12.8%)	31
Overrode	32 (57.1%)	4 (2.1%)	36
Penetrated	1 (1.8%)	7 (3.7%)	8
Redirected	12 (21.4%)	137 (73.3%)	149
Total*	56 (99.9%)	187 (99.9%)	243

*Missing totals excluded from percentage calculations. 15 of the cable guardrail and 1 of the steel beam crashes did not have a police report.

Models for Investigating the Effects of Cable Guardrails

A number of regression type models were developed to estimate the effects of the installation of cable median barrier on crash rates for several crash types, while taking into account a number of other factors generally associated with variation in crash occurrences or crash rates. The data for these analyses consisted of counts of various crash types for each section of N.C. interstate highway, along with the associated roadway characteristics, for the years 1990 through 1997. In these data, certain roadway characteristics (in particular AADT) changed from year to year, along with the crash counts. Several of the procedures suggested by Hauer (1997) were incorporated into the model development:

- The entire N.C. interstate system, except for the sections treated with cable median barrier, was taken as a reference population.
- A negative binomial error structure was assumed for many of the models.
- The models contained specific effects for each crash year to account for various unmeasured effects that may vary from year to year (e.g., weather conditions).

Traffic volumes (AADT) tended to be much higher on the roadway sections where the cable barriers were installed than on most of the reference population. This can be seen from Figure 7 which shows average AADT plotted over time for the treated sections (plotted with a "t") and for the reference population (plotted with an "r"). Crashes/mile for several crash types are also shown in Figure 7. As expected, because of this large discrepancy in traffic volumes, the crashes/mile for the treatment group are much higher than for the reference group. Thus, a reference subpopulation consisting of those reference sites having AADT $\geq$ 50,000 vehicles per day was also identified. Two sets of models were developed, one using the entire reference population and the other based on the subpopulation. With the total reference population, the site by year sample size was approximately 6,300 observations, where an observation is a homogeneous roadway segment with accompanying roadway and crash information for a given year. This was reduced to roughly 2,200 observations when the higher volume subpopulation was used. Examination of results produced by the two sets of models showed them to be quite consistent. As a result, *only* the models based on the *entire reference population* are reported.

The models were fit to the data as generalized linear models in which a specified function of the mean of the response variable (crash count) is modeled as a linear function of the

