cost of this modified rail would be approximately $80 per linear foot, whereas a standard Texas Type T5 traffic rail normally costs about $35 per linear foot.

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Crash Cushion Improvement Priority and Performance Evaluation

MIKE Y. HOUH, KENNETH M. EPSTEIN, and JOE LEE

ABSTRACT

Traffic impact attenuators play a vital role in highway safety. When properly engineered, located, and maintained, impact attenuators can result in the savings of numerous lives and reductions in property damage. However, there have been widespread improper application and use of impact attenuators. The study on which this paper is based focused on location, design, and maintenance of traffic impact attenuators. As a case study, the current management and operational procedures used for the Highway Safety Appurtenances Replacement program of the District of Columbia were evaluated. Traffic characteristics and roadway environmental features that contribute to roadside collisions were identified and analyzed using a multiple regression technique. The analysis revealed that street light luminance, truck percentage, radius of horizontal roadway curvature, and attenuator offset distance are the factors most correlated to roadside collision incidents.

Impact attenuator systems are defined by AASHTO as "protective systems which prevent errant vehicles from impacting hazards by either smoothly decelerating the vehicle to a stop when hit head-on, or by redirecting it away from the hazard for glancing impacts." Many sources have shown that the installation of impact attenuators has proven to be a cost-effective means of saving lives and reducing the severity of fixed-object accidents. For example, the 1981 Highway Safety Stewardship Report (1) ranked it as the second most effective highway safety improvement, with a benefit-to-cost ratio of 3.1. Despite the effectiveness of impact attenuators, problems in location, design, field inspection, maintenance, and performance evaluation still exist.

In the past most crash cushions were installed at locations where the most obvious crash potential existed. As these obviously dangerous locations are improved, the most cost-effective locations in which to install future impact attenuators become less apparent. It can be difficult to identify these locations through the application of common sense and engineering judgment. Recent field reviews of impact

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attenuators in the District of Columbia reveal that the recently installed crash cushions have lower damage rates than do those at older locations. This finding is consistent with the nationwide trend of declining benefit-to-cost ratios for impact attenuator installations. To continue locating impact attenuators in a cost-effective manner, definite procedures are needed for determining disproportionate representations of accidents associated with roadway features and traffic conditions.

The performance of a crash cushion during impact is dependent on its precrash, on-site condition. In other words, small changes in the field installation from the original design or improper maintenance may totally destroy the intended performance. It is therefore desirable that damage or on-site defects be reported and corrected immediately. However, because the frequency with which attenuators are struck varies by season and location, a fixed-schedule field check may never meet the urgently needed fast-reporting requirement. To eliminate the risk that a damaged crash cushion remains undetected or unrepaired until another accident occurs, it is critical to determine the optimal frequency of field inspections and maintenance.

Another problem involved in the evaluation of impact attenuator performance is that a large portion of attenuator collisions go unreported because a well-designed crash cushion can reduce the severity of damage and allow the errant vehicle to be driven away after impact. In 1983 it was found that only 24 attenuator-related accidents were reported by the District of Columbia's Metropolitan Police Department. Thus reported accidents do not reflect the actual number of accidents involving impact attenuators and the extent of damage. To obtain the real picture of impact attenuator performance in the field, an attenuator data inventory was created to collect all available information for analysis.

RESEARCH OBJECTIVES

The goal of this study was to determine problems of location, design, and maintenance associated with the District of Columbia's impact attenuation systems. As a case study, the current management and operational procedures used for the Highway Safety Appurtenances Replacement (HSAR) program were evaluated.

The first objective of this study was to develop procedures for checking the performance of impact attenuators installed on D.C. highways.

The second objective was to evaluate the impact frequency and damage severity for each study location and to determine a maintenance schedule and an inspection interval for the D.C. attenuator system in order to reduce the possibility of unprotected hits.

The third objective was to identify the major descriptors that represent the relationships between crash cushion accidents and roadway environmental factors, so that a mathematical model could be developed to predict the accident potential of a specific location.

SCOPE OF STUDY AND DATA COLLECTION PROCEDURE

The study was restricted to the 88 impact attenuators located on those D.C. highways that were opened to traffic when the study began. All of the field data for each location were collected in 1,000-ft roadway sections measured upstream from the attenuators. The roadway and traffic descriptors downstream from the attenuators are considered to have less effect on attenuator accidents. Therefore this information is not recorded except for roadway illumination data, which may affect a driver's visibility. The illumination data were measured in 600- x 100-ft rectangular areas centered at the nose of each attenuator. A total of 29 data items were collected in the attenuator inventory. These data items were as follows:

A. Permanent data
  1. Basic attenuator information (BAI)
    - Assigned location number
    - Location name
    - Quadrant code
    - Maryland grid number
    - Attenuator type
    - Street classification
    - Installation and/or upgrade costs
    - Installation and/or upgrade dates
    - Field check route number
  2. Traffic control and characteristics (TCC)
    - Average daily traffic (ADT)
    - Truck percentage
    - Attenuator design speed
    - No-passing zone length (including cross hatch area)
    - Number of traffic lanes
    - Traffic control signs
    - Object signs and indications
  3. Geometric factors and pavement conditions (GFPC)
    - Curb height
    - Gradient
    - Horizontal alignment
    - Offset distance
    - Pavement conditions and skid index
    - Street light luminance
    - Object type

B. Accident and maintenance records
  1. Detailed damage condition (number of hits)
  2. Number of times that maintenance was performed
  3. Maintenance costs
  4. Reported accidents
  5. Number of injuries

During FY 1984 (October 1, 1983, to September 30, 1984), a total of 10 field inspections were conducted. It was found that the study locations had been struck 158 times (excluding brush hits). Only 19 attenuator-related accidents were reported by the various police agencies, about 12 percent of the total hits. These accidents included 11 injury accidents and 8 property-damage-only (PDO) accidents. None of these accidents resulted in fatalities, and only 13 injuries were reported. Sixty-seven repairs have been performed on the attenuators, about 43 percent of the total number that were damaged. Of the 158 hits, 96 (61 percent) occurred at locations considered fully protected and 62 (39 percent) occurred at unprotected locations.

RESEARCH PROCEDURE AND METHODOLOGY

After the data were collected, the following methods were used to gain the research objectives:

1. Before-and-after study to determine the effectiveness of the D.C. attenuator system,
2. Benefit-cost analyses to evaluate the economic effectiveness of each attenuator installation,
3. Frequency study to optimize the inspection and maintenance schedules for attenuator system operation,
4. Multiple regression and correlation analyses to determine the influences of roadway and traffic factors on attenuator accidents, and

5. Bivariate sortings to analyze the influences of nonnumerical factors on attenuator accidents.

The before-and-after study is a comparison between the expected accident rate and the actual reported accident rate. In this study, the number of attenuator hits observed in the field was used as the expected accidents. The calculations were done by a spread-sheet program. The computed results were then interpolated on the Poisson curve chart to determine whether the changes were significant at the selected level of significance (Figure 1). To convert the number of hits to accident severities, the following assumptions were used:

- Any visible damage on the attenuator, except brush hits, is treated as a property damage accident;
- Any head-on impact with a deceleration force higher than 10 g is treated as an injury accident;
- Any angular impact with a deceleration force higher than 5 g is treated as an injury accident;
- A strike near the rear end of an attenuator is treated as an injury accident;
- Brush hits are ignored because the driver may successfully avoid the fixed object if no crash cushion is installed; and
- No fatality was assumed because, in the D.C. accident rating procedure, fatalities are rated equally with injuries.

