# Rumble Strips In Connecticut:

# A Before/After Analysis of Safety Benefits

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**Division of Traffic Engineering**
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**16. Abstract**

According to the U.S. Department of Transportation's Federal Highway Administration (FHWA), run-off-road crashes account for nearly one-third of deaths and serious injuries annually. Inattentive driving has been linked to these types of crashes (FHWA, 2001). As a remedial measure, rumble strips have been installed on roadways to alert inattentive drivers that deviate from the travel way. This research attempted to measure the safety benefits achieved from rumble strips along roadways in Connecticut. Safety benefits are considered a reduction in single-vehicle, fixed object, run-off-the-road accidents. From the results of the data description, the number of "rumble strip related" (single vehicle, fixed object, run-off-the road) accidents decreased as well as the number of "asleep" and injury/fatal accidents.

The study incorporated a methodology that uses comparative sections to predict the "what if" scenario of the number of accidents that would have occurred if rumble strips had not been installed. The statistical analysis calculated an index of effectiveness based on accident data for the rumble strip and comparison sections. The index of effectiveness showed a decrease in "rumble strip related" accidents for the collected accident data.

This study used the Comparison Group methodology to predict rumble strip accidents, without reference to causal factors such as driver behavior, accident reporting, and traffic counts. The study concludes with guidance to researchers about causal factors such as traffic that can be incorporated into future rumble strip studies.

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Safety, Pavement, Rumble Strips,
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# METRIC CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO METRIC MEASURES

| SYMBOL | WHEN YOU KNOW | MULTIPLY BY | TO FIND | SYMBOL |
|---|---|---|---|---|
| **LENGTH** | | | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| **AREA** | | | | |
| in$^2$ | square inches | 645.2 | square millimeters | mm$^2$ |
| ft$^2$ | square feet | 0.093 | square meters | m$^2$ |
| yd$^2$ | square yards | 0.836 | square meters | m$^2$ |
| mi$^2$ | square miles | 2.59 | square kilometers | km$^2$ |
| ac | Acres | 0.405 | hectares | ha |
| **MASS** | | | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb.) | 0.907 | megagrams<br>(metric ton) | Mg<br>(t) |
| **VOLUME** | | | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| ft$^3$ | cubic feet | 0.028 | cubic meters | m$^3$ |
| yd$^3$ | cubic yards | 0.765 | cubic meters | m$^3$ |
| **TEMPERATURE (exact)** | | | | |
| ºF | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | ºC |
| **ILLUMINATION** | | | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/m$^2$ | cd/m$^2$ |
| **FORCE and PRESSURE or STRESS** | | | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/in$^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |

## APPROXIMATE CONVERSIONS FROM METRIC MEASURES

| SYMBOL | WHEN YOU KNOW | MULTIPLY BY | TO FIND | SYMBOL |
|---|---|---|---|---|
| **LENGTH** | | | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| **AREA** | | | | |
| mm$^2$ | square millimeters | 0.0016 | square inches | in$^2$ |
| m$^2$ | square meters | 10.764 | square feet | ft$^2$ |
| m$^2$ | square meters | 1.195 | square yards | yd$^2$ |
| km$^2$ | square kilometers | 0.386 | square miles | mi$^2$ |
| ha | hectares (10,000 m$^2$) | 2.47 | acres | ac |
| **MASS** | | | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg<br>(t) | megagrams (1000 kg)<br>(metric ton) | 1.103 | short tons (2000 lb) | T |
| **VOLUME** | | | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| m$^3$ | cubic meters | 35.314 | cubic feet | ft$^3$ |
| m$^3$ | cubic meters | 1.307 | cubic yards | yd$^3$ |
| **TEMPERATURE (exact)** | | | | |
| ºC | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | ºF |
| **ILLUMINATION** | | | | |
| Lx | lux | 0.0929 | foot-candles | fc |
| cd/m$^2$ | candela/m$^2$ | 0.2919 | foot-Lamberts | fl |
| **FORCE and PRESSURE or STRESS** | | | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/in$^2$ |

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## Introduction

Run-off road accidents account for a significant portion of all traffic accidents on a national scale. According to the U.S. Department of Transportation's Federal Highway Administration (FHWA), run-off-road crashes account for nearly one-third of deaths and serious injuries annually. Inattentive driving has been linked to these types of crashes (FHWA, 2001). As a remedial measure, rumble strips have been installed on roadways to alert inattentive drivers that deviate from the travelway. When traversed, rumble strips emit an audible and tactile warning that is heard and felt by distracted drivers. Most rumble strips are placed on roadway shoulders, in advance of potential roadside hazards. The placement of rumble strips provides vehicles with time to take corrective action. Safety benefits, such as a reduction in accidents, may vary in each location that has rumble strips. The purpose of this report is to discuss the safety impacts derived from the installation of rumble strips on Connecticut's roadways. An analysis of accident data will also be presented and any findings and implications will also be presented.

## Rumble Strips in Connecticut

Rumble strips were initially installed on test sections along Connecticut's expressways in 1994. Personnel from the Connecticut Department of Transportation (ConnDOT) evaluated these rumble strips for any effects on the existing pavement, including wear, drainage and durability of the pavement cuts. ConnDOT's Office of Maintenance reviewed the test sections during the winter months, and expressed concerns for the break-up of some of the test section rumble strips due the characteristics of Class 114 pavement. This type of pavement is a very lightweight, open graded, bituminous concrete. Class 114 pavement is no longer used in Connecticut; rather, Class 1 pavement, a bituminous mix, is used. After the preliminary observations were made, rumble strips were then installed along limited-access highways. Appendix A displays a list of limited-access roadway sections with adequate shoulder width for rumble strips. There are a total of 2200 shoulder miles; 1400 shoulder miles of interstate roadway, and 800 shoulder miles of non-interstate expressways, are suitable for rumble strips.

In the fall of 1996, three hundred shoulder miles of rumble strips were installed on various freeway sections in Connecticut. An additional 400 miles of rumble strips were installed on sections of interstate highways in 1997, and another 120 shoulder miles were added in 1998. Also, in 2000, another 200 shoulder miles of rumble strips were installed. The approximate rumble strip locations throughout the state are shown in Figure 1.

There were two major factors for selecting of rumble strip locations. The first consideration was the projected maintenance schedule for pavement resurfacing. For the two initial rumble strip projects, roadway locations were chosen if the roadway had been resurfaced within the previous five years. In subsequent rumble strip projects, locations were selected if they had been recently resurfaced. Another consideration was the available existing shoulder roadway width. A minimum shoulder width of at least three feet was used to select rumble strip locations. The reason for this minimum width was due to the width of the rumble strip pavement cut, the available distance from the edge-line, and the desirable distance from the edge of the pavement. The left shoulders on a few sections of roadways, as well as the right shoulders in some climbing lanes, and most shoulders on the Merritt Parkway do not meet the minimum three foot shoulder requirement.

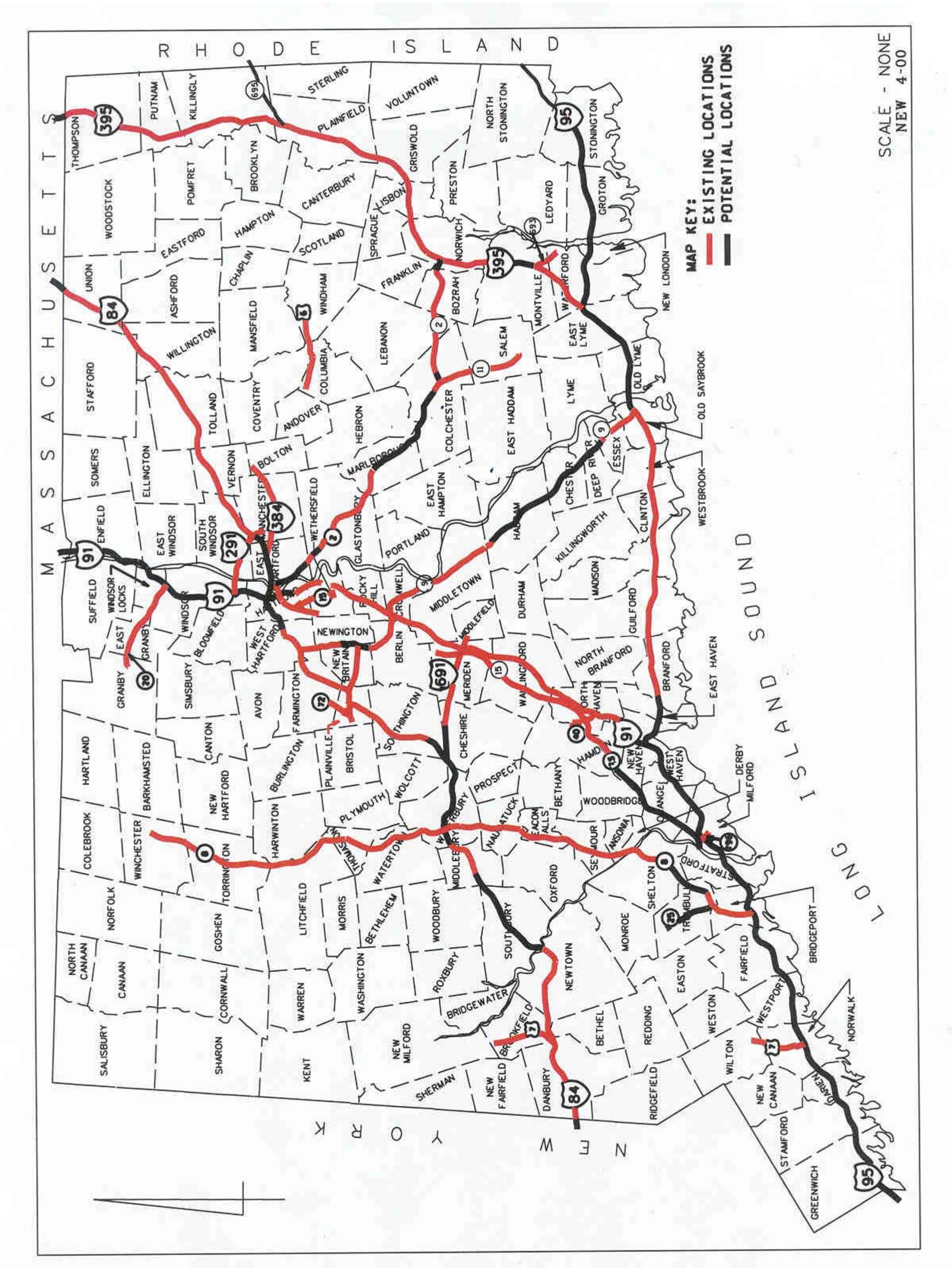

**Figure 1. Connecticut Rumble Strip Locations on Limited Access Highways.**

## Rumble Strip Specifications

## Rumble Strip Specification

The physical dimension of the milled-in rumble strips installed on Connecticut's roadways is displayed in Figure 2. The design and dimension of the rumble strips in Connecticut are similar as those developed by the Pennsylvania Turnpike Commission. The length of rumble strips is approximately 16 inches, and the width of the rumble strips is approximately seven inches with a depth between 1/2 and 5/8 inches. Figure 3 displays a zoomed photographic image of the actual rumble strip milled in the pavement.

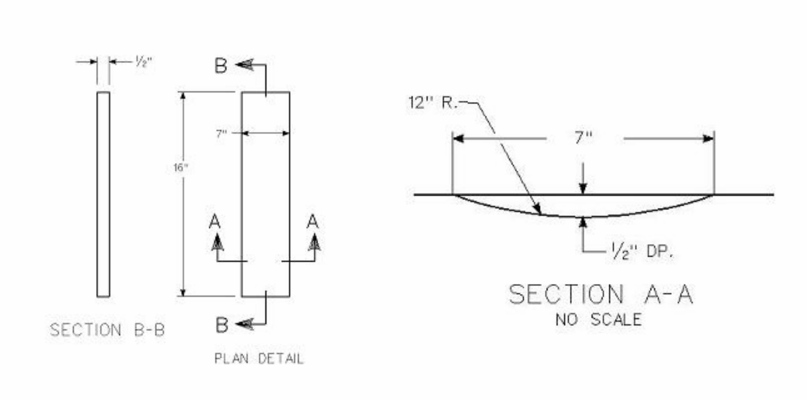

**Figure 2. The Physical Dimensions and Typical Cross-Section of a Rumble Strip.**

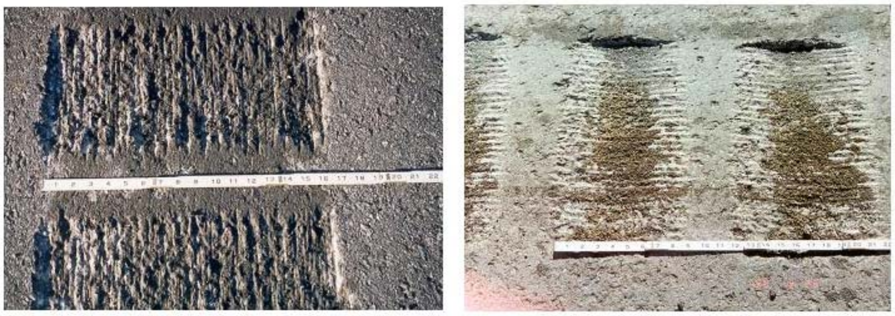

**Figure 3. The Rumble Strip Dimensions in Connecticut.**

In Connecticut, rumble strips are offset 12 inches from the right shoulder and 6 inches offset from the left shoulder. Figure 4 shows the typical offset design for the rumble strips on left and right shoulders. Figure 5 displays actual photographs of rumble strips on the left and right shoulders in Connecticut.