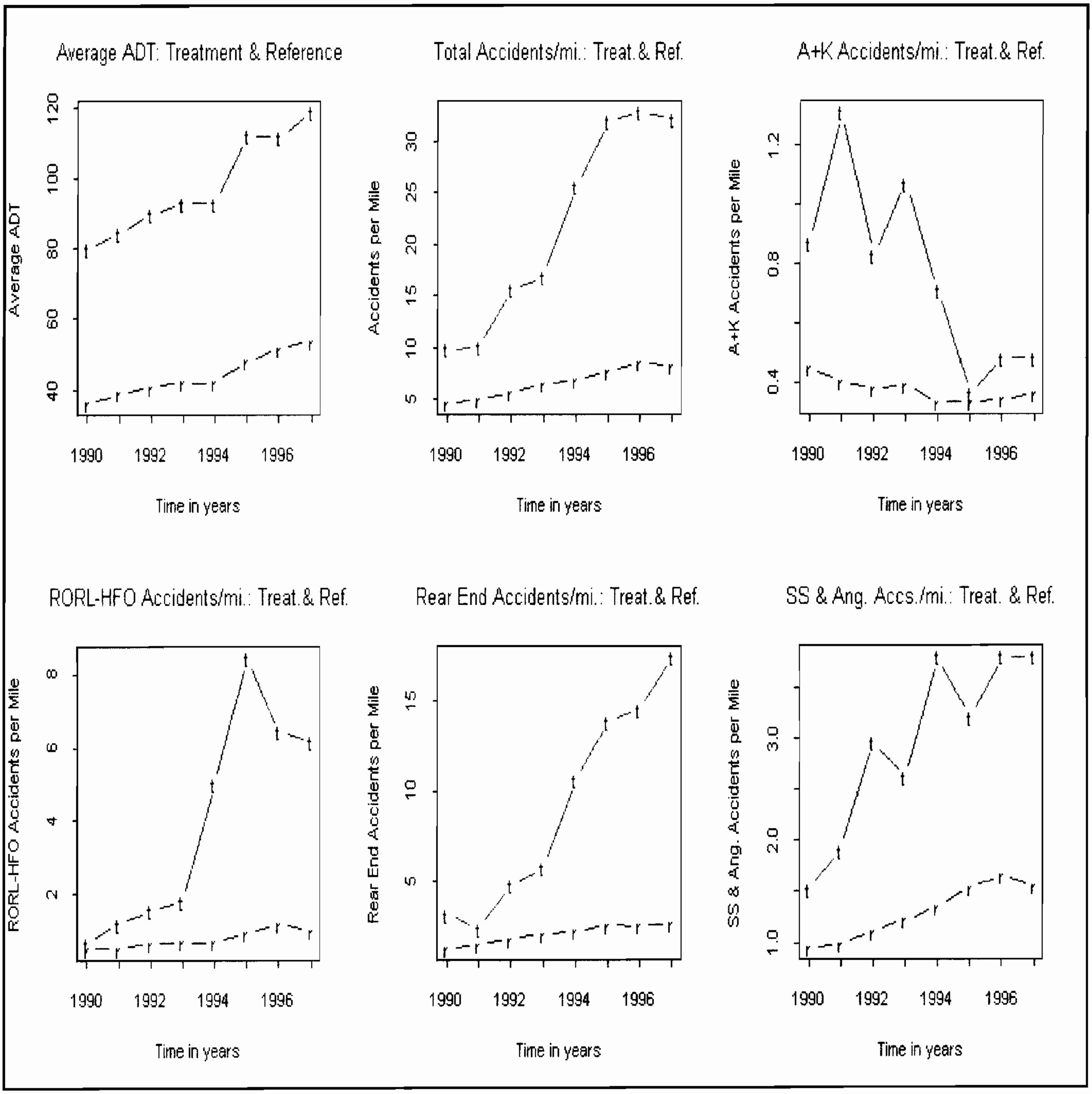

Figure 7. Average traffic volumes and crashes per mile on treatment sites and reference population.

explanatory or predictor variables. In the case of the negative binomial or Poisson models, the log function was used to link the mean of the response variable to the linear function of predictor variables. The explanatory variables used in the model development included:

1. crash year: a categorical or class variable where each year is a specific level,
2. log (AADT),
3. median type: 2 levels, grass or positive barrier,
4. median width in feet,

   In some models median width and (median width)^2 were used as continuous variables. In others, 3 width categories, (≤ 9.2 m (30 ft), 9.2-18.3 m (30-60 ft), and > 18.3 m (60 ft)) were used.

5. right shoulder width in feet,
6. number of lanes: 3 levels, < 6, 6, 8,
7. treatment: 4 levels – a combination of type of segment (treatment/reference) and year (pre-cable /transition to cable/post-cable).

   a. all segments where cable barrier was never installed for all 8 years (reference population),

   b. segments where cable was installed (treatment) and crash year = 1994 (the transition year during which the cable barrier was installed),

   c. segments where cable was installed and crash years = 1995-1997 (post-treatment),

   d. segments where cable was installed and crash years = 1990-1993 (pre-treatment).

In addition to these variables, log (segment length) was included as an offset variable which enters into the linear function with a fixed coefficient of 1.0. This is based on the assumption that crash counts should be proportional to roadway segment length, all other factors being equal.

Models were of the form:

Expected crashes = constant x (segment length) x (other roadway factors) x (crash year factors) x (treatment factors).