These assumptions are made on the basis of information provided by the 1975 FHWA publication, Crash Cushions: Selection Criteria and Design (2) and the 1984 report, Safer Bridge Railings (3).

The benefit-cost analysis computes the payback ratio of each dollar spent on attenuators. The reduction of accident costs (i.e., the difference between expected accident costs and reported accident costs) is the real contribution of the attenuator system. The reductions were treated as the benefit in the benefit-to-cost (B/C) ratio calculation. The 1982 motor vehicle accident costs ($8,000 for an injury and $1,090 for a PDO accident), published by the National Safety Council (NSC), were used to estimate the benefits. Only one injury was assumed for each injury accident. This is a conservative estimate given that the average vehicle occupancy in the District of Columbia is 1.41 persons per vehicle. These motor vehicle accident costs were treated as the present worth when the calculations were made. These costs were then directly converted into the equivalent uniform annual benefit (EUAB). The attenuator costs include capital costs, maintenance costs, and expenses for inspection and reporting. An annual interest rate of 8 percent and a service life of 10 (for sand barrel systems) to 12 (for other types of crash cushions) years were used to determine the capital recovery factor (CRF) for different attenuator sites. No salvage value was included in the calculation of equivalent uniform annual cost (EUAC) because the cost to remove an old attenuator is higher than its residual value.

The frequency studies involve calculations of the probability of damage occurring during a specific inspection interval and the required repair time for each attenuation system before the second hit takes place. Assuming that attenuator accidents are random events, the probability of occurrence of an accident at a particular location during a specific time period can be predicted by using the Poisson equation if the annual number of hits is known. In this case, the Poisson distribution can be expressed as follows (4):

$$P(n) = H^n * e^{-H}/n!$$

where

H = number of hits expected in t days,
n = accident occurrences of interest,
e = natural logarithm base (e = 2.71828), and
n! = n factorial (1*2*3 . . . n).

For each impact attenuator location, the expected number of hits during t days (H) can be calculated as

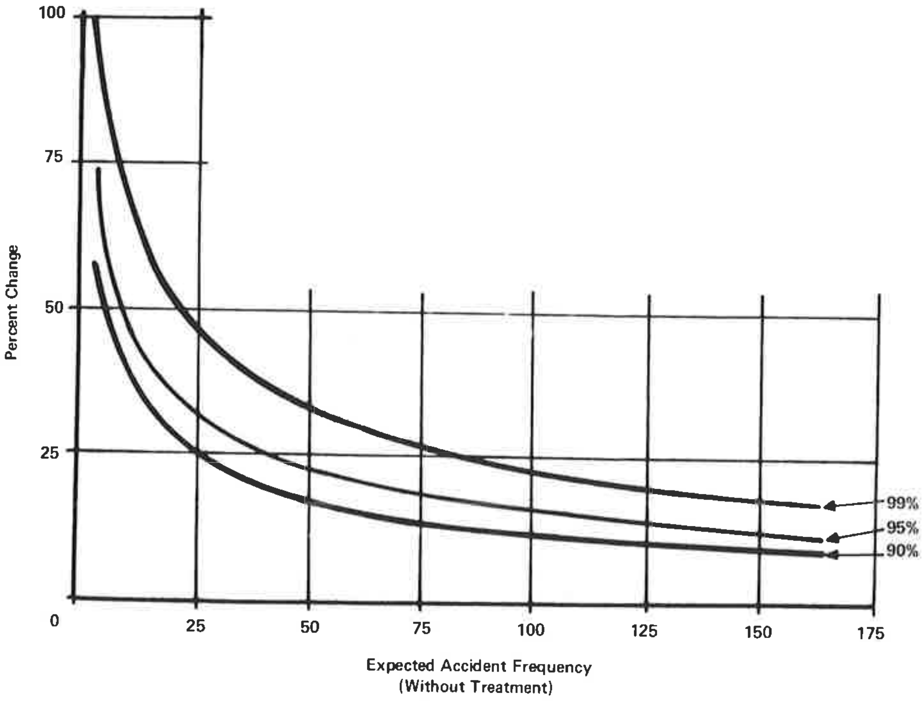

FIGURE 1 Poisson curves.

$$H = \bar{H} * t/365$$

where $\bar{H}$ is the annual number of hits and t is the time period of interest.

The attenuator maintenance interval such that no more than one hit (t_{0-1}) will occur can be determined by the following formulas:

$$t_0 = -[365 * \ln P(0)]/\bar{H}$$

$$t_1 = -[365 * \ln P(1)]/\bar{H}$$

$$t_{0-1} = t_0 + t_1$$

where t_0 is the time interval during which no hit occurs and t_1 is the time interval during which only one hit occurs.

For each location, 10 sets of data with 12 roadway and traffic variables were included in the multiple regression and correlation analyses. Two dependent variables, the number of hits and accident cost, were tested against the 12 independent variables. A brief description of these variables follows.

Dependent variables
Y1 = Number of hits
Y2 = Accident costs for attenuator locations
Independent variables
X1 = Average daily traffic (1,000s)
X2 = Truck percentage
X3 = Attenuator design speed (average running speed + 5 mph)
X4 = Number of approaching traffic lanes
X5 = Pavement service index
X6 = Curb height (in.)
X7 = Roadway gradient variance (percentage)
X8 = Horizontal curvature radius (100 ft)
X9 = Street light luminance (footcandles)
X10 = Length of no-passing zone (100 ft)
X11 = Offset distance (ft)
X12 = Skid index measured at 40 mph

Both correlation and regression analyses were performed on an IBM PC microcomputer using the ABstat software package (5). The major parameters of the analyses included the correlation coefficient (r_{ij}), regression coefficient (R), coefficient of determination (R^2), beta weight (b_{ij}), F-test (F), and a probability factor called "PROB" that indicates the chance of tested observations being drawn from a zero-coefficient population. Correlation coefficients will range from -1 to +1. A coefficient of -1 means perfect negative correlation, a coefficient of 0 means absolutely no correlation, and a coefficient of +1 means perfect positive correlation. In other words, the closer the coefficient is to 0, the weaker the correlation, disregarding the negative or positive relationship. R^2 shows that the proportion of variation in the predicted dependent variable can be explained by independent variables in a regression equation. R indicates how closely the change in a dependent variable is related to the change in the independent variables. The F-test is an indicator of the goodness of fit of the linear equation. The F-test shows whether the observed multiple correlation is due to sampling fluctuation or measurement error. The beta weights indicate the relationship between one independent variable and the predicted dependent variable with other variables held constant (6).

The purpose of bivariate analyses is to group the nonnumerical data on attenuator sites into analytical formats. These data included the following categories:

- C1: Street classifications (six)
- C2: Attenuator types (five)
- C3: Traffic lane distribution
- C4: Fixed-object types
- C5: Usage of object markers
- C6: Existence of traffic control devices

These data cannot be translated into numeric formats. Therefore they cannot be analyzed through numerical analyses. However, their existence can affect the performance of impact attenuators and should not be neglected in this study. These variables were tested against other variables through tabular forms.