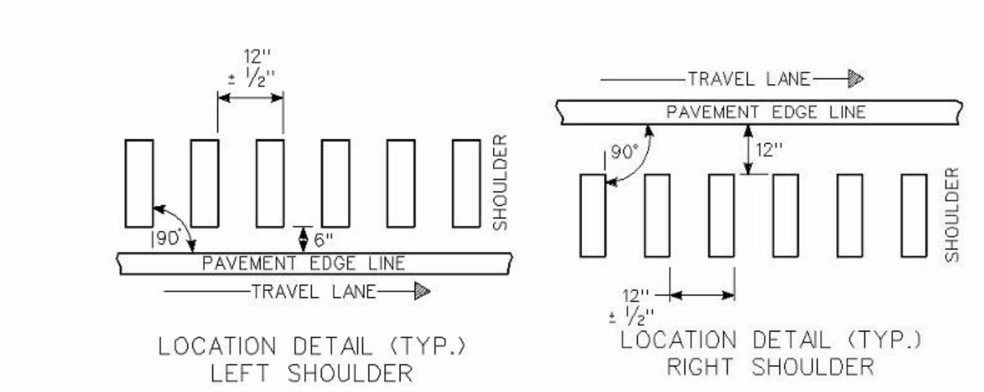

**Figure 4. Rumble Strips Detail for Right and Left Shoulder Offsets.**

**Figure 5. Rumble Strips on the Left and Right Shoulders in Connecticut.**

Another location consideration for installing rumble strips was the proximity to vehicle sensor wire of closed-loop systems and weigh-in-motion stations. In Connecticut, rumble strips are interrupted where the sensor wires cross the shoulders as shown in Figure 6.

**Figure 6. Rumble Strips Interrupted by Loop Detectors.**

Also, rumble strips are interrupted where catch basins are located. Typically, rumble strips are placed two feet from either side of the catch basin, as displayed in Figure 7.

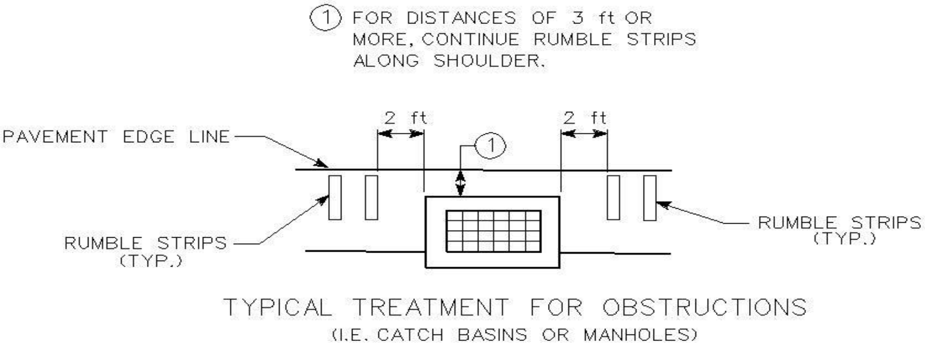

**Figure 7. The Typical Treatment of Rumble Strips in the Vicinity of Catch Basins.**

Rumble strips are not installed on bridge decks, and are discontinued on narrow shoulders of the bridge approach. Rumble strips are not installed on shoulder adjacent to acceleration or deceleration lanes, and also not installed at the beginning of an off-ramp or end of an on-ramp. Figures 8 and 9 depict these rumble strip location specifications.

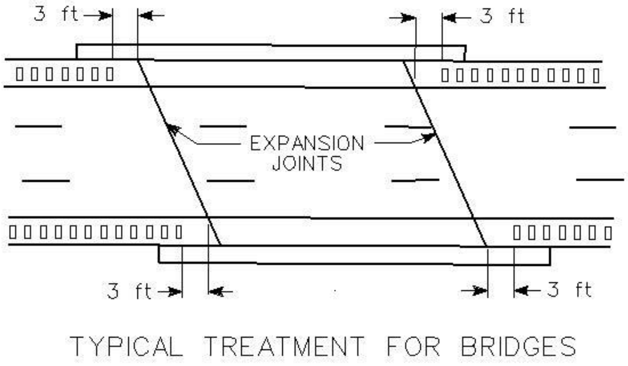

**Figure 8. The Interruption of Rumble Strips in the Vicinity of a Bridge Deck.**

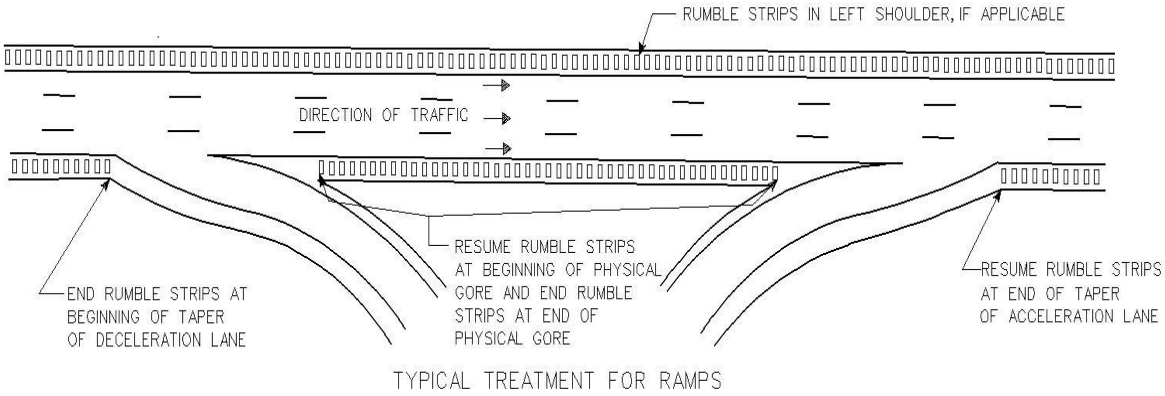

**Figure 9. Rumble Strip Placement in the Vicinity of Ramps.**

## Noise Issues and Installation Costs

Once rumble strips were installed along the limited-access roads in Connecticut, several noise complaints were received from residents in the near vicinity. Since receiving the noise complaints, the offset for rumble strips in the right shoulder roadway was modified from six to 12 inches. The reason for this change was to decrease the incidence of vehicles falsely traversing the rumble strips, particularly drivers that tend to veer into the edge of the travelway. As a result of the offset revision, noise complaints eventually decreased.

Rumble strips were principally installed by dedicated construction projects. Rumble strips were also added as a bid item in resurfacing projects. The approximate construction cost per shoulder mile of installation of rumble strips ranged from $1150 to $1300 for the first two rumble strip projects, slightly higher for the next two smaller projects. These costs were calculated based on the estimates from the first rumble strip project in Connecticut. The estimates include the cost of installation, signing, attenuation systems, and maintenance and protection of traffic. Over the years, the cost has decreased to less than $1000 per shoulder mile.

## Literature Review

Earlier studies examined various aspects of rumble strips including the physical dimensions of the rumble strips, and accident experience. There is some variation concerning the design and location specifications of rumble strips, as dictated by various geographic characteristics, roadway geometry, as well as operational experience throughout the U. S. However, there is agreement among transportation officials regarding the escalation of run-off-the-road accidents and the safety challenges of alerting "drowsy", inattentive drivers. Previous rumble strip research consisted of qualitative studies that present tabulations of accident data, with discussions of the implications. However, very few studies have employed a statistical analysis to either predict or measure the safety benefits from deployment of rumble strips. This next section will discuss some of the existing literature.

The National Highway Traffic Safety Administration (NHTSA) and the National Center of Sleep Disorders Research (NCSDR) developed a report that provides direction for an educational campaign to combat drowsy driving. It is difficult to identify the "drowsy" driver, as evidence is not measurable by means of a blood or breath test as in alcohol-related crashes. The evidence for the "drowsy" driving is from inference, rather than from conclusive test results. Roadway crashes related to sleepiness have the characteristics of being single vehicle, the vehicle leaves roadway, the crash is severe, and the driver does not attempt to avoid the crash (NHTSA & NCSDR, 2000). As Perrillo (1998) reported, educational campaigns to inform the public about dangers of driver fatigue and "drowsy" driving have been initiated, and preventative run-off-the-road technologies such as continuous rumble strips on roadway shoulders have been identified as a source of crash mitigation.

The concept in the design of rumble strips is to provide a method of alerting the fatigued or "drowsy" driver in advance of the approaching obstacle. Cheng, Gonzalez, and Christensen (2000) link driver inattentiveness to fatigue and drowsiness, and the deviation of the vehicle from the roadway. The driver's reaction as the vehicle deviates from the roadway is a critical determinant for an accident occurrence. The shoulder width provides the driver with a reaction area to either return to the travel lane or continue outside of the travel lane. Thus, wider shoulders may provide more reactionary time for vehicles that traverse the rumble strips.

Audible and vibration pavement surface treatments, such as rumble strips, have been used for nearly fifty years (FHWA, 2001). In 1962, a study was performed by the Minnesota Department of Transportation to investigate the effect of rumble strips at rural stop locations. Although the design and placement has changed significantly since that time, the concept of reducing accidents and increasing driver awareness has remained the same (Owens, 1962). During the mid-1980's, researchers from the Pennsylvania Turnpike Commission developed a "Sonic Nap Alert Pattern" (SNAP), as a way to mitigate the large number of drift-off-road accidents. SNAP is a narrow, continuous rumble strip located on the right shoulder, outside of the edge line of pavement. As a result of installing SNAP on roadways, the Pennsylvania Turnpike experienced a significant reduction in drift-off-road accidents.

Since 1990, the New York State Thruway Authority has been installing shoulder rumble strips. Under the STAR (Shoulder Treatment for Accident Reduction) program, there was a reduction in drift-off-road accidents (Golden, 1994). Wood (1994) claims that similar results could be experienced on toll-ways, the Interstate highway system and other rural roadways. As reported by Perrillo (1998), the New York State Department of Transportation (NYSDOT) installs milled rumble strips on rural Interstate highway and parkways in New York.

There are three types of rumble strips installed on roadways in the U.S: milled, rolled or formed. Each differs by installation method, size, shape, placement or spacing on the roadway, and emitted noise when traversed (Perrillo, 1998). According to nationwide survey conducted by Isackson (2000), 31 states responded that they use continuous milled shoulder rumble strips. Only a few states use rolled rumble strips or are developing their own design standard. Milled rumble strips are preferred because of their method of installation, the minimal effects on pavement structures, and the increased noise and vibrations produced. Milled rumble strips can be installed on new, existing or reconstructed asphalt shoulders. Rolled rumble strips are narrow depressions pressed into new or reconstructed hot asphalt using steel pipes welded to drums that pass over the pavement. Rolled rumble strips have maintenance and construction problems including the premature degradation of the shoulder, and the potential for emitting less noise and vibrations once the pavement is worn. Formed rumble strips are installed in Portland Cement Concrete (PCC), and are not used in the northeastern U.S. because of the frequent use of asphalt shoulders (Perrillo, 1998). In Connecticut, continuous milled rumble strips are installed along roadway shoulders.

A Federal Highway Administration (FHWA) technical advisory on roadway shoulder rumble strips investigated the design and installation practices among states. Many states have participated in early rumble strip application efforts, including Illinois, Utah, Pennsylvania, New York, and California. The basic dimensions of milled rumble strips are a width of seven inches, a length of sixteen inches, and a 1/2- inch depth. Milled rumble strips are offset from the edge of the travel lane between four and 12 inches (FHWA, 2001). As mentioned earlier, Connecticut uses the same dimensions as described in the FHWA advisory.

There is some variation among states concerning the offset from the edge line of the travel lane. Some states have an offset of 30 inches on wide shoulders for maintenance and work zone traffic; however, the disadvantage of this lengthy offset is that the further the rumble strip is from the travel lane, the less recovery area beyond the rumble strip. Thus, there is a reduction in the amount of reaction time for vehicles to take corrective action once the rumble strip is traversed. In many states, rumble strips are installed without interruption except for gaps at exit and entrance ramps, street intersections and major driveways (FHWA, 2001). In Connecticut, rumble strips are interrupted in the vicinity of catch basins, sensor wire of closed-loop detectors or weigh-in-motion stations and on and off ramps.