Log [Expected crashes] could then be formulated as a linear function of the explanatory variables such as,

$$
\begin{aligned}
\text{Log (expected crashes)} &= \beta_o + \text{(segment length)} \\
&+ \beta_1 (\log(\text{AADT})) + \beta_2 (\text{median width}) \\
&+ \beta_3 (\text{median width})^2 + \ldots + \text{other roadway terms} \\
&+ \beta_k (Y_{90}) + \beta_{k+1} (Y_{91}) + \ldots \\
&+ \beta_r (T_1) + \beta_{r+1} (T_2) + \beta_{r+2} (T_3).
\end{aligned}
$$

The variables Y_{90}, Y_{91}, . . . , Y_{96} were crash year indicator variables, (i.e.,

$$
Y_{90} = \begin{cases} 1 & \text{if crash year} = 1990 \\ 0 & \text{otherwise} \end{cases}
$$

Similarly, T_1, T_2, T_3 were indicator variables for treatment levels 1-3. Treatment level 4 was taken as the baseline or comparison level, as was crash year 1997. The models were fit to the crash data using SAS PROC GENMOD.

The sections that follow explain how models were fit to a variety of crashes (e.g., total crashes, serious and fatal crashes, rear-ends, angles and sideswipes, etc.). The models were used to compare the treatments described above, as well as to generate predicted numbers of crashes on the sections with the cable guardrail. The predicted numbers of crashes were then compared to the actual numbers of crashes that occurred on these same sections.

Total Crash Models

The response variable in this case was a count of *all crashes* occurring on each homogeneous interstate highway segment for each of the years 1990-1997. A total of 6,111 segments-by-year observations were involved in the analysis. All factors that were statistically significant at a significance level of .05 or less are shown in Table 4. As might be expected, the biggest effect was attributable to traffic volume while the effects of median width, right shoulder width, and number of lanes were also quite significant.

In this table, the "Treatment" line indicates a significant difference between two or more treatment levels. This treatment variable can be further analyzed to determine which specific

Table 4. Total crash model effects.

Factor	DF	χ^2	P-value
Crash year	7	60.95	< .0001
Log (AADT)	1	2999.61	< .0001
Median width categories	2	141.88	< .0001
Right shoulder width	1	14.58	< .0001
Number of lanes	2	35.62	< .0001
Treatment	3	9.02	.0062

treatment comparisons produce significant differences. When a class or categorical variable is included in a PROC GENMOD model, the last level is automatically taken as a baseline level and each of the other levels is compared to that level. Thus, for the treatment variable, the estimated effects were as follows:

1. Comparison of remaining Interstate reference population level with pre-treatment (before cable barrier installation) level.

2. Comparison of level in 1994 (transition year when cable installed) with pre-treatment level.

3. Comparison of pre-treatment level with post-treatment level (i.e., before to after cable barrier installation).

The model described above was fit to all the data. It contains a parameter or scale factor for each of the four data subsets, reference population, pre-treatment, transition, and post-treatment. These are the different levels of the treatment variable. In the model fitting procedure, these scale factors are estimated in such a way as to make the model best fit the crash data on each subset, while also taking into account differences in ADT, median width, etc. Significance tests of these scale factors provide the comparisons described above (e.g., a significant increase in crash rate from pre-treatment to post-treatment).

Table 5 shows the estimated treatment effects for the models pertaining to *total crashes*. The treatment effect estimates in Table 5 are estimates of the parameters β_r, β_{r+1}, and β_{r+2} in the model for log (expected crashes). In terms of expected crashes, the parameter β_r becomes a scale factor, $f_r = e^{\beta r}$. Thus, effect number 1 of Table 5 shows expected crashes for the reference population to be higher by the factor, $f_r = e^{.3298} = 1.39$, than expected crashes for the pre-treatment segments, after adjusting for differences in all other variables (e.g., AADT). This represented a statistically significant effect as shown by the p-value in Table 5.

Table 5. Estimated treatment effects for total crash models.