FINDINGS AND INTERPRETATIONS

Before-and-After Analysis

The results of the before-and-after study are shown in Figure 2. After the accident numbers and traffic exposures were entered, the spread sheet automatically computed the reduction rate for different accident measures. The tested percentage changes were obtained from the Poisson curve chart (Figure 1). The 95 percent curve was selected for this calculation. If the calculated percentage is greater than the value interpolated from the curve, the change is significant. The data in Figure 2 indicate that the installation of impact attenuators has significantly reduced both the frequency and the severity of accidents at these attenuator sites. It is generally agreed by most engineers that the installation of crash cushions reduces the space in which to recover that a driver has available. Thus accident frequency may increase after a crash cushion is installed. However, the results of this study show that the installation of impact attenuators can reduce the total number of reported accidents.

Benefit-Cost Analysis

Table 1 gives the calculation process of EUAC for each study location. The results show that the D.C. attenuator system has an average service life of 6.75 years. In FY 1984 the cost to the D.C. Government to maintain each crash cushion was $1,778.36. Table 2 includes the calculations of EUAB and the B/C ratio. The mean B/C ratio for all study locations was found to be 4.97. The citywide impact attenuator B/C ratio, which is the result of total EUAB divided by total EUAC, was found to be 4.4.

Inspection and Maintenance Frequency Analysis

The probabilities of no damage P(0) or damage from only one hit P(1) can be directly calculated from Table 3. The data in the table indicate that, by using the current 36-day average inspection interval, D.C. engineers have found 98.61 percent of possible damage before the second hit occurs. For the location subject to the highest number of hits (seven hits), there is a probability of about 84.75 percent that the damage was detected before the successive strike took place. The maintenance frequencies for the 99, 95, and 90 percent levels of confidence were calculated for all study locations (Table 4). An average maintenance interval of 10.65 days was found for the D.C. impact attenuator system at the 95 percent level of confidence. Actually, the required maintenance frequency varies with location. The location that has been hit the most times (seven hits) should be repaired immediately (2.67 days).

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      PROJECT LOCATION :  THE DISTRICT'S 88 INPACT ATTENUATORS
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I           I        I        I EXPECTEDI DIFFERENCE  I           I
I FREQUENCY IBEFORE  IAFTER   I ACCIDENTI-------------I           I
I           I        I(ACTUAL)IFREQUENCYI  N   I  %   I           I
I-----------I--------I--------I---------I------I------I           I
I  TOTAL    I        I        I         I      I      I           I
I ACC. NO.  I     158I      19I      158I  139 I0.87  I           I
I-----------I--------I--------I---------I------I------I           I
I  FATAL    I        I        I         I      I      I           I
I ACC. NO.  I       0I       0I        0I    0 I  0   I           I
I-----------I--------I--------I---------I------I------I           I
I  INJURY   I        I        I         I      I      I           I
I ACC. NO.  I      81I      11I       81I   70 I0.86  I           I
I-----------I--------I--------I---------I------I------I           I
I    PDO    I        I        I         I      I      I           I
I ACC. NO.  I      77I       8I       77I   69 I0.89  I           I
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I   NO. OF  I        I        I         I      I      I           I
I INJURIES  I      81I      13I       81I   68 I0.83  I           I
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I1000 VOLUMEI997.545 I997.545 I 997.545 I             I   TEST    I
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I   RATE    IBEFORE  IAFTER   IACCIDENT I      I      ICONFIDENCE I
I           I        I        I  RATE   I  %   I  %   I    95%    I
I-----------I--------I--------I---------I------I------I-----------I
I  TOTAL    I        I        I         I      I      I           I
I ACC. RATE I  0.158 I  0.019 I    0.158 I0.879 I0.12  ISIGNIFICANTI
I-----------I--------I--------I---------I------I------I-----------I
I  FATAL    I        I        I         I      I      I           I
I ACC. RATE I  0.000 I  0.000 I    0.000 I0.000 I      I           I
I-----------I--------I--------I---------I------I------I-----------I
I  INJURY   I        I        I         I      I      I           I
I ACC. RATE I  0.081 I  0.011 I    0.081 I0.864 I0.18  ISIGNIFICANTI
I-----------I--------I--------I---------I------I------I-----------I
I    PDO    I        I        I         I      I      I           I
I ACC. RATE I  0.077 I  0.008 I    0.077 I0.896 I0.19  ISIGNIFICANTI
I-----------I--------I--------I---------I------I------I-----------I
I  INJURY   I        I        I         I      I      I           I
I   RATE    I  0.081 I  0.013 I    0.081 I0.839 I0.18  ISIGNIFICANTI
I-----------I--------I--------I---------I------I------I-----------I
I           I        I        I         I      I      I           I
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FIGURE 2 Measure of effectiveness data comparison work sheet.

TABLE 1 D.C. Attenuation System, Annual Cost Estimation (FY 1983)

Attenuator No.	Installation Cost ($)	Age of Attenuator (years)	Age After Upgrade (years)	Degree of Freedom	Annual Capital Cost ($)	Maintenance No.	Maintenance Material Cost ($)	Maintenance Labor Cost ($)	Inspection Cost ($)	Reporting Cost ($)	EUAC ($)
1	11,900.00	16	9	0.1490	1,773.10	2	548.26	50.00	57.20	14.77	2,443.33
2	11,900.00	16	9	0.1490	1,773.10	1	42.00	25.00	57.20	14.77	1,912.07
3	7,000.00	16	9	0.1490	1,043.00	1	176.00	25.00	57.20	14.77	1,315.97
4	6,000.00	16	9	0.1490	894.00	1	0.00	25.00	57.20	14.77	990.97
5	8,000.00	14		0.0000	0.00	0	0.00	0.00	57.20	14.77	71.97
6	8,000.00	14		0.0000	0.00	0	0.00	0.00	57.20	14.77	71.97
7	10,000.00	12		0.1327	1,327.00	1	138.94	25.00	57.20	14.77	1,562.91
8	3,600.00	12	9	0.1490	536.40	2	346.00	50.00	57.20	14.77	1,004.37
10	30,000.00	12		0.1327	3,981.00	0	0.00	0.00	57.20	14.77	4,052.97
11	30,000.00	12		0.1327	3,981.00	1	0.00	50.00	57.20	14.77	4,102.97
12	30,000.00	12	8	0.1490	4,470.00	1	0.00	25.00	57.20	14.77	4,566.97
13	30,000.00	11		0.1327	3,981.00	0	0.00	0.00	57.20	14.77	4,052.97
14	30,000.00	12		0.1327	3,981.00	1	240.00	50.00	57.20	14.77	4,342.97
15	30,000.00	12		0.1327	3,981.00	1	196.00	50.00	57.20	14.77	4,298.97
16	6,000.00	11	9	0.1490	894.00	1	717.00	25.00	57.20	14.77	1,707.97
17	7,921.00	11	9	0.1490	1,180.23	2	409.36	50.00	57.20	14.77	1,711.56
18	7,921.00	11	9	0.1490	1,180.23	2	198.00	50.00	57.20	14.77	1,500.20
19	8,300.00	10		0.1327	1,101.41	1	176.72	75.00	57.20	14.77	1,425.10
20	4,000.00	10		0.1490	596.00	3	509.20	75.00	57.20	14.77	1,252.17
21	11,500.00	9		0.1327	1,526.05	0	0.00	0.00	57.20	14,77	1,598.02
22	11,500.00	9		0.1327	1,526.05	0	0.00	0.00	57.20	14.77	1,598.02
23	2,150.00	9		0.1490	320.35	1	0.00	25.00	57.20	14.77	417.32
24	4,237.00	9		0.1490	631.31	1	198.00	25.00	57.20	14.77	926.28
25	4,237.00	9		0.1490	631.31	1	163.20	25.00	57.20	14.77	891.48
26	4,237.00	9		0.1490	631.31	2	217.80	50.00	57.20	14.77	971.08
27	4,237.00	9		0.1490	631.31	2	375.52	50.00	57.20	14.77	1,128.80
28	4,237.00	9		0.1490	631.31	1	0.00	25.00	57.20	14.77	728.28
29	4,237.00	9		0.1490	631.31	2	86.60	50.00	57.20	14.77	839.88
30	4,237.00	9		0.1490	631.31	3	1,534.00	125.00	57.20	14.77	2,362.28
31	4,237.00	9		0.1490	631.31	1	0.00	25.00	57.20	14.77	728.28
32	11,393.00	10		0.1490	1,697.56	1	742.00	25.00	57.20	14.77	2,536.53