There are ongoing tests with alternative roadway safety designs to alert drivers and reduce the number of accidents. The Mississippi Department of Transportation (MDOT) is currently experimenting with a design consisting of the combination of rumble strips and roadway striping. The rumble strips are a raised texture enhanced by the retro-reflective property of the pavement marking (FHWA, 2002). The Delaware Department of Transportation installed centerline rumble strips along the roadway, and as a result, reported a 90 percent decrease in head-on collision, and a zero fatality rate (USDOT, 2002). In Arizona, rumble strips were installed in an effort to provide an advance warning of crosswalks, and reduce pedestrian collisions. It was found that the advance rumble strips were not successful as a crosswalk safety device, especially in an urban situation (Cynecki, Sparks and Grote, 1993). The Kansas Department of Transportation uses rumble strips in advance of work zones, where two or more lanes of traffic in opposite directions share a lane. Unlike the configuration used in Connecticut, these rumble strips are placed across the entire width of a travel lane. A study in Kansas measured the sounds and vibrations emitted by both removable and asphalt rumble strips. The results of the study indicate that the vibration felt by passenger vehicles is not the same as that from heavy vehicles. This study indicated that the composition of traffic, such as the mix of heavy vehicles and passenger cars, should be considered when installing rumble strips in a work zone area (Walton and Meyer, 2002). Ongoing rumble strip research efforts continue in Georgia, Michigan, Virginia, Colorado, Maryland, Alaska, Oklahoma, and Nevada (FHWA, 2001).

Concerns have been expressed among the bicycle community regarding the use of rumble strips on roadway facilities, the location and placement of rumble strips on the edge of pavement, and the depth of the rumble strips (Isackson, 2000). A Technical Advisory issued by FHWA (2001) recommends that agencies involved with the application of rumble strips should work concurrently with bicycle groups in developing design standards, policies and implementation techniques. This includes enforcement agencies, emergency groups and roadway users.

An FHWA (2001) synthesis suggested that the high priority research on shoulder rumble strips be divided into two categories: design and driver interaction. The latter category of driver interaction involves human behavioral studies on the reaction of inattentive drivers to rumble strips. For example, behavioral studies that ascertain the amount of time a driver needs to make corrective action may eventually lead to a determination of a minimum shoulder width for the rumble strip. The reaction time and subsequent reaction provide a basis for the design of the rumble strip, as well as its effectiveness in alerting inattentive drivers. Harwood (1993) suggests that roadway safety studies involving rumble strips be conducted to measure the attitudes toward rumble strips. Attitudes toward rumble strips differ by driver age. Observations of human reaction to the noise and vibration emitted by rumble strips may reveal that rumble strips have adverse effects on a particular driver age group. Other studies mention that drivers traverse rumble strips intentionally, out of curiosity or boredom. Similarly, Meyer (2000) observed drivers crossing the centerline to avoid traversing the rumble strips. It is these human reactions that may provide insight into the effectiveness of the rumble strip into alerting the driver.

The Roadway Safety Foundation, a non-profit organization, identified a gap in road safety research particularly involving the effectiveness of safety treatments, such as rumble strips. However, there have been studies conducted to measure the performance of rumble strips in terms of the reduction in traffic accidents. Griffith (1999) examined data from California and Illinois to estimate the safety effects of continuous shoulder rumble strips on freeways. The estimation procedure involved the prediction of what would have been the expected number of accidents at rumble strip sites, if rumble strips were not installed. The expected number of accidents in the after period was then compared to the actual number of accidents. From this comparison, the safety effect of the improvement could be estimated. Hauer (1997) fully describes this methodology in his book, "Observational Before-After Studies in Road Safety". This approach involves matching treatment sites (those that have rumble strips) to comparison sites (those that do not have rumble strips). Griffith (1999) also presents a slight variation of this approach, whereby more comparison sites are used in the analysis than treatment sites.

Cheng, Gonzalez and Christensen (2000) evaluate the effectiveness of rumble strips in Utah by using comparisons of accident rates with and without rumble strips. Statistical tests such as the student's t-test and f-test were also used to verify whether variance derived from the statistical analysis of accident rates were from the same sample population. If the result is true (null hypothesis), then the statistical results are not viable. The Virginia Department of Transportation conducted a before/after analysis of continuous shoulder rumble strips using a methodology of statistical sampling, statistical tests (Normal, Chi-square and Poisson distribution tests), and a yoked comparison test. The yoked comparison test uses a one-to-one matching between a rumble strip site and a site without rumble strips.

As pointed out in 2001 VDOT report, most studies do not use statistical tests or procedures to evaluate the effectiveness of rumble strips; rather, they use experience, knowledge and judgement (VDOT, 2001).

This next section discusses the basic accident trends in Connecticut, and will present the study area, data collection and methodology used to determine whether rumble strips have had any impact in the reduction of accidents. The statistical approach to measure the accident data is described by Hauer (1997). Like the Virginia study, comparison sites will also be used in the analysis to determine and estimate the potential safety effects gained from rumble strips.

## Study Area and Data Collection

In 1995, rumble strips were installed on approximately 300 shoulder miles, or 73 sections of limited-access highways in Connecticut. Appendix A provides a listing of these roadway sections with their description of location. For this study, numerical section numbers were assigned to each of the 73 sections of roadway. The selected roadway sections range in length from less than one mile to over 18 miles. As described earlier in this report, the criteria for selecting these roadway sections was based on the pavement age and inclusion in the pavement resurfacing schedule at ConnDOT, and the width of the shoulder. Specifically, the age of the pavement had to be less than five years, with a minimum shoulder width of three feet.

The first part of the data collection involved gathering accident data for a period of three years before (1993-1995) and three years after (1996-1998) the installation of rumble strips. Accident data for single-vehicle, fixed-object, off-shoulder accidents were defined as "rumble strip related" accidents for this study. The accident data were downloaded from either mainframe data files from ConnDOT's Office of Planning, or from the accident analysis program, "Intersection Magic". The accident data were imported into Microsoft Access, and queries were developed to filter out only "rumble strip related" accidents. The queries used to filter out the accident data were based on the location criteria of route, direction, mileage, as well as other accident criteria for collision type, road surface, vehicle object location, and special roadway features. The results of these queries were further examined and filtered for accidents that had occurred on the same side of the road as the rumble strip. Table 1 lists the filtering criteria used in the accident data queries.

**Table 1**
**Criteria Used for Accident Data**

| Accident Data Field Description | Filter Criteria |
|---|---|
| **Route, Direction** | Must match the location of the rumble strip |
| **Mileage Accident Data** | Mileage must be within limits of rumble strip |
| **Type of Collision** | Fixed object or Fixed Object Overturn |
| **Road Surface** | Wet or Dry road conditions (no ice or snow) |
| **Special Road Features** | Exclude bridges, tunnels and ramps |
| **Road Type** | Mainline only |
| **Vehicle 1 Object Location** | Match rumble strip shoulder (left or right) |

Additional queries were performed to filter out accidents for the following contributing factors: "driver fell asleep", "driver under the influence", "driver inattentive" or "driver incapacitated". Accidents involving injuries and fatalities were also queried. Eventually, additional control criteria were established to discard accident data that were not applicable for this study. For example, any accident data that had a pavement surface of snow or ice were eliminated from this study.

## Accident Trends in Connecticut

Prior to the comparative and statistical analysis of the collected "rumble-strip related" accident data, the overall accident history for Connecticut was compiled and examined for any trends that might provide insight for this research. In particular, the accident history for the criteria listed in Table 1 was examined. The accident history for Connecticut was compiled for the three years before (1993-1995) and after (1996-1998) the installation of rumble strips. In particular, fixed-object accidents, off-road and shoulder accidents, and "asleep" accidents were examined. Table 2 lists and Figure 10 plots the fixed-object accident data in Connecticut. It was found that in the three-year period prior to the installation of rumble strips in Connecticut (1993-1995), there was an increase in fixed object accidents followed by a decrease, as shown by the inverted "U" pattern in Figure 10. The three-year period after the rumble strip installation in Connecticut (1996-1998) also showed an increase and decrease in fixed object accidents. This decrease is especially evident in 1998, when the number of fixed object accidents was lower than the previous years.

**Table 2**
**Total Fixed Object Accidents**
**In Connecticut (1993-1998)**

| Year | Total Number of Fixed Object Accidents |
|---|---|
| 1993 | 14765 |
| 1994 | 15140 |
| 1995 | 14316 |
| 1996 | 15245 |
| 1997 | 14869 |
| 1998 | 13387 |

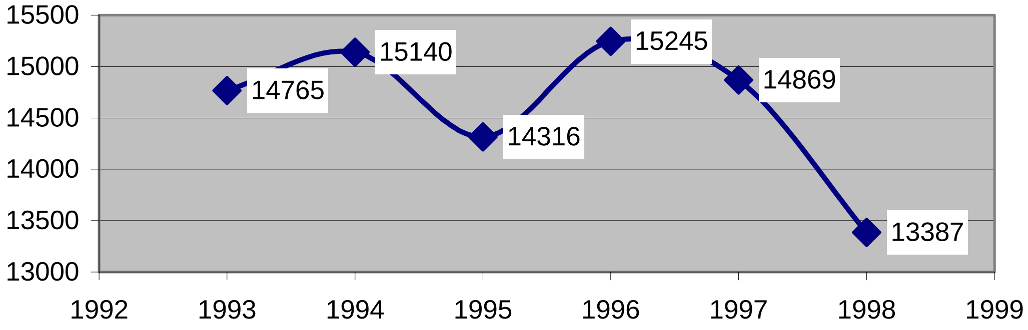

**Figure 10. Total Fixed Object Accidents in Connecticut (1993-1998).**

In 2001, the Fatality Analysis Reporting System (FARS) reported that more than half of the national total of single vehicle crashes occur off-roadway. In Connecticut, off-road and shoulder accidents exhibited an increase in the three years after the installation of rumble strips. Table 3 and Figure 11 depict this trend.

**Table 3**
**Total Off Road & Shoulder Accidents**
**In Connecticut (1993-1998)**

| Year | Total Off Road & Shoulder Accidents |
|---|---|
| 1993 | 12489 |
| 1994 | 12424 |
| 1995 | 12126 |
| 1996 | 13520 |
| 1997 | 13783 |
| 1998 | 12585 |

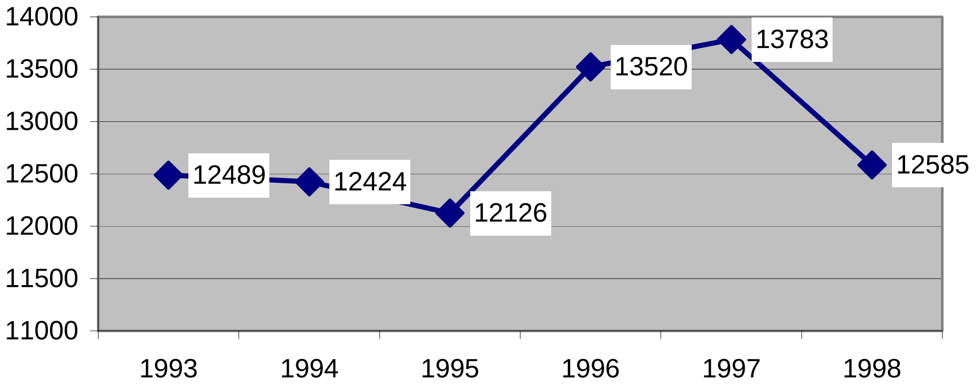

**Figure 11. Total Off Road & Shoulder Accidents in Connecticut (1993-1998).**

Table 4 and Figure 12 display the "asleep" accidents in Connecticut from 1993 through 1998. "Asleep" accidents are those accidents coded with a contributing factor of "driver fell asleep". As discussed in the literature section of this report, inattentive driving is a national problem. Studies have been conducted by the National Highway Traffic Safety Administration (NHTSA) that examines the causes of "drowsy" driving. Groups such as NHTSA as well as the National Center on Sleep Disorders Research (NCSDR), and the National Heart, Lung and Blood Institute of the National Institutes of Health joined efforts to report on this problem. It is agreed that crashes that are related to sleepiness result in the vehicle leaving the roadway. In Connecticut, the number of “asleep" accidents continues to rise. As shown in Table 4, even in the years following the installation of rumble strips (1996-1998), the number of "asleep" accidents has increased.