Effect	Estimate	χ^2_1	P-value
1. Reference vs Pre-treatment	.3298	8.04	.0046
2. 1994 Transition vs Pre-treatment	.3473	3.05	.0808
3. Post-treatment vs Pre-treatment	.3441	5.92	.0150

Table 5 also shows that in the 1994 transition year the total crash rate (on the treated segments) was significantly higher than the pre-treatment rate. Indeed, the rate increased to about the same level as that of the reference population and remained at approximately that same level throughout the post-treatment period (effect numbers 2 and 3). The post-treatment versus pre-treatment comparison was also statistically significant. A comparison of the reference level with the post-treatment level (a separate comparison and not shown in table) was not significant, $\chi^2_{1df} = .03$, $p = .8711$.

These results can be summarized as follows. First, the reference group was different from the pre-treatment group in terms of total crashes. While the reference group was indicated earlier (Figure 7) to have lower crashes per mile than the treatment sites, the reference group had a higher expected crash/mile rate than the pre-treatment group after adjustments were made for differences in all model variables. This "switch" was primarily due to adjusting for the much higher AADT levels on the treatment segments. Second, the total crash rate on the cable sites after treatment was higher than in the pre-treatment years. (As discussed later, this was certainly not unexpected given that an "obstacle" -- the cable barrier -- had been placed close to the median shoulder edge.)

In addition to determining significant changes/differences among the treatment categories, it is often also of interest to more directly examine how crash frequencies themselves change in response to an intervention. Complications to direct examination of crash frequencies, however, arise from two sources. First, as traffic volumes increase over time, crash frequencies would also be expected to change in response to traffic volume and perhaps to other changes in the roadway environment. The second source of complication arises from the fact that sites may have been selected for treatment because of having abnormal crash frequencies in the pre-treatment period for certain types of crashes (i.e., there is selection bias in the choice of treatment sites). In this case, it might be expected that crash frequencies would tend to return to a more normal range regardless of any treatment.

In view of these complications, it is of interest to examine the actual *crash* frequencies along with those that would be *predicted* under certain assumptions. In the following analyses, actual crash frequencies (for the various crash types) are listed along with predicted values from two, and sometimes three, different models. One of these models (Model R) was estimated by using data from only the reference population. Predicted values from this model are listed for all eight years and permit comparisons of actual crash frequencies on the treatment segments with predicted values that would be expected based on data from the remainder of the N.C. interstate system in both the pre-treatment and post-treatment periods.

A second model (Model RB) was of exactly the same form as Model R, but was estimated from data which includes the pre-treatment (before) subset along with the reference population. In this model, differences between the pre-treatment crash data and reference population crash data can produce changes in the estimated model parameters, and, hence, in the predicted values. Since the size of the reference population subset is much greater than that of the pre-treatment subset, differences in model parameters and predicted values between this model and the reference group-only model will, generally, be small. Predicted values for the years 1994-1997 are listed from this model. The assumptions for this model are that the treatment sites are basically the same as the reference population, but that the pre-treatment crash data should be given some consideration by including it along with the reference population data in a negative binomial prediction model.

The third model is reasonable only if it is thought that the pre-treatment crash experience is, somehow, essentially different from that of the reference population and that this difference is not due to selection bias, nor can it be explained by any other of the variables included in the model. In this case, another variable (scale factor) was included in the model (Model RBS), to account for this difference in crash frequencies and to project this difference into the model predictions. Predictions from this model will, thus, show a much greater influence of pre-treatment crash frequencies than those from Model RB.

Table 6 shows the total crash frequencies on the treatment segments for crash years 1990-1997, along with the three sets of predicted values. All three predictive models were used to compare the effects of different assumptions or strategies.

Table 6. Actual and predicted total crashes.

Year	Actual	Model R	Model RB	Model RBS
1990	90	126.3		
1991	84	119.4		
1992	131	187.0		
1993	141	202.0		
1994	216	213.4	211.9	191.6
1995	269	273.8	271.9	244.6
1996	276	286.5	284.5	256.1
1997	271	273.1	271.3	244.1