TABLE 1 Continued

Attenuator No.	Installation Cost ($)	Age of Attenuator (years)	Age After Upgrade (years)	Degree of Freedom	Annual Capital Cost ($)	Maintenance			Inspection Cost ($)	Reporting Cost ($)	EUAC ($)
						No.	Material Cost ($)	Labor Cost ($)			
33	742.00	8		0.1490	110.56	1	0.00	50.00	57.20	14.77	232.53
34	18,000.00	8		0.1327	2,388.60	1	248.00	75.00	57.20	14.77	2,783.57
35	2,570.00	7		0.1490	382.93	2	1,434.00	175.00	57.20	14.77	2,063.90
36	18,000.00	7		0.1327	2,388.60	0	0.00	0.00	57.20	14.77	2,460.57
37	18,000.00	7		0.1327	2,388.60	0	0.00	0.00	57.20	14.77	2,460.57
38	7,250.00	7		0.1327	962.08	1	346.00	50.00	57.20	14.77	1,430.05
39	7,250.00	7		0.1490	1,080.25	2	1,236.00	125.00	57.20	14.77	2,513.22
40	5,000.00	6		0.1490	745.00	1	371.00	25.00	57.20	14.77	1,212.97
41	5,000.00	6		0.1490	745.00	1	173.00	25.00	57.20	14.77	1,014.97
42	9,000.00	6		0.1327	1,194.30	1	30.00	12.50	57.20	14.77	1,308.77
43	9,000.00	6		0.1327	1,194.30	1	30.00	12.50	57.20	14.77	1,308.77
48	9,000.00	7		0.1327	1,194.30	0	0.00	12.50	57.20	14.77	1,278.77
49	9,000.00	7		0.1327	1,194.30	0	0.00	12.50	57.20	14.77	1,278.77
50	9,000.00	7		0.1327	1,194.30	0	0.00	0.00	57.20	14.77	1,266.27
51	9,000.00	7		0.1327	1,194.30	1	0.00	50.00	57.20	14.77	1,316.27
52	2,150.00	5		0.1490	320.35	0	0.00	0.00	57.20	14.77	392.32
53	2,150.00	5		0.1490	320.35	0	0.00	0.00	57.20	14.77	392.32
54	2,150.00	5		0.1490	320.35	0	0.00	0.00	57.20	14.77	392.32
55	19,000.00	5		0.1327	2,521.30	1	346.00	125.00	57.20	14.77	3,064.27
56	3,700.00	5		0.1490	551.30	0	0.00	0.00	57.20	14.77	623.27
57	6,000.00	4		0.1490	894.00	0	0.00	0.00	57.20	14.77	965.97
58	4,250.00	4		0.1490	633.25	1	0.00	25.00	57.20	14.77	730.22
59	19,000.00	4		0.1327	2,521.30	0	0.00	0.00	57.20	14.77	2,593.27
60	6,500.00	4		0.1490	968.50	3	1,311.00	75.00	57.20	14.77	2,426.47
61	4,000.00	4		0.1490	596.00	1	717.00	25.00	57.20	14.77	1,409.97
62	4,250.00	4		0.1490	633.25	0	0.00	0.00	57.20	14.77	750.22
63	5,000.00	6		0.1490	745.00	1	915.00	75.00	57.20	14.77	1,806.97
64	4,250.00	4		0.1490	633.25	0	0.00	0.00	57.20	14.77	705.22
65	4,250.00	4		0.1490	633.25	0	0.00	0.00	57.20	14.77	705.22
66	4,250.00	4		0.1490	633.25	1	298.00	12.50	57.20	14.77	1,015.72
68	6,590.00	4		0.1490	981.91	1	173.00	12.50	57.20	14.77	1,239.38
69	6,700.00	4		0.1490	998.30	1	0.00	12.50	57.20	14.77	1,082.77
70	5,000.00	4		0.1490	745.00	0	0.00	0.00	57.20	14.77	816.97
71	4,250.00	4		0.1490	633.25	0	0.00	0.00	57.20	14.77	705.22
72	19,000.00	4		0.1327	2,521.30	1	594.00	75.00	57.20	14.77	3,262.27
73	19,000.00	4		0.1327	2,521.30	1	594.00	50.00	57.20	14.77	3,237.27
74	19,000.00	3		0.1327	2,521.30	0	0.00	0.00	57.20	14.77	2,593.27
75	28,000.00	3		0.1327	3,715.60	0	0.00	0.00	57.20	14.77	3,787.57
76	9,000.00	3		0.1327	1,194.30	0	0.00	0.00	57.20	14.77	1,266.27
77	9,000.00	3		0.1327	1,194.30	0	0.00	0.00	57.20	14.77	1,266.27
78	11,400.00	3		0.1327	1,512.78	1	0.00	12.50	57.20	14.77	1,597.25
79	28,000.00	3		0.1327	3,715.60	0	0.00	0.00	57.20	14.77	3,787.57
80	30,000.00	3		0.1327	3,981.00	1	0.00	12.50	57.20	14.77	4,065.47
81	28,000.00	3		0.1327	3,715.60	0	0.00	0.00	57.20	14.77	3,787.57
82	19,000.00	3		0.1327	2,521.30	0	0.00	0.00	57.20	14.77	2,593.27
83	19,000.00	3		0.1327	2,521.30	0	0.00	0.00	57.20	14.77	2,593.27
85	6,000.00	2		0.1490	894.00	0	0.00	0.00	57.20	14.77	965.97
86	15,000.00	2		0.1327	1,990.50	1	214.80	50.00	57.20	14.77	2,327.27
87	18,000.00	2		0.1327	2,388.60	0	0.00	0.00	57.20	14.77	2,460.57
88	19,000.00	2		0.1327	2,521.30	0	0.00	0.00	57.20	14.77	2,593.27
89	750.00	2		0.1490	111.75	0	0.00	0.00	57.20	14.77	183.72
90	19,000.00	2		0.1327	2,521.30	1	0.00	25.00	57.20	14.77	2,618.27
91	5,000.00	2		0.1490	745.00	2	1,903.00	100.00	57.20	14.77	2,819.97
93	19,000.00	2		0.1327	2,521.30	0	0.00	0.00	57.20	14.77	2,593.27
107	8,000.00	2		0.1327	1,061.60	0	0.00	0.00	57.20	14.77	1,133.57
108	8,000.00	2		0.1327	1,061.60	0	0.00	0.00	57.20	14.77	1,133.57
109	2,150.00	1		0.1490	320.35	1	594.00	25.00	57.20	14.77	1,011.32
Total	958,533.00				129,207.53	67	18,542.40	2,412.50	5,033.60	1,299.76	156,495.79
Average	10,892.42	6.75			1,468.27	0.76	210.71	27.41	57.20	14.77	1,778.36