**Table 4**
**Total "Asleep" Accidents**
**In Connecticut (1993-1998)**

| Year | Total Number of "Asleep" Accidents |
|---|---|
| 1993 | 659 |
| 1994 | 763 |
| 1995 | 1055 |
| 1996 | 1111 |
| 1997 | 968 |
| 1998 | 1104 |

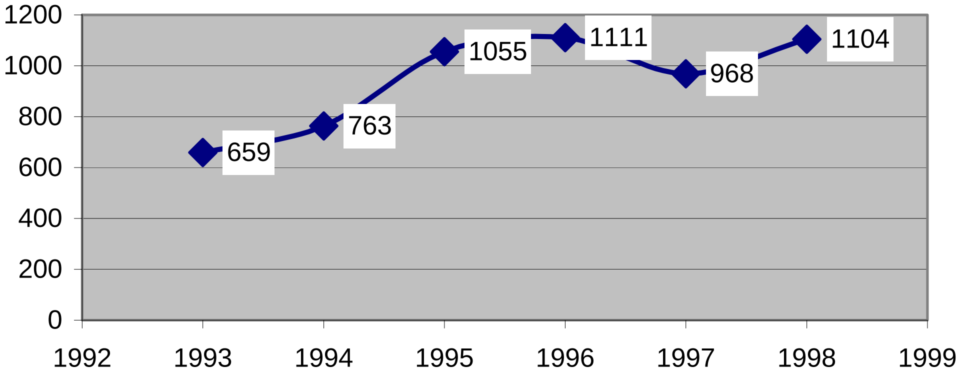

**Figure 12. Total "Asleep" Accidents in Connecticut (1993-1998).**

As part of this preliminary review, accident severity in Connecticut was also examined. Accident severity data was separated into categories of injuries and fatalities. Table 5 and Figure 13 present the injury data, and Table 6 and Figure 14 shows the fatality data. Note that the data listed in Tables 5 and 6 are the accidents that have at least a single injury or fatality, and not the total number of injuries or fatalities. For example, if an accident resulted in five injured persons, it was coded as a single injury-accident. Since 1993, injury-accidents have increased in Connecticut. The fatal accident data did not show any consistent trend.

### Table 5
### Total Injury Accidents
### In Connecticut (1993-1998)

| Year | Total Number of Injury Accidents |
|---|---|
| 1993 | 29620 |
| 1994 | 32116 |
| 1995 | 32575 |
| 1996 | 33849 |
| 1997 | 32623 |
| 1998 | 31468 |

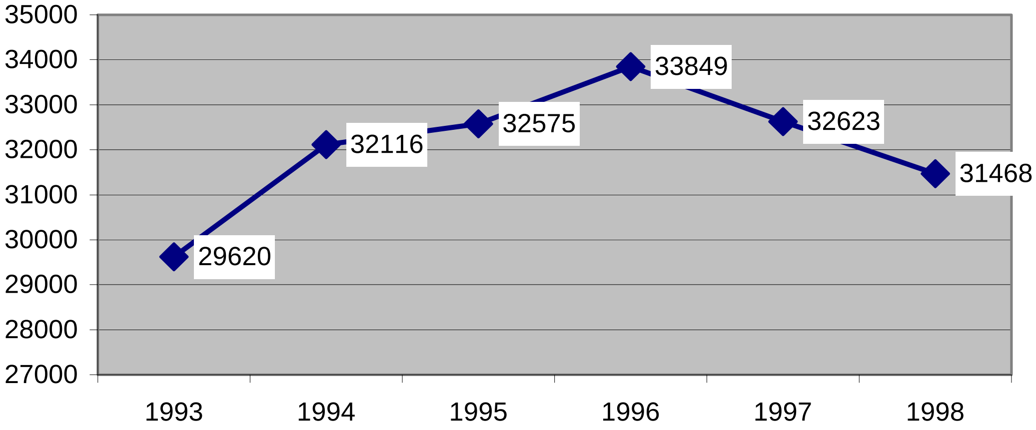

**Figure 13. Total Injury Accidents in Connecticut (1993-1998).**

### Table 6
### Total Fatal Accidents
### In Connecticut (1993-1998)

| Year | Total Number of Fatal Accidents |
|---|---|
| 1993 | 324 |
| 1994 | 286 |
| 1995 | 288 |
| 1996 | 296 |
| 1997 | 316 |
| 1998 | 308 |

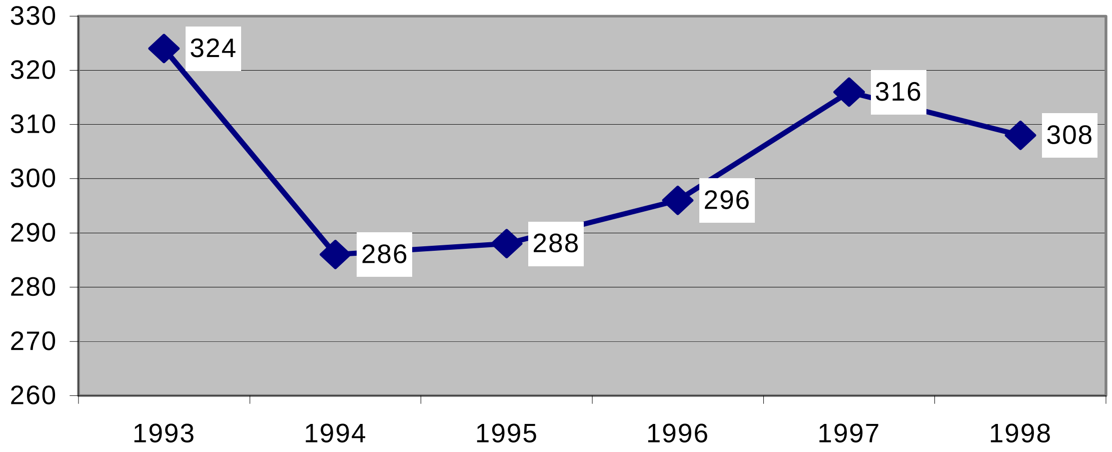

**Figure 14. Total Fatal Accidents in Connecticut (1993-1998).**

The purpose of the accident history for the State of Connecticut was to initially investigate whether there was an obvious trend or pattern of accidents, such as fixed-object or off-road and shoulder accidents. This would indicate that rumble strips may potentially be a source of crash mitigation. Note that the accident history does not account for inclement weather patterns, such as snow and ice. As part of southern New England, Connecticut has experienced inconsistent weather patterns, particularly during the winter months (November through March). Thus, at this point, there does not seem to be a conclusive accident trend other than an overall increase in vehicular accidents during the last three available years (1999-2001), as shown in Table 7 and Figure 15. Conclusions cannot be drawn about any safety effects. Rather, further study including filtering specific accidents for roadways containing rumble strips is necessary in order to determine any changes in roadway safety.

## Table 7
## Total Number of Accidents In Connecticut (1993-2001)

| Year | Total Number of Accidents |
|---|---|
| 1993 | 67637 |
| 1994 | 73469 |
| 1995 | 72538 |
| 1996 | 78383 |
| 1997 | 74776 |
| 1998 | 72555 |
| 1999 | 78322 |
| 2000 | 82787 |
| 2001 | 83256 |

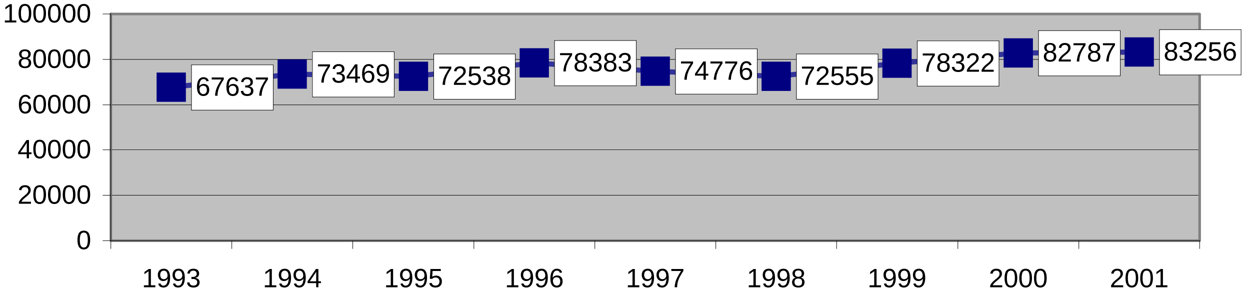

**Figure 15. Total Accidents in Connecticut (1993-2001).**

### Data Description

As mentioned earlier, the first part of the data collection process involved gathering accident data for a period of three years before and after the installation of rumble strips. Appendix B displays the results of the data collection for each of the 73 roadway sections. The table in Appendix B is divided into two sections, the left section lists the “before" accident history, and the right section displays the "after" accident history. The darkened columns contain the total accidents for that particular roadway section, and the adjacent columns contain "rumble strip related" accidents. For this study, "rumble strip related" accidents are defined as single-vehicle, fixed-object, off-shoulder accidents. The expectation of this portion of the accident analysis was that there would be an overall decrease in accidents from the "before" to the "after" period for the rumble strip sections.

Table 8 summarizes the "rumble strip related" accidents for each route by year. The percent change for each route is also shown. Note that the percentage change in accidents for some routes is more apparent than other routes. In particular, Route 6, Route 15, and Route 40 show substantial decreases in "rumble strip related" accidents. However, caution should be exercised when comparing the results for each route in Table 8.

**Table 8**
**Summary of "Rumble Strip Related" Accidents by Year**

| Year | Route 6 | Route 7 | Route 8 | Route 9 | Route 11 | Route 15 | Route 20 | Route 40 | Route 72 | Route 693 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Before** | | | | | | | | | | |
| **1993-1994** | 3 | 6 | 64 | 24 | 4 | 42 | 2 | 0 | 21 | 1 |
| **1994-1995** | 9 | 9 | 76 | 46 | 9 | 35 | 4 | 1 | 24 | 6 |
| **1995-1996** | 4 | 12 | 69 | 31 | 4 | 38 | 6 | 3 | 17 | 3 |
| **Total** | 16 | 27 | 209 | 101 | 17 | 115 | 12 | 4 | 62 | 10 |
| **After** | | | | | | | | | | |
| **1996-1997** | 3 | 10 | 58 | 34 | 5 | 19 | 4 | 0 | 9 | 3 |
| **1997-1998** | 4 | 14 | 74 | 32 | 5 | 17 | 4 | 1 | 23 | 5 |
| **1998-1999** | 3 | 4 | 74 | 37 | 5 | 29 | 2 | 2 | 25 | 4 |
| **Total** | 10 | 28 | 206 | 103 | 15 | 65 | 10 | 3 | 57 | 12 |
| **% Change** | -37.50% | 3.70% | -1.44% | 1.98% | -11.76% | -43.48% | -16.67% | -25.00% | -8.06% | 20.00% |

Some routes have a lower number of "rumble strip related" accidents, due to location and operational factors such as ADT (average daily traffic), and vehicular lanes. Therefore, even a small reduction in the number of accidents appears significant in this analysis. This makes it difficult to compare the accident history among the rumble strip sections. Further investigation including site trips may be warranted for those roadway sections that exhibit an increase in accidents after rumble strips were installed.

Table 9 displays the total number of accidents for the 73 rumble strip sections. Note, the first column of this table lists a total of all accidents, not just "rumble strip related" accidents. The percentage change in total number of accidents for these roadway sections, in the "after" period, slightly increased 0.40%. However, there was an overall reduction in "rumble strip related" accidents (-11.30%). An encouraging outcome of the data description was the decrease in the number of accidents where the driver "fell asleep".

**Table 9**
**Total Before/After Accidents**

| Year | Total Accidents | Rumble Strip Related Accidents | Rumble Strip Related Accidents (Asleep) | Rumble Strip Related Accidents (Injury) | Rumble Strip Related Accidents (Fatality) |
|---|---|---|---|---|---|
| **Before** | | | | | |
| **1993-1994** | 3217 | 169 | 20 | 59 | 1 |
| **1994-1995** | 3007 | 219 | 28 | 55 | 1 |
| **1995-1996** | 3615 | 187 | 34 | 48 | 3 |
| **Total** | 9839 | 575 | 82 | 162 | 5 |
| **After** | | | | | |
| **1996-1997** | 3406 | 146 | 20 | 49 | 1 |
| **1997-1998** | 3221 | 179 | 26 | 55 | 2 |
| **1998-1999** | 3251 | 185 | 22 | 61 | 0 |
| **Total** | 9878 | 510 | 68 | 165 | 3 |
| **% Change** | 0.40% | -11.30% | -17.07% | 1.85% | -40.00% |

As described in the literature review section of this report, the "drowsy driver" has become an increasing safety hazard. Rumble strips are considered an operational means to warn "drowsy drivers" and reduce "drift-off-the road" accidents. Also, the total number of "rumble strip related" fatal accidents decreased (-40.0%) in the "after" period. However, the number of injury-accidents slightly increased (1.85%). As mentioned earlier, both the injury and fatal accidents reflect the actual number of "rumble strip related" accidents that had an occurrence of an injury or fatality, and not the total of injuries or fatalities.

Note that the accident data presented in Tables 8 and 9 were collected from roadways with rumble strips. The accident data does not necessarily account for other causal factors that may attribute to these accidents, such as average daily traffic (ADT), illumination, and roadway geometry that may impact these results. In order to determine whether there are safety benefits that could potentially benefit roadways without rumble strips, the next step of this analysis was to compare the accident history of roadway sections with rumble strips to those without rumble strips. Recent research was performed by the Virginia Department of Transportation (2001), that compared the accident history of roadway sections containing rumble strips to comparison sections of roadway that do not have rumble strips. The overall intent of the comparative sections was to improve the estimation of safety benefits gained from the use of rumble strips.