Consider first the predictions labeled Model R. As described above, these predicted values for the treatment sites and years were estimated by a negative binomial model fit to data from only the *reference population*. In other words, Model R makes no use of crash data from the treated sections. Comparison of the Model R and actual values suggest the treatment effect estimates of Table 5, namely, that total crashes on the treatment segments were substantially lower than the predicted values for the pre-treatment years of 1990-1993. Actual crashes increased sharply in 1994 and again in 1995 to the approximate level of those predicted from the reference population. The column labeled Model RB gives predicted values for 1994-1997 from essentially the same model but with crash data from *both the reference group and the pre-treatment (1990-1993) sites*. Including these crashes lowered the predicted values slightly. Finally, Model RBS produced the values shown in the final column and used the same crash data as the model for Model RB, but the model included an indicator variable for the treatment segments. This essentially gives more "weight" to the pre-treatment data in the prediction than in the previous (Model RB) prediction. As can be seen, Model RBS projects that the lower values of 1990-1993 would continue through 1997.

All three models have advantages and disadvantages. The second prediction (Model RB) is more along the lines of an empirical Bayes technique in that it includes some information from both the reference population and pre-treatment segments, but with outcomes weighted more heavily toward the reference population because of the larger sample size. This model indicates little difference between actual and predicted total crashes in the post period. Model RBS, which gives added weight to the pre-treatment sites, indicates lower predicted crash frequencies in the post-treatment years when compared to actual crashes. *In summary, these models indicate a significant increase in total crashes from pre- to post-treatment, but only to a level equivalent to the rest of the interstate system.*

Serious Injury and Fatal Accidents

The primary goal of the cable barrier treatment is to eliminate severe, cross-median, head-on crashes. While it could be hypothesized that certain types of crashes (e.g. ran-off-road fixed object impacts) would increase on sections with the cable barrier, the overall *severity* of crashes should decrease if the treatment is successful. Thus, serious crashes were examined in the pre-treatment, post-treatment, and reference populations.

Models for serious injury and fatal (A+K) crashes included the explanatory variables of crash year, log (ADT), median width and median width squared, number of lanes, and treatment. The estimated treatment effects are shown in Table 7. These show that A+K crashes per mile were significantly higher on the pre-treatment segments than for the reference population (as

Table 7. Estimated treatment effects for serious injury and fatal crashes.

Effect	Estimate	χ^2_1	P-value
1. Reference vs Pre-treatment	-.3664	4.14	.0419
2. 1994 Transition vs Pre-treatment	-.2412	0.29	.5589
3. Post-treatment vs Pre-treatment	-.8915	5.62	.0187

indicated by the negative sign for the estimate.) This would be expected since the segments to receive the cable barrier were selected because of a history of serious crashes. Table 7 also shows that A+K crashes on the treatment segments decreased in the 1994 transition year, and decreased further in the post-treatment period to a level significantly lower than the pre-treatment level. Post-treatment rates were also lower than that of the reference population, although this difference was not very significant, p = .1142.

Just as in the analysis of total crashes, the results were further analyzed by comparing actual and predicted A+K crashes for the treatment sites. The results are listed in Table 8. Predicted values for Model RB and Model R were made under the same conditions as those of Table 6. *Comparing actual and predicted crashes tended to confirm the results based on the treatment effect estimates -- the actual A+K crashes were lower than either of the predictions in the post-treatment years.*

Table 8. Actual and predicted A+K crashes.

Year	Actual	Model RB	Model R
90	8		7.1
91	11		5.5
92	7		6.4
93	9		6.5
94	6	5.6	5.5
95	3	6.1	6.0
96	4	6.0	5.8
97	4	6.2	6.1

Ran-Off-Road-Left Hit-Fixed Object (RORL-HFO) Crashes

Since the installation of the cable barrier adjacent to the paved inner shoulder decreases the effective clear-recovery width, one would expect RORL-HFO crashes to increase. Estimated treatment effects from a model for RORL-HFO crashes which contained crash year, log (ADT), median width categories, median type, and number of lanes as the other explanatory variables are shown in Table 9. These results show the pre-treatment level of these crashes was essentially the same as that of the reference population (i.e., no significant difference in rates). A significant

Table 9. Estimated treatment effects for RORL-HFO crashes.