TABLE 2 D.C. Impact Attenuation System, Benefit-Cost Analysis

Attenuator No.	No. of Hits	Expected Accident Number and Severity			Reported Accident Number and Severity			Estimated Benefit ($)	EUAC ($)	Benefit-to-Cost Ratio
		No.	Injury	Cost ($)	No.	Injury	Cost ($)			
1	4	4	1	12,360.00	1	0	1,090.00	11,270.00	2,443.33	4.61
2	0	0	0	0.00	0	0	0.00	0.00	1,912.07	0.00
3	3	3	0	3,270.00	1	0	1,090.00	2,180.00	1,315.97	1.66
4	2	2	1	10,180.00	0	0	0.00	10,180.00	990.97	10.27
5	6	6	2	22,540.00	2	1	10,180.00	12,360.00	71.97	NA
6	4	4	0	4,360.00	0	0	0.00	4,360.00	71.97	NA
7	1	1	1	9,090.00	0	0	0.00	9,090.00	1,562.91	5.82
8	5	5	2	21,450.00	0	0	0.00	21,450.00	1,004.37	21.36
10	4	4	3	28,360.00	0	0	0.00	28,360.00	4,052.97	7.00
11	2	2	1	10,180.00	0	0	0.00	10,180.00	4,102.97	2.48
12	3	3	3	27,270.00	0	0	0.00	27,270.00	4,566.97	5.97

TABLE 2 Continued

Attenuator No.	No. of Hits	Expected Accident Number and Severity			Reported Accident Number and Severity			Estimated Benefit ($)	EUAC ($)	Benefit-to-Cost Ratio
		No.	Injury	Cost ($)	No.	Injury	Cost ($)			
13	3	3	3	27,270.00	0	0	0.00	27,270.00	4,052.97	6.73
14	1	1	0	1,090.00	0	0	0.00	1,090.00	4,342.97	0.25
15	1	1	1	9,090.00	0	0	0.00	9,090.00	4,298.97	2.11
16	5	5	4	37,450.00	0	0	0.00	37,450.00	1,707.97	21.93
17	2	2	2	18,180.00	1	2	17,090.00	1,090.00	1,711.56	0.64
18	1	1	0	1,090.00	0	0	0.00	1,090.00	1,500.20	0.73
19	2	2	2	18,180.00	0	0	0.00	18,180.00	1,425.10	12.76
20	6	6	4	38,540.00	2	2	18,180.00	20,360.00	1,252.17	16.26
21	1	1	0	1,090.00	0	0	0.00	1,090.00	1,598.02	0.68
22	0	0	0	0.00	0	0	0.00	0.00	1,598.02	0.00
23	2	2	1	10,180.00	0	0	0.00	10,180.00	417.32	24.39
24	1	1	0	1,090.00	0	0	0.00	1,090.00	926.28	1.18
25	3	3	1	11,270.00	0	0	0.00	11,270.00	891.48	12.64
26	5	5	3	29,450.00	0	0	0.00	029,450.00	971.08	30.33
27	6	6	2	22,540.00	0	0	0.00	22,540.00	1,128.80	19.97
28	2	2	2	18,180.00	0	0	0.00	18,180.00	728.28	24.96
29	2	2	1	10,180.00	0	0	0.00	10,180.00	839.88	12.12
30	7	7	3	31,630.00	0	0	0.00	31,630.00	2,362.28	13.39
31	1	1	0	1,090.00	0	0	0.00	1,090.00	728.28	1.50
32	2	2	0	2,180.00	0	0	0.00	2,180.00	2,536.53	0.86
33	2	2	1	10,180.00	1	1	9,090.00	1,090.00	232.53	4.69
34	2	2	1	10,180.00	0	0	0.00	10,180.00	2,783.57	3.66
35	4	4	4	36,360.00	1	1	9,090.00	27,270.00	2,063.90	13.21
36	0	0	0	0.00	0	0	0.00	0.00	2,460.57	0.00
37	0	0	0	0.00	0	0	0.00	0.00	2,460.57	0.00
38	3	3	0	3,270.00	0	0	0.00	3,270.00	1,430.05	2.29
39	3	3	2	19,270.00	1	0	1,090.00	18,180.00	2,513.22	7.23
40	1	1	1	9,090.00	0	0	0.00	9,090.00	1,212.97	7.49
41	1	1	1	9,090.00	0	0	0.00	9,090.00	1,014.97	8.96
42	0	0	0	0.00	0	0	0.00	0.00	1,308.77	0.00
43	0	0	0	0.00	0	0	0.00	0.00	1,308.77	0.00
48	2	2	1	10,180.00	1	1	9,090.00	1,090.00	1,278.77	0.85
49	0	0	0	0.00	0	0	0.00	0.00	1,278.77	0.00
50	1	1	0	1,090.00	0	0	0.00	1,090.00	1,266.27	0.86
51	0	0	0	0.00	0	0	0.00	0.00	1,316.27	0.00
52	0	0	0	0.00	0	0	0.00	0.00	392.32	0.00
53	0	0	0	0.00	0	0	0.00	0.00	392.32	0.00
54	0	0	0	0.00	0	0	0.00	0.00	392.32	0.00
55	3	3	1	11,270.00	1	1	9,090.00	2,180.00	3,064.27	0.71
56	0	0	0	0.00	0	0	0.00	0.00	623.27	0.00
57	0	0	0	0.00	0	0	0.00	0.00	965.97	0.00
58	3	3	1	11,270.00	0	0	0.00	11,270.00	730.22	15.43
59	1	1	1	9,090.00	0	0	0.00	9,090.00	2,593.27	3.51
60	5	5	3	29,450.00	0	0	0.00	29,450.00	2,426.47	12.14
61	3	3	3	27,270.00	2	0	2,180.00	25,090.00	1,409.97	17.79
62	2	2	0	2,180.00	0	0	0.00	2,180.00	705.22	3.09
63	1	1	1	9,090.00	0	0	0.00	9,090.00	1,806.97	5.03
64	0	0	0	0.00	0	0	0.00	0.00	705.22	0.00
65	0	0	0	0.00	0	0	0.00	0.00	705.22	0.00
66	0	0	0	0.00	0	0	0.00	0.00	1,015.72	0.00
68	1	1	0	1,090.00	0	0	0.00	1,090.00	1,239.38	0.88
69	1	1	0	1,090.00	0	0	0.00	1,090.00	1,082.77	1.01
70	0	0	0	0.00	0	0	0.00	0.00	816.97	0.00
71	1	1	0	1,090.00	0	0	0.00	1,090.00	705.22	1.55
72	6	6	2	22,540.00	1	1	9,090.00	13,450.00	3,262.27	4.12
73	3	3	2	19,270.00	0	0	0.00	19,270.00	3,237.27	5.95
74	0	0	0	0.00	0	0	0.00	0.00	2,593.27	0.00
75	1	1	0	1,090.00	0	0	0.00	1,090.00	3,787.57	0.29
76	0	0	0	0.00	0	0	0.00	0.00	1,266.27	0.00
77	0	0	0	0.00	0	0	0.00	0.00	1,266.27	0.00
78	5	5	2	21,450.00	2	2	18,180.00	3,270.00	1,597.25	2.05
79	0	0	0	0.00	0	0	0.00	0.00	3,787.57	0.00
80	1	1	1	9,090.00	1	1	9,090.00	0.00	4,065.47	0.00
81	1	1	1	9,090.00	1	0	1,090.00	8,000.00	3,787.57	2.11
82	2	2	0	2,180.00	0	0	0.00	2,180.00	2,593.27	0.84
83	0	0	0	0.00	0	0	0.00	0.00	2,593.27	0.00
85	1	1	0	1,090.00	0	0	0.00	1,090.00	965.97	1.13
86	3	3	3	27,270.00	0	0	0.00	27,270.00	2,327.27	11.72
87	0	0	0	0.00	0	0	0.00	0.00	2,460.57	0.00
88	0	0	0	0.00	0	0	0.00	0.00	2,593.27	0.00
89	0	0	0	0.00	0	0	0.00	0.00	183.72	0.00
90	1	1	0	1,090.00	0	0	0.00	1,090.00	2,618.27	0.42
91	6	6	5	46,540.00	0	0	0.00	46,540.00	2,819.97	16.50
93	0	0	0	0.00	0	0	0.00	0.00	2,593.27	0.00
107	0	0	0	0.00	0	0	0.00	0.00	1,133.57	0.00
108	0	0	0	0.00	0	0	0.00	0.00	1,133.57	0.00
109	1	1	1	9,090.00	0	0	0.00	9,090.00	1,011.32	8.99
Total	158	158	81	820,220.00	19	13	124,710.00	695,510.00	156,495.78	
Average	1.80	1.80	0.92	9,320.68	0.22	0.15	1,417.16	7,903.52	1,778.36	4.97