## Comparative Sections

In order to identify roadway sections that qualify as comparative sections, a comprehensive list of limited-access highways in Connecticut with a minimum shoulder width of 3 feet was compiled. Appendix C displays these roadway sections. Initially, other roadway features such as illumination, number of roadway lanes, demographic classification (rural or urban), and average daily traffic (ADT) were used for selecting comparative "non-rumble strip" sections from this list. The objective was to match the roadway characteristics of each rumble strip section to that of a corresponding "non-rumble strip" section of roadway. Once identified, comparisons of the accident history for rumble strip and "non-rumble strip" sections would then be drawn from roadway sections with similar operating characteristics.

The data for roadway features (illumination, roadway lanes, rural/urban classification and ADT) are not contained in a single, composite digital file. Rather, each feature is contained in a separate file that is ordered by route and mileage. Unfortunately, the beginning and ending mileages for each roadway feature file do not correspond to the other files, making it difficult to find comparison sections. Therefore, in order to identify comparison roadway sections that match the characteristics of rumble strip sections, this analysis used the spatial query component in GIS (Geographic Information Systems). Spatial queries were developed using Intergraph's GeoMedia Professional program to filter out the desired roadway features for these "non-rumble strip" sections.

As mentioned earlier, rumble strips were installed on 73 sections of roadway in Connecticut. In order to facilitate this spatial query methodology, the original 73 rumble strip sections were aggregated into 16 different groups based on similarities in illumination, number of lanes, rural/urban classification, and ADT. Correspondingly, 16 spatial queries in the GIS were developed to filter out roadway sections that matched each unique combination of features. Table 10 displays the 16 different groups that were aggregated from the 73 rumble strip sections based on illumination, rural/urban classification, and ADT. Note that this table does not contain the number of lanes, as all of the 16 groups have 2 lanes.

Unfortunately, the results of the spatial queries showed that there were only a few roadway sections that qualified as suitable "non-rumble strip" sections. Thus, in order to continue to compare rumble strip and "non-rumble strip" sections, it was decided that contiguous portions of the roadway adjoining the rumble strip sections would serve as appropriate comparison sections for this analysis. Contiguous sections of roadway to the rumble strips were considered to have similar operating characteristics (illumination, number of lanes, rural/urban setting) to the rumble strip sections. These roadway sections are part of the limited-access highway locations listed in Appendix C.

**Table 10**
**Aggregated Roadway Sections for Spatial Queries**

| Group Number | Average Daily Traffic (ADT) | Illumination (Yes or No) | Rural/Urban (Rural or Urban) |
|---|---|---|---|
| **1** | 0-10,000 | No | Rural |
| **2** | 10,000-20,000 | Yes | Urban |
| **3** | 10,000-20,000 | Yes | Rural |
| **4** | 10,000-20,000 | No | Urban |
| **5** | 10,000-20,000 | No | Rural |
| **6** | 20,000-30,000 | Yes | Urban |
| **7** | 20,000-30,000 | Yes | Rural |
| **8** | 20,000-30,000 | No | Urban |
| **9** | 20,000-30,000 | No | Rural |
| **10** | 30,000-40,000 | Yes | Urban |
| **11** | 30,000-40,000 | Yes | Rural |
| **12** | 30,000-40,000 | No | Urban |
| **13** | 40,000-50,000 | Yes | Urban |
| **14** | 40,000-50,000 | No | Urban |
| **15** | 50,000-60,000 | Yes | Urban |
| **16** | 50,000-60,000 | No | Urban |

To facilitate the comparison of accidents for rumble and "non-rumble" strip sections, the original 73 rumble strip sections were aggregated to 11 sections. The accident analysis results for the 11 rumble strip sections are displayed in Table 11. Note that for the 11 rumble strip sections, each has an "R" listed next to its Section ID. For tables described later in this report, a letter "C" in the "Section ID" column represents a comparative section. The column "Side of Road" indicates the side of the road where rumble strips were installed on sections of roadway containing rumble strips. With the exception of sections 10R and 11R, rumble strips were installed on both sides of the roadway.

### Table 11
### Total Before/After Accidents for 11 Aggregated Rumble Strip Sections

| Section ID | Route | Direction | Start Mile | End Mile | Total Accidents Before | Total Accidents After | Percent (%) Change | Side of Road |
|---|---|---|---|---|---|---|---|---|
| **1R** | 8 | NB | 19.28 | 25.14 | 23 | 20 | -13.04% | Right and Left |
| **2R** | 8 | NB | 42.64 | 50.11 | 36 | 36 | 0.00% | Right and Left |
| **3R** | 8 | SB | 19.28 | 25.14 | 20 | 18 | -10.00% | Right and Left |
| **4R** | 9 | NB | 0.23 | 3.91 | 7 | 7 | 0.00% | Right and Left |
| **5R** | 9 | NB | 24.47 | 27.43 | 26 | 29 | 11.54% | Right and Left |
| **6R** | 9 | NB | 37.49 | 39.93 | 9 | 4 | -55.56% | Right and Left |
| **7R** | 9 | SB | 37.49 | 40.71 | 11 | 9 | -18.18% | Right and Left |
| **8R** | 9 | SB | 24.47 | 29.10 | 36 | 35 | -2.78% | Right and Left |
| **9R** | 9 | SB | 0.23 | 3.91 | 10 | 13 | 30.00% | Right and Left |
| **10R** | 15 | NB | 50.20 | 59.72 | 58 | 24 | -58.62% | Right and Left |
| **11R** | 15 | SB | 50.20 | 59.72 | 34 | 15 | -55.88% | Right |
| **Total** | | | | | 270 | 210 | -22.22% | Right |

Seven out of the 11 rumble strip sections showed a decrease in the number of accidents during the six-year (three years "before", three years "after") study period. Sections 2R and 4R did not have any change in accidents, as indicated by a 0.00% in the last column. Sections 5R and 9R showed an increase in the number of accidents. These sections are along Route 9 northbound in Middletown and Route 9 southbound in Old Saybrook. Appendix D graphically displays the accidents for each of the 11 aggregated sections. The figures in Appendix D show the total accidents, and accidents where the contributing factor was "driver was asleep", "driver under the influence", "driver incapacitated", or "driver inattentive" for each of the 11 rumble strip sections. Overall, there was a 22.22% decrease in "rumble strip related" accidents from the "before" period to the "after" period.

Table 12 displays the before and after accidents for rumble strip sections where the contributing factor was "driver was asleep". According to the National Highway Traffic Safety Administration (NHTSA), drowsy, inattentive driving contributes greatly toward drift-off-the-road accidents. Although "drowsy driving" is a national transportation safety issue, counter-measures including rumble strips and driver educational safety programs have been initiated in several states to mediate the problem.

**Table 12**
**Before/After "Asleep" Accidents for 11 Rumble Strip Sections**

| Section ID | Route | Direction | Start Mile | End Mile | Total "Before" Asleep Accidents | Total "After" Asleep Accidents | Percent (%) Change |
|---|---|---|---|---|---|---|---|
| **1R** | 8 | NB | 19.28 | 25.14 | 3 | 2 | -33.33% |
| **2R** | 8 | NB | 42.64 | 50.11 | 13 | 9 | -30.77% |
| **3R** | 8 | SB | 19.28 | 25.14 | 0 | 0 | 0% |
| **4R** | 9 | NB | 0.23 | 3.91 | 1 | 1 | 0% |
| **5R** | 9 | NB | 24.47 | 27.43 | 2 | 2 | 0% |
| **6R** | 9 | NB | 37.49 | 39.93 | 2 | 0 | -100% |
| **7R** | 9 | SB | 37.49 | 40.71 | 2 | 1 | -50% |
| **8R** | 9 | SB | 24.47 | 29.10 | 10 | 5 | -50% |
| **9R** | 9 | SB | 0.23 | 3.91 | 1 | 1 | 0% |
| **10R** | 15 | NB | 50.20 | 59.72 | 12 | 3 | -75% |
| **11R** | 15 | SB | 50.20 | 59.72 | 2 | 1 | -50% |
| **Total** | | | | | 48 | 25 | -47.91% |

The results in Table 12 show that there was a considerable decrease during the study period in "asleep" accidents for seven of the 11 rumble strip sections. Caution should be exercised when reviewing the data in Tables 12. Because there are not many "asleep" accidents in the before period, a slight decrease in the number of accidents result in a significant percentage change. Four other roadway sections indicated no change in accidents where the contributing factor was "driver asleep".

Table 13 displays the results of the injury and fatal accidents for each of the 11 rumble strip sections. Note that there was an overall decrease (-50%) in fatal accidents. Since the total number of injury and fatal accidents are low, caution should be exercised when drawing any conclusions regarding the effectiveness of rumble strips with injury and fatal accidents.

## Table 13
## Injury and Fatal Accidents for 11 Rumble Strip Sections

| Section ID | Route | Direction | Start Mile | End Mile | Total "Before" Injury Accidents | Total "After" Injury Accidents | Percent (%) Change | Total "Before" Fatal Accidents | Total "After" Fatal Accidents | Percent (%) Change |
|---|---|---|---|---|---|---|---|---|---|---|
| **1R** | 8 | NB | 19.28 | 25.14 | 5 | 7 | 40.00% | 1 | 0 | -100.00% |
| **2R** | 8 | NB | 42.64 | 50.11 | 11 | 8 | -27.27% | 0 | 1 | 100.00% |
| **3R** | 8 | SB | 19.28 | 25.14 | 10 | 10 | 0.00% | 0 | 0 | 0.00% |
| **4R** | 9 | NB | 0.23 | 3.91 | 2 | 2 | 0.00% | 0 | 0 | 0.00% |
| **5R** | 9 | NB | 24.47 | 27.43 | 10 | 13 | 30.00% | 0 | 1 | 100.00% |
| **6R** | 9 | NB | 37.49 | 39.93 | 3 | 1 | -66.67% | 0 | 0 | 0.00% |
| **7R** | 9 | SB | 37.49 | 40.71 | 4 | 6 | 50.00% | 1 | 0 | -100.00% |
| **8R** | 9 | SB | 24.47 | 29.10 | 8 | 10 | 25.00% | 0 | 0 | 0.00% |
| **9R** | 9 | SB | 0.23 | 3.91 | 3 | 2 | -33.33% | 0 | 0 | 0.00% |
| **10R** | 15 | NB | 50.20 | 59.72 | 15 | 10 | -33.33% | 2 | 0 | -100.00% |
| **11R** | 15 | SB | 50.20 | 59.72 | 12 | 4 | -66.67% | 0 | 0 | 0.00% |
| **Total** | | | | | 83 | 73 | 12.05% | 4 | 2 | -50.00% |

From Table 13, the number of injury accidents increased, at 12.05%. One section, 10R, showed a decrease for both injury and fatal accidents. Section 2R showed a decrease in injury accidents and an increase in fatal accidents. Sections 1R and 7R had an increase in injury accidents, but a decrease in fatal accidents. Sections 3R and 4R had no change in injury or fatal accidents. Appendix E graphically shows the injury and fatal accidents for each of the 11 rumble strip sections.

As mentioned earlier, comparison sections were selected for the analysis to infer whether rumble strips would reduce accidents on roadways. Table 14 lists the 11 adjacent "non-rumble strip" roadway sections, including the route, direction, starting and ending mileage, and the side of roadway. Accordingly, accident data were collected for three years before and after the installation of rumble strips, for the corresponding side of roadway. Accident data for the comparative sections were collected for only the side of roadway that corresponds to the rumble strip sections. For example, if the rumble strip section had rumble strips on the right side of the road, then the accident data were collected for only that side of road for rumble strip and "non-rumble strip", comparative sections.

### Table 14
### Rumble Strip Comparative "Non-Rumble Strip" Sections

| Section ID | Route | Direction | Comparison Section<br>Start Mile | End Mile | Length (miles) | Side of Road |
|---|---|---|---|---|---|---|
| **1C** | 8 | NB | 13.42 | 19.28 | 5.86 | Right and Left |
| **2C** | 8 | NB | 35.17 | 42.64 | 7.47 | Right and Left |
| **3C** | 8 | SB | 13.42 | 19.28 | 5.86 | Right and Left |
| **4C** | 9 | NB | 3.91 | 7.59 | 3.68 | Right and Left |
| **5C** | 9 | NB | 27.43 | 30.39 | 2.96 | Right and Left |
| **6C** | 9 | NB | 35.05 | 37.49 | 2.44 | Right and Left |
| **7C** | 9 | SB | 34.27 | 37.49 | 3.22 | Right and Left |
| **8C** | 9 | SB | 19.84 | 24.47 | 4.63 | Right and Left |
| **9C** | 9 | SB | 3.91 | 7.59 | 3.68 | Right and Left |
| **10C** | 15 | NB | 37.62 | 47.14 | 9.52 | Right |
| **11C** | 15 | SB | 37.62 | 47.14 | 9.52 | Right |

Table 15 provides the accident data collection results for the 11 comparison "non-rumble strip" sections.