Effect	Estimate	χ^2_1	P-value
1. Reference vs Pre-treatment	-.0929	.19	.6661
2. 1994 Transition vs Pre-treatment	1.1749	15.05	.0001
3. Post-treatment vs Pre-treatment	1.1225	22.76	<.0001

increase occurred in 1994 and persisted through the post-treatment period. A comparison of post-treatment with reference showed post-treatment levels to be significantly higher, $\chi^2_1 = 82.45$, $p < .0001$. These results are further confirmed by the actual and predicted values of table 10. *Thus, the expected increase in RORL-HFO crashes with the installation of a cable median barrier was confirmed in the data.*

Table 10. Actual and predicted RORL-HFO crashes.

Year	Actual	Model RB	Model R
90	6		8.8
91	10		8.2
92	13		12.1
93	15		12.2
94	42	12.3	12.3
95	71	16.9	16.8
96	54	20.7	20.6
97	52	18.0	17.9

Rear-End Crashes

The question of how the cable barrier might affect rear-end crashes is somewhat complex. One could hypothesize that since rear-end crashes make up a large proportion (approximately 30 percent) of total interstate crashes, changes in rear-end crash frequencies associated with the installation of cable barrier should follow a similar pattern to that for total crashes. Alternatively, one could also hypothesize that the reduction in clear median width might increase rear-end crashes under high-speed, congested traffic conditions by providing drivers with less room to avoid potential collisions. A model for rear-end crashes as a function of crash year, log (ADT), median width categories, median type, number of lanes, right shoulder width, and treatment yielded the treatment effect estimates listed in Table 11. Similar to total crashes, rear-end

Table 11. Estimated treatment effects from rear-end crash model.

Effect	Estimate	χ^2_1	P-value
1. Reference vs Pre-treatment	.6979	12.19	.0002
2. 1994 Transition vs Pre-treatment	.5963	3.67	.0553
3. Post-treatment vs Pre-treatment	.6574	8.33	.0039

crashes in the pre-treatment period were significantly lower than expected based on the reference population. The frequency of these crashes increased in 1994 and was significantly higher in the post-treatment period than pre-treatment. A comparison of post-treatment and reference levels showed no significant difference, $\chi^2_1 = .10$, $p = .7492$.

Actual and predicated values are listed in Table 12. As in Table 6, the values listed under Model RBS are based on a model which allows the treatment sites to be scaled differently from

Table 12. Actual and predicted rear-end crashes.

Year	Actual	Model RBS	Model RB	Model R
90	29			50.1
91	20			51.2
92	40			90.4
93	48			106.3
94	89	60.1	104.2	107.4
95	116	86.2	151.6	156.1
96	122	77.4	137.8	142.0
97	146	81.9	143.0	147.4

the reference population, essentially giving more weight to the pre-treatment data than in the Model RB combined data set.

The model results showed that rear-end crashes increased significantly from pre- to post-treatment. While actual rear-end crash frequencies were numerically lower in 1995 and 1996 from those predicted from the reference population, the difference in the post period was not significant.

Ran-Off-Road-Left Overturn Crashes

The issue examined here was whether the installation of cable in the median affected a potentially serious accident type -- overturns. The significant factors in a model for crashes of this type were crash year, median width categories, number of lanes, median type, and treatment. Note that traffic volume was not significantly associated with crashes of this type. The estimated treatment effects of Table 13 show that the pre-treatment rate of RORL-overturn crashes was significantly higher than that of the reference. There were no significant changes in the transition or post-treatment period, and a comparison between post-treatment and reference showed the post-treatment rate to be significantly higher than the reference, $\chi^2_1 = 8.87$, $p = .0029$.

Table 13. Estimated treatment effects from RORL-overturn model.

Effect	Estimate	χ^2_1	P-value
1. Reference vs Pre-treatment	-.7461	4.38	.0364
2. 1994 Transition vs Pre-treatment	.2518	.12	.7238
3. Post-treatment vs Pre-treatment	.3854	.69	.4066

Actual and predicted values of RORL-overturns shown in Table 14 confirm the results of Table 13. It does appear that, while the frequencies were very low, actual overturn crashes in the post-treatment data set were higher than predicted by either model.