Note: Citywide B/C ratio = 4.44.

TABLE 3 Probability of Damage Occurring During Inspection Intervals (36 days)

Attenuator No.	Type	No. of Hits	ADT	Period (days)	Inspection Period (days)	Expected Hits (H)	Probability of No Hit (0)	Probability of One Hit P(1)	Probability of No and One Hit	Probability of More Than One Hit
1	S16	4	64,800	365	36	0.3945	0.6740	0.2659	0.9399	9.0601
2	S17	0	64,800	365	36	0.000	1.0000	0.0000	1.0000	0.0000
3	S26	3	59,040	365	36	0.2959	0.7439	0.2201	0.9640	0.0360
4	S15	2	23,200	365	36	0.1973	0.8210	0.1619	0.9829	0.0171
5	HS4	6	37,380	365	36	0.5918	0.5533	0.3275	0.8808	0.1192
6	HS4	4	20,000	365	36	0.3945	0.6740	0.2659	0.9399	0.0601
7	HC	1	57,200	365	36	0.0986	0.9061	0.0894	0.9954	0.0046
8	S9	5	34,920	365	36	0.4932	0.6107	0.3012	0.9119	0.0881
10	HSB	4	27,300	365	36	0.3945	0.6740	0.2659	0.9399	0.0601
11	HSB	2	27,000	365	36	0.1973	0.8210	0.1619	0.9829	0.0171
12	S5	3	8,000	365	36	0.2959	0.7439	0.2201	0.9640	0.0360
13	HSB	3	29,000	365	36	0.2959	0.7439	0.2201	0.9640	0.0360
14	HSB	1	13,000	365	36	0.0986	0.9061	0.0894	0.9954	0.0046
15	HSB	1	49,000	365	36	0.0986	0.9061	0.0894	0.9954	0.0046
16	S7	5	23,200	365	36	0.4932	0.6107	0.3012	0.9119	0.0881
17	S4	2	36,600	365	36	0.1973	0.8210	0.1619	0.9829	0.0171
18	S4	1	39,180	365	36	0.0986	0.9061	0.0894	0.9954	0.0046
19	HC	2	64,800	365	36	0.1973	0.8210	0.1619	0.9829	0.0171
20	S11	6	42,800	365	36	0.5918	0.5533	0.3275	0.8808	0.1192
21	HC	1	29,000	365	36	0.0986	0.9061	0.0894	0.9954	0.0046
22	HC	0	16,980	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
23	S9	2	19,800	365	36	0.1973	0.8210	0.1619	0.9829	0.0171
24	S10	1	25,800	365	36	0.0986	0.9061	0.0894	0.9554	0.0046
25	S11	3	34,200	365	36	0.2959	0.7439	0.2201	0.9640	0.0360
26	S8	5	22,700	365	36	0.4932	0.6107	0.3012	0.9119	0.0881
27	S9	6	29,400	365	36	0.5918	0.5533	0.3275	0.8808	0.1192
28	S8	2	27,300	365	36	0.1973	0.8210	0.1619	0.9829	0.0171
29	S3	2	27,300	365	36	0.1973	0.8210	0.1619	0.9829	0.0171
30	S6	7	29,400	365	36	0.6904	0.5014	0.3462	0.8475	0.1525
31	S9	1	51,624	365	36	0.0986	0.9061	0.0894	0.9954	0.0046
32	S5	2	15,000	365	36	0.1973	0.8210	0.1619	0.9829	0.0171
33	S3	2	39,190	365	36	0.1973	0.8210	0.1619	0.9829	0.0171
34	HC	2	9,780	365	36	0.1973	0.8210	0.1619	0.9829	0.0171
35	S4	4	22,740	365	36	0.3945	0.6740	0.2659	0.9399	0.0601
36	HC	0	2,160	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
37	HC	0	2,160	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
38	G6	3	12,720	365	36	0.2959	0.7439	0.2201	0.9640	0.0360
39	S7S7	3	17,940	365	36	0.2959	0.7439	0.2201	0.9640	0.0360
40	S10	1	19,500	365	36	0.0986	0.9061	0.0894	0.9954	0.0046
41	S10	1	19,500	365	36	0.0986	0.9061	0.0894	0.9954	0.0046
42	HC	0	9,300	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
43	HC	0	9,300	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
48	HC	2	29,580	365	36	0.1973	0.8210	0.1619	0.9829	0.0171
49	HC	0	29,380	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
50	G6	1	34,560	365	36	0.0986	0.9061	0.0894	0.9954	0.0046
51	G6	0	34,560	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
52	S10	0	9.780	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
53	S9	0	9,780	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
54	S10	0	9,780	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
55	G6S5	3	47,220	365	36	0.2959	0.7439	0.2201	0.9640	0.0360
56	S10	0	47,220	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
57	S12	0	45,220	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
58	S9	3	34,200	365	36	0.2959	0.7439	0.2201	0.9640	0.0360
59	G6S2	1	34,200	365	36	0.0986	0.9061	0.0894	0.9954	0.0046
60	S17	5	41,400	365	36	0.4932	0.6107	0.3012	0.9119	0.0881
61	S13	3	47,220	365	36	0.2959	0.7439	0.2201	0.9640	0.0360
62	S10	2	46,200	365	36	0.1973	0.8210	0.1619	0.9829	0.0171
63	S10	1	46,200	365	36	0.0986	0.9061	0.0894	0.9954	0.0046
64	S11	0	46,200	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
65	S10	0	46,200	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
66	S10	0	46,200	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
68	S17	1	41,400	365	36	0.0986	0.9061	0.0894	0.9954	0.0046
69	S18	1	14,200	365	36	0.0986	0.9061	0.0894	0.9954	0.0046
70	S11	0	47,220	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
71	S11	1	46,200	365	36	0.0986	0.9061	0.0894	0.9955	0.0045
72	B5S3	6	41,400	365	36	0.5918	0.5533	0.3275	0.8808	0.1192
73	S6S2	3	47,220	365	36	0.2959	0.7439	0.2201	0.9640	0.0360
74	G4	0	47,280	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
75	H14	1	39,000	365	36	0.0986	0.9061	0.0894	0.9955	0.0045
76	G3	0	14,040	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
77	G3	0	14,040	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
78	G5S3	5	110,220	365	36	0.4932	0.6107	0.3012	0.9119	0.0881
79	H14	0	37,380	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
80	H14	1	12,600	365	36	0.0986	0.9061	0.0894	0.9954	0.0046
81	H14	1	59,040	365	36	0.0986	0.9061	0.0894	0.9954	0.0046
82	G5	2	21,000	365	36	0.1973	0.8210	0.1619	0.9640	0.0171
83	G3	0	26,000	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
85	S11	1	30,000	365	36	0.0986	0.9061	0.0894	0.9954	0.0046
86	G3	3	11,400	365	36	0.2959	0.7439	0.2201	0.9640	0.0360
87	HC	0	9,780	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
88	G5	0	25,200	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
89	S3	0	42,800	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
90	G2	1	1,200	365	36	0.0986	0.9061	0.0894	0.9954	0.0046
91	S11	6	34,200	365	36	0.5918	0.5533	0.3275	0.8808	0.1192
93	G3	0	30,000	365	36	0.0000	1.0000	0.0000	1.0000	0.0000