### Table 15
### Total Before/After Accidents for 11 Comparison "Non-Rumble Strip" Sections

| Section ID | Route | Direction | Start Mile | End Mile | Total "Before" Accidents | Total "After" Accidents | Percent (%) Change |
|---|---|---|---|---|---|---|---|
| **1C** | 8 | NB | 13.42 | 19.28 | 37 | 59 | 59.46% |
| **2C** | 8 | NB | 35.17 | 42.64 | 31 | 35 | 12.90% |
| **3C** | 8 | SB | 13.42 | 19.28 | 20 | 28 | 40.00% |
| **4C** | 9 | NB | 3.91 | 7.59 | 15 | 16 | 6.67% |
| **5C** | 9 | NB | 27.43 | 30.39 | 16 | 9 | -31.25% |
| **6C** | 9 | NB | 35.05 | 37.49 | 15 | 14 | -6.67% |
| **7C** | 9 | SB | 34.27 | 37.49 | 25 | 22 | -12% |
| **8C** | 9 | SB | 19.84 | 24.47 | 17 | 13 | -23.53% |
| **9C** | 9 | SB | 3.91 | 7.59 | 21 | 24 | 14.29% |
| **10C** | 15 | NB | 37.62 | 47.14 | 39 | 36 | -7.69% |
| **11C** | 15 | SB | 37.62 | 47.14 | 29 | 38 | 31.03% |
| **Total** | | | | | 265 | 294 | 10.94% |

From inspection, it is evident that some roadway sections, 1C, 2C, 3C, 4C, 9C, and 11C, experienced an increase in the number of accidents from the three year period prior to the installation of rumble strips ("before") to three year period after the installation of rumble strips. The remaining five comparative sections (5C, 6C, 7C, 8C and 10C) had a decrease in accidents. As a result, there was a 10.94% overall increase in the number of accidents from the "before" period to the "after" period for the comparison sections.

Table 16 displays the "asleep" accidents for the 11 comparison sections. There were a total of 28 "asleep" accidents for the "before" period and 51 "asleep" accidents in the "after" period. Thus, on "non-rumble strip" sections of roadway, there was a significant increase (82.1%) in "asleep" accidents. When traversed, rumble strips emit a loud, arousing sound that alerts drivers in advance of a fixed object. Therefore, it is fair to assume that rumble strips could potentially reduce the number of "asleep" accidents on these comparison sections of roadway.

**Table 16**
**Before/After "Asleep" Accidents for 11 Comparative Sections**

| Section ID | Route | Direction | Starting Mile | Ending Mile | "Before" Total Asleep Accidents | "After" Total Asleep Accidents | Percent (%) Change |
|---|---|---|---|---|---|---|---|
| **1C** | 8 | NB | 13.42 | 19.28 | 4 | 9 | 125.00% |
| **2C** | 8 | NB | 35.17 | 42.64 | 3 | 6 | 100.00% |
| **3C** | 8 | SB | 13.42 | 19.28 | 0 | 4 | 400.00% |
| **4C** | 9 | NB | 3.91 | 7.59 | 2 | 7 | 250.00% |
| **5C** | 9 | NB | 27.43 | 30.39 | 1 | 2 | 100.00% |
| **6C** | 9 | NB | 35.05 | 37.49 | 1 | 1 | 0.00% |
| **7C** | 9 | SB | 34.27 | 37.49 | 2 | 1 | -50.00% |
| **8C** | 9 | SB | 19.84 | 24.47 | 3 | 1 | -66.67% |
| **9C** | 9 | SB | 3.91 | 7.59 | 2 | 9 | 350.00% |
| **10C** | 15 | NB | 37.62 | 47.14 | 7 | 9 | 28.57% |
| **11C** | 15 | SB | 37.62 | 47.14 | 3 | 2 | -33.33% |
| **Total** | | | | | 28 | 51 | 82.1% |

Table 17 shows that there were a total of 143 injury accidents for the data collection period, 75 injury accidents in the "before" period, and 68 accidents in the "after" period.

## Table 17
## Injury and Fatal Accidents for 11 Comparative Sections

| Section ID | Route | Dir | Starting Mile | Ending Mile | Total "Before" Injury Accidents | Total "After" Injury Accidents | Percent (%) Change | Total "Before" Fatal Accidents | Total "After" Fatal Accidents | Percent (%) Change |
|---|---|---|---|---|---|---|---|---|---|---|
| **1C** | 8 | NB | 13.42 | 19.28 | 12 | 8 | -33.33% | 0 | 0 | 0.00% |
| **2C** | 8 | NB | 35.17 | 42.64 | 7 | 9 | 28.57% | 0 | 1 | 100.00% |
| **3C** | 8 | SB | 13.42 | 19.28 | 6 | 8 | 33.33% | 0 | 0 | 0.00% |
| **4C** | 9 | NB | 3.91 | 7.59 | 4 | 2 | -50.00% | 0 | 0 | 0.00% |
| **5C** | 9 | NB | 27.43 | 30.39 | 4 | 1 | -75.00% | 0 | 1 | 100.00% |
| **6C** | 9 | NB | 35.05 | 37.49 | 6 | 3 | -50.00% | 0 | 0 | 0.00% |
| **7C** | 9 | SB | 34.27 | 37.49 | 7 | 4 | -42.86% | 0 | 0 | 0.00% |
| **8C** | 9 | SB | 19.84 | 24.47 | 5 | 7 | 40.00% | 0 | 0 | 0.00% |
| **9C** | 9 | SB | 3.91 | 7.59 | 2 | 4 | 100.00% | 0 | 0 | 0.00% |
| **10C** | 15 | NB | 37.62 | 47.14 | 12 | 11 | -8.33% | 1 | 1 | 0.00% |
| **11C** | 15 | SB | 37.62 | 47.14 | 10 | 11 | 10.00% | 1 | 0 | -100.00% |
| **Total** | | | | | 75 | 68 | -9.33% | 2 | 3 | 50.00% |

There were a total of five fatal accidents, two in the "before" period and three in the "after" period. Again, because these are comparative sections, an inference can be made concerning the potential safety benefits obtained from the installation of rumble strips on these roadway sections.

Table 18 displays the compiled accident data for both the "before" and "after" periods. For the rumble strip sections, it is apparent that rumble strips reduced the number of accidents on roadways from the "before" period to the "after" period. From Table 18 Sections 1, 3, and 11, exhibit a decrease in accidents on the rumble strip section and an increase in accidents on the adjacent comparative section. Sections 2 and 4 exhibit no change in accidents for the rumble strip sections and an increase in accidents on the adjacent comparative sections. Sections 6, 7, 8 and 10 show decreases in accidents for both the rumble strip section and the adjacent comparative sections. Conversely, Section 5 shows unusual results whereby there was an increase in accidents on the rumble strip section, and a decrease in accidents on the comparative section. For sections 2, 4 and 5, further investigation is needed to determine the cause of the increase of accidents. The implications from Table 18 indicate that "rumble-strip related" accidents on adjacent comparative sections may potentially be reduced by the installation of rumble strips.

**Table 18**
**Summary of Accident Data for Rumble Strip and "Non-Rumble Strip" Sections**

| Section ID | Rumble or Comparison Section | Route | Dir | Start Mile | End Mile | Total "Before" Accidents | Total "After" Accidents | Percent (%) Change |
|---|---|---|---|---|---|---|---|---|
| **1R** | Rumble | 8 | NB | 19.28 | 25.14 | 23 | 20 | -13.04% |
| **1C** | Comparison | 8 | NB | 13.42 | 19.28 | 37 | 59 | 59.46% |
| **2R** | Rumble | 8 | NB | 42.64 | 50.11 | 36 | 36 | 0.00% |
| **2C** | Comparison | 8 | NB | 35.17 | 42.64 | 31 | 35 | 12.90% |
| **3R** | Rumble | 8 | SB | 19.28 | 25.14 | 20 | 18 | -10.00% |
| **3C** | Comparison | 8 | SB | 13.42 | 19.28 | 20 | 28 | 40.00% |
| **4R** | Rumble | 9 | NB | 0.23 | 3.91 | 7 | 7 | 0.00% |
| **4C** | Comparison | 9 | NB | 3.91 | 7.59 | 15 | 16 | 6.66% |
| **5R** | Rumble | 9 | NB | 24.47 | 27.43 | 26 | 29 | 11.53% |
| **5C** | Comparison | 9 | NB | 27.43 | 30.39 | 16 | 9 | -43.75% |
| **6R** | Rumble | 9 | NB | 37.49 | 39.93 | 9 | 4 | -55.56% |
| **6C** | Comparison | 9 | NB | 35.05 | 37.49 | 15 | 14 | -6.67% |
| **7R** | Rumble | 9 | SB | 37.49 | 40.71 | 11 | 9 | -18.18% |
| **7C** | Comparison | 9 | SB | 34.27 | 37.49 | 25 | 22 | -12.00% |
| **8R** | Rumble | 9 | SB | 24.47 | 29.10 | 36 | 35 | -2.77% |
| **8C** | Comparison | 9 | SB | 19.84 | 24.47 | 17 | 13 | -23.52% |
| **9R** | Rumble | 9 | SB | 0.23 | 3.91 | 10 | 13 | 30.00% |
| **9C** | Comparison | 9 | SB | 3.91 | 7.59 | 21 | 24 | 14.29% |
| **10R** | Rumble | 15 | NB | 50.20 | 59.72 | 58 | 24 | -58.62% |
| **10C** | Comparison | 15 | NB | 37.62 | 47.14 | 39 | 36 | -7.69% |
| **11R** | Rumble | 15 | SB | 50.20 | 59.72 | 34 | 15 | -55.88% |
| **11C** | Comparison | 15 | SB | 37.62 | 47.14 | 29 | 38 | 31.03% |
| **Total** | Rumble | | | | | 270 | 210 | -22.22% |
| **Total** | Comparison | | | | | 265 | 294 | 10.94% |

Table 19 shows the compiled results of the "before" and "after" injury and fatal accidents for both the rumble strip and comparison sections. Rumble strip sections 2, 6, 9, 10, 11 had a decrease in injury accidents. Again, it is difficult to draw conclusions regarding injury and fatal accidents because of the small number of accidents. However, Sections 1, 7, and 10 showed a decrease in fatal accidents on the rumble strip sections.

**Table 19**
**Before/After Total Injury Accidents**

| Section ID | Route | Dir | Start Mile | End Mile | Total "Before" Injury Accidents | Total "After" Injury Accidents | Percent (%) Change | Total "Before" Fatal Accidents | Total "After" Fatal Accidents | Percent (%) Change |
|---|---|---|---|---|---|---|---|---|---|---|
| **1R** | 8 | NB | 19.28 | 25.14 | 5 | 7 | 40.00% | 1 | 0 | -100.00% |
| **1C** | 8 | NB | 13.42 | 19.28 | 12 | 8 | -33.33% | 0 | 0 | 0.00% |
| **2R** | 8 | NB | 42.64 | 50.11 | 11 | 8 | -27.27% | 0 | 1 | 100.00% |
| **2C** | 8 | NB | 35.17 | 42.64 | 7 | 9 | 28.57% | 0 | 1 | 100.00% |
| **3R** | 8 | SB | 19.28 | 25.14 | 10 | 10 | 0.00% | 0 | 0 | 0.00% |
| **3C** | 8 | SB | 13.42 | 19.28 | 6 | 8 | 33.33% | 0 | 0 | 0.00% |
| **4R** | 9 | NB | 0.23 | 3.91 | 2 | 2 | 0.00% | 0 | 0 | 0.00% |
| **4C** | 9 | NB | 3.91 | 7.59 | 4 | 2 | -50.00% | 0 | 0 | 0.00% |
| **5R** | 9 | NB | 24.47 | 27.43 | 10 | 13 | 30.00% | 0 | 1 | 100.00% |
| **5C** | 9 | NB | 27.43 | 30.39 | 4 | 1 | -75.00% | 0 | 0 | 0.00% |
| **6R** | 9 | NB | 37.49 | 39.93 | 3 | 1 | -66.67% | 0 | 0 | 0.00% |
| **6C** | 9 | NB | 35.05 | 37.49 | 6 | 3 | -50.00% | 0 | 0 | 0.00% |
| **7R** | 9 | SB | 37.49 | 40.71 | 4 | 6 | 50.00% | 1 | 0 | -100.00% |
| **7C** | 9 | SB | 34.27 | 37.49 | 7 | 4 | -42.86% | 0 | 0 | 0.00% |
| **8R** | 9 | SB | 24.47 | 29.10 | 8 | 10 | 25.00% | 0 | 0 | 0.00% |
| **8C** | 9 | SB | 19.84 | 24.47 | 5 | 7 | 40.00% | 0 | 0 | 0.00% |
| **9R** | 9 | SB | 0.23 | 3.91 | 3 | 2 | -33.33% | 0 | 0 | 0.00% |
| **9C** | 9 | SB | 3.91 | 7.59 | 2 | 4 | 100.00% | 0 | 0 | 0.00% |
| **10R** | 15 | NB | 50.20 | 59.72 | 15 | 10 | -33.33% | 2 | 0 | -100.00% |
| **10C** | 15 | NB | 37.62 | 47.14 | 12 | 11 | -8.33% | 1 | 1 | 0.00% |
| **11R** | 15 | SB | 50.20 | 59.72 | 12 | 4 | -66.67% | 0 | 0 | 0.00% |
| **11C** | 15 | SB | 37.62 | 47.14 | 10 | 11 | 10.00% | 1 | 0 | -100.00% |
| **Total** | Rumble | | | | 83 | 73 | -12.05% | 4 | 2 | -50.00% |
| **Total** | Comparison | | | | 75 | 68 | -9.33% | 2 | 2 | 0.00% |

## Summary of Data

For this research, accident data were collected for a three-year period before and a three-year period after the initial installation of rumble strips. The results from a comparison of the "before" and "after" accidents for roadway sections with rumble strips, showed a decrease in the number of "rumble-strip related" accidents. Also, there was a decrease in both injury and fatal accidents from the "before" period to the "after" period for rumble strip sections. As part of this analysis, accident data were compiled for comparison roadway sections. The intent of evaluating these comparison sections was to measure the safety benefits gained from the installation of rumble strips in contrast to those comparison sections of roads that do not have rumble strips. Safety benefits include a reduction in off-shoulder accidents, as well as a decrease in injury and fatal accidents. Table 20 summarizes the data collected for this study. Overall, the roadway sections with rumble strips experienced a decrease in "rumble strip related" accidents, as well as a decrease in injury and fatal accidents. The comparison sections experienced an increase in accidents, and an increase in fatal accidents.