Table 14. Actual and predicted RORL - Overturns.

Year	Actual	Model RB	Model R
90	4		1.3
91	3		1.1
92	1		1.0
93	2		1.3
94	3	1.2	1.1
95	3	1.2	1.2
96	5	1.4	1.4
97	4	1.4	1.4

Sideswipe and Angle Crashes

These are another fairly frequent type of crash occurring on interstate highways. Significant factors in a model for these crashes were crash year, log (ADT), median width categories, number of lanes, median type, and treatment. In Table 15 the estimated treatment effects showed the reference versus pre-treatment comparison to be the only significant effect, with the reference population rate significantly higher than the pre-treatment rate. A comparison of reference versus post-treatment showed reference to again be significantly higher, $\chi^2_1 = 29.56$, $p < .0001$. *Actual and predicted values are shown in Table 16, and the predicted values based on the reference group only (Model R), as well as the combined reference and "before" groups (Model RB), were much larger than the actual number of sideswipe and angle crashes.*

Table 15. Estimated treatment effects from sideswipe and angle crash model.

Effect	Estimate	χ^2_1	P-value
1. Reference vs Pre-treatment	.7961	19.48	<.0001
2. 1994 vs Pre-treatment	.2086	.41	.5230
3. Post-treatment vs Pre-treatment	-.0103	.00	.9658

Table 16. Actual and predicted sideswipe and angle crashes.

Year	Actual	Model RB	Model R
90	14		37.5
91	16		34.3
92	25		49.3
93	22		55.5
94	32	57.1	58.7
95	27	75.1	77.0
96	32	74.1	76.1
97	32	67.3	69.0

Ran-Off-Road-Left, Head-On (RORL - HO) Crashes

This type of crash is one which the cable barrier was specifically installed to prevent. However, it is also a very rare type which makes statistical analysis difficult. Table 17 lists the frequency of occurrence of these crashes on both the reference and treatment sites for all eight years. Since the reference population contained roughly 950 miles of interstate highway as

Table 17. Ran-Off-Road-Left, Head-On crashes.

Year	Reference	Treatment
90	14	1
91	8	0
92	12	1
93	15	1
94	11	1
95	13	0
96	23	0
97	13	0

compared to 8.42 miles in the treatment segments, a single RORL - head-on crash on the treatment sections represents nearly a 10-fold increase over the average rate per mile on the reference segments.

A Poisson model was fit to these data. The statistically significant variables in the model were log (ADT), median type, and median width (3 categories). A three-level treatment variable which included 1994 as part of the post-treatment was included in the model. Since no head-on crashes occurred in the original post-treatment period, this effect could not be estimated. The estimated reference versus pre-treatment effect was -1.3258 with $\chi_1^2 = 4.66,\ p = .0308$, while the estimated post-treatment versus pre-treatment was -1.6542, $\chi^2 = 2.04,\ p = .1532$. *Thus, the model confirms the fact of significantly higher RORL head-on crash rates for the pre-treatment sites relative to the reference population.*

The estimated post-treatment versus pre-treatment effect was even greater in magnitude but not very significant, which might be expected given the nature of these data. Predicted numbers of RORL-head on crashes for the post-treatment sites based on pre-treatment and reference data were .33, .40, .40, and .41 for accident years 1994-1997, respectively, and in actuality one such crash occurred in the 1994 transition year. *No head-on crashes occurred from 1995-1997, after the cable barrier had been installed.*

Equivalent Property Damage Only and Severity Index Calculations

The equivalent property damage only index (EPDO) is a mathematical formula used by the Traffic Engineering Branch of the NCDOT to reflect economic loss associated with crashes. Crash severity is defined as the most severe injury that occurs in a crash. The equation is periodically updated to reflect changes in the costs of crashes. The EPDO currently used is the following:

EPDO Index = 76.8 (A+K) + 8.4 (B+C) + PDO, where

K = number of fatal crashes
A = number of A injury crashes (incapacitating injuries that will prevent normal activities for more than 24 hours)
B = number of B injury crashes (non-incapacitating injuries that will not prevent daily activities for more than 24 hours)
C = number of C injury crashes (complaint of pain or momentary unconsciousness)
PDO = number of property damage only crashes

The Severity Index (S.I.) averages the severity of all crashes at a location and is calculated in the following manner:

S.I. = EPDO / number of crashes = 76.8 (A+K) + 8.4 (B+C) + PDO / N, where

N = number of crashes at the location

Typical values for the S.I. are the following:

Low	S.I. < 6.0
Average	S.I. = 6.0 to 7.0
Moderate	S.I. = 7.0 to 14.0
High	S.I. = 14.0 to 20.0
Very High	S.I. > 20.0

EPDO and S.I. values were calculated for each year (i.e., before, during, and after) for the section of roadway where the cable median barrier was installed. Results are presented in Table 18. Here, S.I. values ranged from 8.7 to 13.7 during the before period of 1990-1993. The overall S.I. for this period was 9.7, a moderate value. During the transition year the S.I. was 5.5, a low value. After the cable median barrier was installed, the S.I. values ranged from 4.2 to 5.0, even though total crashes on the section increased markedly. The overall S.I. for this period was 4.7, a low value. Thus, the economic losses associated with this section of roadway following cable barrier installation were greatly reduced.

Table 18. EPDO and S.I. calculations by year for the section of roadway where the cable median barrier was installed.

Year	EPDO	Total Crashes	S.I.
1990	925.8	90	10.3
1991	1147.2	84	13.7
1992	1016.8	131	7.8
1993	1230.2	141	8.7
1994	1188.8	216	5.5
1995	1140.2	269	4.2
1996	1393.2	276	5.0
1997	1277.2	271	4.7

Summary

Two kinds of data were analyzed to evaluate the cable median barrier – follow-up crash investigations and historical crash data. HSRC staff performed follow-up crash investigations in Wake, Durham, and Orange counties from July 1, 1997 through June 30, 1999 (24 months) as part of a National Cooperative Highway Research Program (NCHRP) contract. For 56 impacts into the cable barrier system where crash reports were available, there were no fatalities and only one serious ("A") injury. One of the crashes resulted in rollover. These in-field results were consistent with the data analysis reported below.

Using historical crash data, a number of regression type models were developed to estimate the effects of the installation of cable guardrails on crash rates for several crash types, while taking into account a number of other factors generally associated with variation in crash occurrences or crash rates. The data for these analyses consisted of counts of crashes of the various types for each section of N.C. interstate highway along with the associated roadway characteristics, for the years 1990 through 1997. Certain roadway characteristics (in particular traffic volume) changed from year to year, as, of course, did the crash counts. The entire N.C. interstate system was taken as a reference population; a negative binomial error structure was assumed for many of the models, and the models contained specific effects for each crash year to account for various unmeasured effects that may vary from year to year (e.g., weather conditions). These models used the reference population to predict numbers of crashes on the cable sections. Key results include:

- Total crashes and rear-end crashes were lower than expected before the cable barrier was installed and increased afterwards to about the levels expected based on the other interstate road sections.
- Serious and fatal (A+K) crashes were higher than expected before the cable barrier and decreased afterwards to lower than expected levels.
- Ran-off-road-left hit-fixed-object crashes were about as expected before the cable and increased substantially afterwards. These crashes would obviously be expected to increase with the installation of the cable median barrier.
- Angle and sideswipe crashes were lower than expected before the cable barrier and remained at this level afterwards.

- Ran-off-road-left overturn crashes were higher than expected before the cable barrier and remained at this level afterwards.
- Ran-off-road-left head-on crashes were higher than expected before the cable barrier. After cable barrier installation, none of these crashes occurred.

In summary, these analyses indicate that several kinds of crashes increased on the sections where cable median barrier was installed. However, these sections showed improved overall safety due to fewer serious and fatal crashes, as well as fewer head-on crashes. Overall Severity Index values were greatly reduced after barrier installation.

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