TABLE 3 Continued

Attenuator No.	Type	No. of Hits	ADT	Period (days)	Inspection Period (days)	Expected Hits (H)	Probability of No Hit (0)	Probability of One Hit P(1)	Probability of No and One Hit	Probability of More Than One Hit
107	G2S1	0	12,600	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
108	G2S1	0	12,600	365	36	0.0000	1.0000	0.0000	1.0000	0.0000
109	S4	1	30,000	365	36	0.0986	0.9061	0.0894	0.9954	0.0046
Total		158								
Average		1.795		365	36	0.17708	0.8377	0.1483	0.9861	0.0139
Citywide		158		365	36	15.5835	.0000	.0000	.0000	1.0000

TABLE 4 Frequency Table for Attenuator Maintenance

Attenuator No.	Type	No. of Hits	Period (days)	Annual Average Hits	Action Days for P(0) = 0.99	Action Days for P(0) = 0.95	Action Days for P(0) = 0.90
1	S16	4	365	4	0.92	4.68	9.61
2	S17	0	365	0	NA	NA	NA
3	S26	3	365	3	1.22	6.24	12.82
4	S15	2	365	2	1.83	9.36	19.23
5	HS4	6	365	6	0.61	3.12	6.41
6	HS4	4	365	4	0.92	4.68	9.61
7	HC	1	365	1	3.67	18.72	38.46
8	S9	5	365	5	0.73	3.74	7.69
10	HSB	4	365	4	0.92	4.68	9.61
11	HSB	2	365	2	1.83	9.36	19.23
12	S5	3	365	3	1.22	6.24	12.82
13	HSB	3	365	3	1.22	6.24	12.82
14	HSB	1	365	1	3.67	18.72	38.46
15	HSB	1	365	1	3.67	18.72	38.46
16	S7	5	365	5	0.73	3.74	7.69
17	S4	2	365	2	1.83	9.36	19.23
18	S4	1	365	1	3.67	18.72	38.46
19	HC	2	365	2	1.83	9.36	19.23
20	S11	6	365	6	0.61	3.12	6.41
21	HC	1	365	1	3.67	18.72	38.46
22	HC	0	365	0	NA	NA	NA
23	S9	2	365	2	1.83	9.36	19.23
24	S10	1	365	1	3.67	18.72	38.46
25	S11	3	365	3	1.22	6.24	12.82
26	S8	5	365	5	0.73	3.74	7.69
27	S9	6	365	6	0.61	3.12	6.41
28	S8	2	365	2	1.83	9.36	19.23
29	S3	2	365	2	1.83	9.36	19.23
30	S6	7	365	7	0.52	2.67	5.49
31	S9	1	365	1	3.67	18.72	38.46
32	S5	2	365	2	1.83	9.36	19.23
33	S3	2	365	2	1.83	9.36	19.23
34	HC	2	365	2	1.83	9.36	19.23
35	S4	4	365	4	0.92	4.68	9.61
36	HC	0	365	0	NA	NA	NA
37	HC	0	365	0	NA	NA	NA
38	G6	3	365	3	1.22	6.24	12.82
39	S7	3	365	3	1.22	6.24	12.82
40	S10	1	365	1	3.67	18.72	38.46
41	S10	1	365	1	3.67	18.72	38.46
42	HC	0	365	0	NA	NA	NA
43	HC	0	365	0	NA	NA	NA
48	HC	2	365	2	1.83	9.36	19.23
49	HC	0	365	0	NA	NA	NA
50	G6	1	365	1	3.67	18.72	38.46
51	G6	0	365	0	NA	NA	NA
52	S10	0	365	0	NA	NA	NA
53	S9	0	365	0	NA	NA	NA
54	S10	0	365	0	NA	NA	NA
55	G6S4	3	365	3	1.22	6.24	12.82
56	S10	0	365	0	NA	NA	NA
57	S12	0	365	0	NA	NA	NA
58	S9	3	365	3	1.22	6.24	12.82
59	G6S2	1	365	1	3.67	18.72	38.46
60	S17	5	365	5	0.73	3.74	7.69
61	S13	3	365	3	1.22	6.24	12.82
62	S10	2	365	2	1.83	9.36	19.23
63	S10	1	365	1	3.67	18.72	38.46
64	S11	0	365	0	NA	NA	NA
65	S10	0	365	0	NA	NA	NA
66	S10	0	365	0	NA	NA	NA
68	S17	1	365	1	3.67	18.72	38.46
69	S18	1	365	1	3.67	18.72	38.46
70	S11	0	365	0	NA	NA	NA
71	S11	1	365	1	3.67	18.72	38.46
72	G5S3	6	365	6	0.61	3.12	6.41
73	G6S2	3	365	3	1.22	6.24	12.82
74	G4	0	365	0	NA	NA	NA

TABLE 4 Continued

Attenuator No.	Type	No. of Hits	Period (days)	Annual Average Hits	Action Days for P(0) = 0.99	Action Days for P(0) = 0.95	Action Days for P(0) = 0.90
75	HI4	1	365	1	3.67	18.72	38.46
76	G3	0	365	0	NA	NA	NA
77	G3	0	365	0	NA	NA	NA
78	G5S3	5	365	5	0.73	3.74	7.69
79	HI4	0	365	0	NA	NA	NA
80	HI4	1	365	1	3.67	18.72	38.46
81	HI4	1	365	1	3.67	18.72	38.46
82	G5	2	365	2	1.83	9.36	19.23
83	G3	0	365	0	NA	NA	NA
85	S11	1	365	1	3.67	18.72	38.46
86	G3	3	365	3	1.22	6.24	12.82
87	HC	0	365	0	NA	NA	NA
88	G5	0	365	0	NA	NA	NA
89	S3	0	365	0	NA	NA	NA
90	G2	1	365	1	3.67	18.72	38.46
91	S11	6	365	6	0.61	3.12	6.41
93	G3	0	365	0	NA	NA	NA
107	G2S1	0	365	0	NA	NA	NA
108	G2S1	0	365	0	NA	NA	NA
109	S4	1	365	1	3.67	18.72	38.46
Total		158			125.25	639.22	1,313.02
Average		1.80	365		2.09	10.65	21.88

Note: NA means the data are not available; however, the damage should be repaired as soon as possible.