**Table 20**
**Total Before/After Comparison of Accident Data**

| **Total Accidents - Rumble Strip Section (Before)** | **Total Accidents - Rumble Strip Section (After)** | **Percent (%) Change** | **Total Injury Accidents - Rumble Strip Section (Before)** | **Total Injury Accidents - Rumble Strip Section (After)** | **Percent (%) Change** | **Total Fatal Accidents - Rumble Strip Section (Before)** | **Total Fatal Accidents - Rumble Strip Section (After)** | **Percent (%) Change** |
|---|---|---|---|---|---|---|---|---|
| **270** | **210** | **-22.22%** | **83** | **73** | **-12.05%** | **4** | **2** | **-50.00%** |
| **Total Accidents - Comparison Section (Before)** | **Total Accidents - Comparison Section (After)** | **Percent (%) Change** | **Total Injury Accidents - Comparison Strip Section (Before)** | **Total Injury Accidents - Comparison Section (After)** | **Percent (%) Change** | **Total Fatal Accidents - Comparison Section (Before)** | **Total Accidents - Comparison Section (After)** | **Percent (%) Change** |
| **265** | **294** | **10.94%** | **75** | **68** | **-9.33%** | **2** | **3** | **50.00%** |

Table 21 shows the daily vehicle miles traveled (DVMT) in Connecticut for study period (1993-1998). Note that from 1994 to 1998, DVMT increased annually. This may provide some explanation as to the annual increase in accidents for specific pairs of consecutive years as shown in Table 7. This next section will use the compiled accident data for both rumble strip and comparative section to test the statistical significance of the data.

**Table 21**
**Daily Vehicle Miles Traveled (DMVT)**
**On Interstates and Freeways in Connecticut**

| Year | Daily Vehicle Miles Traveled (DMVT) |
|---|---|
| 1993 | 33417 |
| 1994 | 30429 |
| 1995 | 31470 |
| 1996 | 31633 |
| 1997 | 32666 |
| 1998 | 33644 |

## Statistical Analysis

Hauer (1997) describes Before-After studies for a roadway safety treatment as comprised of two tasks: 1) the prediction of the safety of an entity in the "after" period, had the safety treatment not been applied, and 2) the estimation of safety for the treated entity in the "after" period. In this study, the "before" period refers to the period of time prior to the installation of rumble strips, and the "after" period refers to the time after the installation of rumble strips. The first part of this statistical analysis will attempt to predict the number of accidents for the roadway sections in the study area if rumble strips were not installed. Prediction implies a guess; for this study the guess is what would have been the safety, or number of accidents, had rumble strips not been installed.

In the "naïve" approach described by Hauer (1997), safety would be the same for both "before" and "after" periods for the study entity. However, this implies that various factors such as operating conditions (traffic, pavement conditions, vehicle fleet) are the same in both the "before" and "after" periods. However, reality does not match this "naïve" approach, and the statistical modeling of safety improvements should attempt to account for changes in these operating factors.

The statistical analysis will also estimate roadway safety, through the count of accidents, in the "after" period. In order to estimate the roadway safety for this analysis, some frequently used terms must be defined. Table 22 describes the statistical terms as defined by Hauer (1997) and used in this analysis.

The term $\pi$ is the expected number of target accidents of a specific entity in the "after" period if a safety treatment, such as rumble strips, was not applied. The term, $\lambda$, is the expected number of target accidents of the entity in the "after" period. Note that $\pi$ will be predicted, and $\lambda$ will be estimated. Also notice that there are two entries in Table 22 for the index of effectiveness, $\theta$. The index of effectiveness, $\theta = \frac{\lambda}{\pi}$, does not take into account the possibility of statistical bias. The bias reflects the fact that roadway sections selected for a treatment, such as rumble strips, are not randomly chosen. Hauer (1997) points out for road safety studies, many factors are considered for selecting a treatment site, including traffic flow (ADT), accident history, roadway geometry, and urban/rural classification. This is unlike many statistical analyses, which use a randomized approach whereby data samples or test sites are selected at random, a statistical model is developed, and statistical calculations are performed on the randomly selected data. The revised entry for the index of effectiveness, $\theta^*$, has denominator, $\left[1 + Var\{\hat{\pi}\}/\pi^2\right]$, that accounts for the statistical bias, and this formula will be used throughout this statistical analysis.

There are a couple of rules of thumb for the index of effectiveness, $\theta$. If the result is such that $\theta > 1$, this implies that there are more accidents occurring on the rumble strips sections than if rumble strips had not been installed. Rumble strips for that particular group of roadway sections may be a detriment to safety. If the result is such that $\theta < 1$, this implies that there are fewer accidents on sections of road with rumble strips than if the road was left untreated. This implies a benefit toward safety by the installation of rumble strips.

**Table 22**
**Statistical Notations and Definitions**

| Statistical Notation | Definition |
|---|---|
| $\pi$ | The expected number of target accidents of a specific entity in the "after" period in absence of a safety treatment. $\pi$ is predicted. |
| $\lambda$ | The expected number of target accidents of the entity in the "after" period. $\lambda$ is estimated. |
| $\delta = \pi - \lambda$ | The reduction in the "after" period of the expected number of target accidents. |
| $\theta = \dfrac{\lambda}{\pi}$ | The ratio of what safety was with the treatment to what it would have been without the treatment. $\theta$ is also called the "index of effectiveness". |
| $\theta^* = (\lambda / \pi) / \left[1 + Var\{\hat{\pi}\} / \pi^2\right]$ | Index of Effectiveness with bias removed |

Hauer (1997) describes a four-step process for a before/after study. Table 23 summarizes these steps. Note that $\hat{\lambda}$ refers to an estimated value of $\lambda$, and $\hat{\delta}$ and $\hat{\theta}$ refers to estimates for $\delta$ and $\theta$, respectively. The second step of the statistical analysis predicts the variance of $\hat{\lambda}$, and $\hat{\pi}$, represented by $V\hat{a}r\{\hat{\lambda}\}$, and $V\hat{a}r\{\hat{\pi}\}$. Given $\lambda$ and $\pi$ from step 1 and their variances $V\hat{a}r\{\hat{\lambda}\}$ and $V\hat{a}r\{\hat{\pi}\}$ from step 2, the third step in the analysis was to calculate $\delta$, the reduction in the "after" period of the expected number of target accidents. This step also includes the computation of $\theta$, the index of effectiveness. The final step is to estimate the variance of both $\delta$ and $\theta$, or $V\hat{a}r\{\hat{\delta}\}$ and $V\hat{a}r\{\hat{\theta}\}$.

**Table 23**
**Four Step Statistical Process for Estimating**
**Safety of a Roadway Treatment**

| Step | Description |
|---|---|
| **Step 1 - Estimate $\lambda$ and predict $\pi$.** | $\lambda$ is estimated from the number of accidents for the study area after the installation of rumble strips. $\pi$ is the expected number of accidents for the treatment group or $r_T / \kappa$ (See Table 25 ) |
| **Step 2 - Estimate $V\hat{a}r\{\hat{\lambda}\}$ and $V\hat{a}r\{\hat{\pi}\}$** | The count of accidents after the installation of rumble strips is used to estimate $Var\{\hat{\lambda}\}$. The method used to predict $\hat{\pi}$ will be used to predict $V\hat{a}r\{\hat{\pi}\}$. |
| **Step 3 - Estimate $\delta$ and $\theta$** | $\hat{\lambda}$ and $\hat{\pi}$ are from Step 1, and $V\hat{a}r\{\hat{\lambda}\}$ and $V\hat{a}r\{\hat{\pi}\}$ are from Step 2. The following equations: $\delta = \pi - \lambda$ and $\theta^* = (\lambda / \pi) / \left[1 + Var\{\hat{\pi}\} / \pi^2\right]$ are used for Step 3. |
| **Step 4 - Estimate $Var\{\hat{\delta}\}$ and $Var\{\hat{\theta}\}$** | $\hat{\lambda}$ and $\hat{\pi}$ are from Step 1, and $V\hat{a}r\{\hat{\lambda}\}$ and $V\hat{a}r\{\hat{\pi}\}$ from Step 2, where $Var\{\hat{\delta}\} = Var\{\hat{\pi}\} + Var\{\hat{\lambda}\}$, and $Var\{\hat{\theta}\} = \theta^2 \left[\left(Var\{\hat{\lambda}\} / \lambda^2\right) + \left(Var\{\hat{\pi}\} / \pi^2\right)\right] / \left[1 + Var\{\hat{\pi}\} / \pi^2\right]^2$. |

Hauer (1997) cites two important decisions regarding the study design. The first decision is a determination of the number of roadway sections from which to collect accident data. The second decision is the length of the study. Accident data were collected for six years, three-years "before" the installation of rumble strips and three-years "after". As discussed earlier, there were 11 rumble strip sections and 11 comparison sections. Also, as part of the study design, it is critical to determine the sufficient number of accidents needed to predict a change in safety. This depends on the desired level of precision for the safety estimation, as well as the duration of the "before" and "after" periods.

Hauer (1997) describes how sample size can affect safety estimation. Small accident counts may be sufficient to reach satisfactory conclusions about the effects of a safety treatment. However, when the effect on safety is modest, then more accident data are needed to increase the precision of estimating a safety treatment. Therefore, in order to determine the number of accidents needed this study, the researcher must decide on a desired level of precision for the safety estimation. The following equation given by Hauer (1997) calculates the number of accidents needed to achieve a certain level of precision for a safety study: $\sum K(j) = 2/\sigma\{\hat{\theta}\}$. In this equation $\sum K(j)$ is the expected number of accidents in the "before" period for entities 1 to $j$, and $\sigma\{\hat{\theta}\}$ is the standard deviation for the index of effectiveness, $\theta$. This equation assumes that the "before" and "after" periods in the study are of the same length of time, such as a three year "before" period, and a three year "after" period. In order to visualize the desired level of precision for this study, it is important to consider the properties of the normal distribution. Hauer (1997) points out that for a normal distribution, 67% of the probability mass is within ($\pm$) one standard deviation of the mean ($\sigma$), 95% of the probability mass is within ($\pm$) two standard deviations ($2\sigma$) of the mean, and 99.5% of the probability mass is within 3 standard deviations ($3\sigma$) of the mean.

For this research, Table 24 provides an estimate for the number of accidents needed for this study. The first column of Table 24 displays the desired level of precision, in terms of standard deviation. The second column shows the number of accidents needed. For example, if the desired precision is 0.10, then 200 accidents are needed. The assumption from this table is that the index of effectiveness, $\hat{\theta}$, has a value of 1. In order to show that rumble strips are beneficial to safety, the value of $\theta$ has to be less than or equal to 1, ($\leq 1$). From Table 24, it is evident that if a higher precision of safety is desired, then more accidents are needed. Hauer (1997) maintains that the standard deviation of the estimate, $\sigma$, has to be two to three times smaller than the expected effect on safety. For instance, if the desired level of precision is to detect a 10% change in accidents, then the standard deviation should be considered at 0.05 or 0.03, and would require at least 800 accidents. Due to operational constraints, it is not always possible to collect such a large amount of accidents. However, the larger the number of accidents in both "before" and "after" periods, the greater the statistical precision.