Correlation and Multiple Regression Analyses

The correlation matrix (Figure 3) indicates that the relationships between the 12 independent variables and the number of hits are quite logical. For example, it shows that ADT, truck percentage, and number of lanes are highly correlated ($r > 0.5$). The interrelationship between pavement rating and skid index is also strong. The strongest negative correlation (-0.36885) was found between speed and street light luminance.

The relationships between the dependent variable, number of hits (Y1), and the 12 independent variables can be described by the following regression model:

$$\begin{aligned} Y1 = 0.3329 &- 0.0104\ X1 + 1.0892\ X2 + 0.0111\ X3 \\ &- 0.0911\ X4 - 0.1296\ X5 - 0.0102\ X6 \\ &- 0.1011\ X7 - 0.2030\ X8 - 1.5653\ X9 \\ &- 0.1811\ X10 - 0.1361\ X11 + 0.0612\ X12 \end{aligned}$$

$Se = 1.3578$, $R = 0.7347$, $R^2 = 0.5398$
$F = 7.2332$, $dof = [12,74]$, $PROB = 0.0000$

This multiple regression equation shows that truck percentage (X2), horizontal curvature (X8), street light luminance (X9), length of no-passing zone (X10), and attenuator offset (X11) are strongly correlated with the number of hits (Y1). However, length of no-passing zone (X10) cannot pass the F-test at the 5 percent level of significance. A comparison between the calculated F-value and the F-test table value shows that the multiple regression model passes the 5 percent level of significance. The coefficient of determination indicates that this model can explain 53.98 percent of the total variation in the number of hits. When each single independent variable was tested against Y1, it was found that the significant independent variables can be ranked according to priority as follows:

X9 = Street light luminance, negatively correlated;
X2 = Truck percentage, positively correlated;
X8 = Length of horizontal curvature radius, negatively correlated; and
X11 = Offset distance, negatively correlated.

Theoretically, a predictive model should not include the insignificant variables. The reconstruction of this model using the four significant variables at the 5 percent level of significance showed the following information:

$$\begin{aligned} Y1 = 2.8706 &+ 0.8129\ X2 - 0.2131\ X8 \\ &- 1.7401\ X9 - 0.1538\ X11 \end{aligned}$$

$Se = 1.3920$, $R = 0.6812$, $R^2 = 0.4640$
$F = 17.7478$, $dof = [4,82]$, $PROB = 0.0000$

	X1 ADT	X2 TRUCK	X3 SPEED	X4 LANES	X5 PVT	X6 CURB	X7 GRADIENT	X8 RADIUS	X9 LIGHT	X10 MARKING	X11 OFFSET	X12 SKID	Y1 HITS
X1	1												
X2	0.5308	1											
X3	0.4216	0.3611	1										
X4	0.6818	0.5758	0.4201	1									
X5	0.0779	-0.1032	0.0316	-0.1373	1								
X6	0.0191	0.1490	-0.1633	0.1594	-0.0955	1							
X7	-0.0395	0.0356	-0.0361	-0.0915	0.1295	-0.0786	1						
X8	0.0947	0.1292	0.2164	0.1449	-0.0510	-0.1211	-0.0458	1					
X9	-0.2057	-0.1359	-0.3689	-0.1328	0.0368	0.0590	0.0852	0.3048	1				
X10	0.3284	0.1880	0.3249	0.2049	0.0682	0.2504	-0.1829	0.1257	-0.0431	1			
X11	0.1469	0.0141	0.3327	-0.0459	0.2474	-0.2075	0.0192	0.1562	-0.0809	0.2833	1		
X12	0.2122	-0.0012	0.2140	0.0388	0.5883	-0.2415	0.0810	-0.1373	-0.1168	0.1011	0.1972	1	
Y1	0.0916	0.3329	0.0908	0.1477	-0.0953	0.0170	-0.1111	-0.4092	-0.4548	0.1917	-0.2767	0.1201	1

FIGURE 3 Correlation matrix—number of hits versus independent variables X1-X12.

Comparison with the table value of the F-distribution showed that this reconstructed model is also significant. However, the interpretation power of this model decreases to 46.4 percent because of the dropout of the insignificant variables.

The multiple regression equation for accident cost (Y2) and the other 12 independent variables can pass the F-test at the 5 percent level of significance. However, the equation can only interpret 39.22 percent of accident cost change. This low value of R cast doubt on the usefulness of the model for the purpose of predicting accident severity.

Bivariate Analyses

The bivariate analyses of variables generated the following findings:

- Locations on Interstates, freeways, and expressways, which account for about 73 percent of the total locations, took 85 percent of the total hits. This finding is due primarily to lower street light illumination.
- During the study period, the Hi-dro Cell sandwich and sand barrel locations suffered the most hits, with a ratio of 3.0 and 2.13 per location, respectively.
- Attenuators located at gore areas had 4.4 times the number of hits that were sustained by the ones located at one side of a roadway. Attenuators located on the right side of a highway were twice as likely to be hit as were those on the left side. Locations with three to five approaching lanes were more likely to be hit.
- Bridge gores, tunnel gores, and retaining walls had impact frequencies of 4, 3, and 2.4 hits, respectively, per location per year.
- Locations with object markers were hit 50 percent less often than locations without them.

CONCLUSION

For more than a decade impact attenuators have been used by many state and local transportation agencies to prevent errant vehicles from colliding with rigid roadside hazards. However, limited research has been conducted in this field because attenuators are usually placed on roadways with high speeds and volumes where the number of collisions represents a small percentage of the total traffic. The attenuator's capabilities for reducing accident frequency and severity have made a study more difficult because few accident records are available. Despite these difficulties, the District of Columbia has provided an ideal climate for conducting this study because of its limited geographic area and large number of attenuator installations.

Through extensive data collection, a comprehensive procedure was developed and is currently used by the D.C. Government to determine improvement priorities and to evaluate the performance of impact attenuators. This procedure consists of before-and-after studies, benefit-cost analyses, damage frequency studies, multiple regression and correlation analyses, and bivariate sortings.

On the basis of this procedure and the crash cushion accident and impact records of FY 1984, the following conclusions can be drawn from this study:

1. Street light illumination, truck percentage, radius of horizontal roadway curvature, and offset distance were the major factors that determined the frequency of damage to impact attenuators. This finding may imply that driver's visibility, vehicle width, and effective roadway width for travel play major roles in roadside collision incidents, given that, during the study period, 15 (79 percent) of the 19 total reported crash cushion accidents occurred during nighttime hours. The predictive regression models can be used to select and to assign priority to the candidate locations if these descriptors can be measured in the field.
2. The schedules for field inspection and maintenance should vary with impact frequency and the selected level of significance. In the District of Columbia it was found that by conducting monthly field investigations, the engineer can be 95 percent confident that about 99 percent of the damage was detected before the second hit occurred.
3. The conventional before-and-after study and benefit-cost analysis are usually conducted 3 years after a highway facility is built. These methods cannot serve the need for continuous evaluation of impact attenuators because most of the D.C. crash cushions were installed long before the study was conducted. Therefore these methods were modified to compare actual accident measures with expected measures. The before-and-after study shows that the installation of impact attenuators has significantly reduced both the frequency and the severity of accidents in the District of Columbia. The citywide benefit-to-cost ratio for the District of Columbia attenuator system was found to be 4.4, which is higher than the 3.1 national average.

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