**Table 24**
**Number of Accidents Needed for Study**

| **Desired Level of Precision** $\sigma\{\hat{\theta}\}$ | **Number of Accidents Needed for Study** $2/\sigma^2\{\hat{\theta}\}$ |
|---|---|
| 0.10 | 200 |
| 0.05 | 800 |
| 0.01 | 20000 |
| 0.005 | 80000 |

Typical statistical analysis for predicting safety benefits from a safety treatment use a regression -to-mean approach. The drawback of this approach is that it can solely estimate the safety benefits from a <u>combination</u> of effects, rather than just by the safety treatment. Hauer (1997) claims that it is difficult to determine how much safety is affected only by a treatment, because there are outside influences or causal factors such as traffic volume, weather, driver behavior, and accident reporting that affect overall safety. Some causal factors and external influences are difficult to quantify, and present some bias in the statistical calculation of safety benefits.

Unlike the regression-to-mean approach, the Comparison Group (C-G) methodology accounts for external factors. The idea is that each treatment section has its own separate comparison section. For this study, each of the 11 rumble strip sections had a separate comparison section. The C-G method is based on the premise that in the absence of a safety treatment, such as rumble strips, the ratio of the expected number of accidents during the "before" and "after" periods would be the same for both the treatment and comparison sections. Unlike the "naïve" approach which fails to distinguish between the effect of a treatment and other causal factors that change over time, the C-G method generates estimates that specifically reflect the safety effect of a treatment (Hauer, 1997). The drawback of the C-G approach is the increase of variance of the final estimates.

Hauer (1997) outlines that in order to predict the safety effects of a safety treatment, such as rumble strips, it is necessary to predict the safety in the "after" period, if the treatment had not been applied. To predict the safety received from rumble strips, an 'odds ratio', $\omega$, was computed. The 'odds ratio', represents the ratio of the number of expected accidents in the "after" period to the expected number of accidents in the "before" period. The equation: $\omega = r_c / r_t$, where $r_c$ is the ratio of the expected accident counts for the comparison group ($r_c = \nu / \mu$), and $r_t$ is the corresponding ratio for the treatment group, ($r_t = \pi / \kappa$). The values for $\nu$, $\mu$, $\pi$, and $\kappa$ represent the actual accident counts for the treatment and comparative sections in the "after" periods and are shown in the 2 by 2 matrix in Table 25.

**Table 25**
**Matrix of Before/After Accident Counts**
**For Treatment and Comparison Groups**

| | Treatment Group | Comparison Group |
|---|---|---|
| **Before** | K, $\kappa$ | M, $\mu$ |
| **After** | L, $\lambda$ | N, $\nu$ |

Note that from Table 22, the value of $\pi$ is the expected number of accidents for a specific entity in the "after" period, in absence of a safety treatment. Because a safety treatment, was implemented, $\pi / \kappa$ was used instead of $\lambda / \kappa$, and the value of $\pi$ describes the condition of what the number of accidents would have been if treatment had not been implemented. Using the matrix shown in Table 25, an 'odds' ratio, $\omega$, was calculated for each of the 11 rumble strip sections and their respective comparison sections.

Table 26 shows the 'odds' ratio, $\omega$, for each of the 11 study sections, along with their mean and variance. Hauer (1997) describes a time series for each group of treatment and comparison entities. For each group, a mean value, $\varepsilon\{\omega\}$, and a variance, $VAR\{\omega\}$, was calculated. In order for a comparison group to be valid, it must satisfy the requirement that the mean of the 'odds' ratios be equal to 1, $\varepsilon\{\omega\}=1$. As mentioned earlier, accident data were collected for a total of six years (three years before and three years after the installation of rumble strips). Therefore, a time series of 'odds' ratios were calculated for every two consecutive years within the six-year period. Thus, five 'odds' ratios were computed for each of the 11 study sections, along with their mean and variance.

**Table 26**
**'Odds' Ratio, Mean and Variance**
**For the 11 Rumble Strip Sections**

| Rumble Strip Section & Comparison Section | Odds Ratio $\omega$ | Mean $\varepsilon\{\omega\}$ | Variance $VAR\{\omega\}$ |
|---|---|---|---|
| **Section 1** | 1.70 | 0.98 | 0.58 |
| **Section 2** | 1.07 | 0.94 | 0.25 |
| **Section 3** | 1.41 | 0.51 | 0.08 |
| **Section 4** | 0.88 | *N/A | *N/A |
| **Section 5** | 0.46 | 1.30 | 2.47 |
| **Section 6** | 1.59 | 0.66 | 0.29 |
| **Section 7** | 0.93 | 0.75 | 0.14 |
| **Section 8** | 0.72 | 1.06 | 0.32 |
| **Section 9** | 0.78 | 0.69 | 0.20 |
| **Section 10** | 2.09 | 1.25 | 0.55 |
| **Section 11** | 2.70 | 2.15 | 13.43 |

*Not available - Division by zero

Recall that if the mean of the odds ratio was less than 1 (<1), this would imply that there were a smaller number of accidents in the treatment section (rumble strip section) than the comparison section ("non-rumble strip" section), and the treatment is beneficial for safety. If the mean of the 'odds' ratio was greater than 1 (>1), this indicates that there were more accidents in the treatment section than the comparison section, and the treatment is detrimental to safety. From Table 26, sections 1, 2, 3, 6, 7, and 9 have a mean value of the 'odds' ratio less than 1 (<1). Thus, rumble strips are a positive safety enhancement on these roadway sections. Sections 5, 8, 10 and 11 had mean values of the 'odds' ratio greater than 1 (>1), indicating that the rumble strips may be harmful to roadway safety. Section 4 did not have a time series of 'odds' ratios due to a value of 0 or no accidents recorded for one of the six years of the study periods for the rumble strip section. As a result, a division by zero error occurred from the calculation of 'odds' ratios, and mean and variance values could not be determined.

Hauer (1997) explains that the number of accidents for each treated site is usually small. As described earlier in this section, it is difficult to draw precise conclusions about the effects of the safety treatment with a small number of accidents. The more entities or accidents, the more precise the safety estimates. Thus, by pooling accident data for several roadway sections, there is a greater chance for more precise safety estimates for this study. The drawback of pooling the data is that each section's distinct characteristics would not be represented by the pooled safety estimate. In order to determine whether the precision of safety increases with more accident data, the next step of the analysis pooled the accident data for select roadway sections.

The decisive factor in selecting roadway sections from which to pool accident data, was the mean value of the 'odds' ratio. As previously discussed, if the mean of the 'odds' ratio, $\varepsilon\{\omega\}$, for each section was less than 1, then rumble strips are considered a positive safety enhancement on the roadway sections. From Table 26, sections 1, 2 have a mean value for the 'odds' ratio, $\varepsilon\{\omega\}$ of 0.98, and 0.94, respectively. These values satisfies the condition of $\varepsilon\{\omega\}<1$. Section 7 also has a mean value for the 'odds' ratio of less than 1 ($\varepsilon\{\omega\}<1$), as well as a low variance, $VAR\{\omega\}$**,** of 0.14**.** Other roadway sections in this study, sections 3, 6, and 9, had mean values for the 'odds' ratio of less than 1, but these were not considered significant values to be pooled for the analysis. Therefore, accident data was pooled for sections 1, 2 and 7. Table 27 shows the pooled accident data for sections 1, 2 and 7. Overall, there were more accidents on the comparison sections for sections 1, 2 and 7 than the rumble strip sections for both "before" and "after" periods.

**Table 27**
**Pooled Accident Data for Roadway Sections 1, 2 and 7**

| | **Accidents on Rumble Strip Sections (1,2,7)** | **Accidents on Comparison Sections (1,2,7)** |
|---|---|---|
| **Before** | 70 | 93 |
| **After** | 65 | 116 |

Table 28 shows the pooled accident data for sections 1, 2 and 7 separated by year, as well as their 'odds' ratio calculations. The mean for time series of 'odds' ratios, $\varepsilon\{\omega\}$, for the pooled accident data for sections 1, 2 and 7 was 0.99. The pooled variance, $VAR\{\omega\}$, for these three sites was 0.059. Note that the mean was nearly 1, which implies that rumble strips for these three sections may be beneficial toward safety. The drawback from pooling the data is that each site has distinct operating characteristics, such as traffic flow, that may not match other sites used in the group of pooled data. Thus, pooled estimate of safety does not reflect the unique combination of operating characteristics at each study site.

**Table 28**
**Pooled Accidents Data for Roadway Sections 1, 2 and 7**

| Year | Accidents on Rumble Strip Sections (1,2,7) | Accidents on Comparison Sections (1,2,7) | Odds Ratio |
|---|---|---|---|
| **1993-1994** | 17 | 27 | |
| **1994-1995** | 27 | 30 | 0.65 |
| **1995-1996** | 26 | 36 | 1.16 |
| **1996-1997** | 15 | 28 | 1.23 |
| **1997-1998** | 26 | 43 | 0.82 |
| **1998-1999** | 24 | 45 | 1.06 |
| | | **Mean** | 0.99 |
| | | **Variance** | 0.059 |

Table 29 shows the results of the estimation component of the statistical analysis. The formulas for each component of the analysis are also given. Note that the values of $\hat{\lambda}$ and $V\hat{a}r\{\hat{\lambda}\}$, the expected number of accidents in the "after" period and its corresponding variance, are taken from entry $L$ in the matrix shown in Tables 25, whose numeric value is 65 in Table 27. From Table 29, if rumble strips were not installed on sites 1, 2 and 7, there would have been 86 accidents, $\hat{\pi}$, on rumble strips sections rather than 65 accidents, $\hat{\lambda}$. This means that there was a reduction of 21 accidents, $(\hat{\pi} - \hat{\lambda})$, due to the existence of rumble strips. The index of effectiveness, $\hat{\theta}$, is 0.71. This represents the ratio of safety for the rumble strip sections to what safety would have been if rumble strips were not installed. For this study, the index of effectiveness is the ratio of actual accidents on rumble strip sections to the estimated number of accidents on these roadway sections if rumble strips were not installed.

**Table 29**
**Statistical Results for Sections 1, 2 and 7**

| Statistic | Formula | Value | Explanation |
|---|---|---|---|
| Variance | | 0.059 | |
| $\hat{\lambda}$ | $L$ | 65 | Expected number of accidents to occur in the "after" period |
| $\hat{r}_c$ | $(N/M)/(1+1/M)$ | 1.23 | Comparison ratio of expected "after" accidents to "before" accidents |
| $\hat{\pi}$ | $\hat{r}_T K$ | 86.38 | The expected number of accidents for rumble strips sections in the "after" period if rumble strips were not installed |
| $V\hat{a}r\{\hat{\lambda}\}$ | $L$ | 210 | Expected variance of the number of expected accidents |
| $V\hat{a}r\{\hat{\pi}(j)\}$ | $\hat{\pi}^2\left[1/K + V\hat{a}r\{\hat{r}_T / r_T^2\}\right]$ | 482.49 | Expected variance of the expected number of accidents for rumble strip sections had rumble strips not been installed |
| $\hat{\delta}$ | $\pi - \lambda$ | 21.38 | Reduction in the "after" period of the expected number of accidents for the rumble strip sections |
| $\hat{\theta}$ | $(\lambda/\pi)/\left[Var\{\hat{\pi}\}/\pi^2\right]$ | 0.71 | Index of Effectiveness or the ratio of safety for the rumble strip sections to what would be without the treatment |
| $\hat{\sigma}\{\hat{\delta}\}$ | $\sqrt{Var\{\hat{\pi}\} + Var\{\hat{\lambda}\}}$ | 26.31 | Standard deviation of the reduction in the "after" period for rumble strip sections |
| $\hat{\sigma}\{\hat{\theta}\}$ | $\hat{\theta} * \sqrt{(V\hat{a}r\{\hat{\lambda}\}/\hat{\lambda}^2 + V\hat{a}r\{\hat{\pi}}$ | 0.22 | Standard deviation of the Index of Effectiveness |

The next step in this analysis was to use combined accident data for the 11 rumble strip sections with their respective comparison sections. Table 30 shows the compiled accident data for all 11 rumble strip sections and their comparison sections. From Table 30, there was a decrease in accidents on the rumble strip sections from the "before" to the "after" periods. For the comparison sections, there was an increase in the number of accidents.

**Table 30**
**Compiled Accident Data for 11 Roadway Sections**

| | Rumble Strip Sections | Comparison Sections |
|---|---|---|
| **Before** | 270 | 265 |
| **After** | 210 | 294 |

Table 31 shows the results of the 'odds' ratio calculation for the 11 roadway sections. Notice that the mean of the 'odds' ratio was 1.06, a value slightly higher 1. The variance is very low.

**Table 31**
**Compiled Accident Data for 11 Roadway Sections**

| Year | Accidents on Rumble Strip Sections | Accidents on Comparison Sections | Odds Ratio |
|---|---|---|---|
| **1993-1994** | 86 | 76 | |
| **1994-1995** | 100 | 95 | 1.05 |
| **1995-1996** | 84 | 94 | 1.15 |
| **1996-1997** | 61 | 82 | 1.17 |
| **1997-1998** | 69 | 109 | 1.14 |
| **1998-1999** | 80 | 103 | 0.80 |
| | | **Mean** | 1.06 |
| | | **Variance** | 0.024 |

Table 32 displays the statistical estimation results for the 11 rumble strip sections. First, if rumble strips had not been installed, there would have been 298 accidents, $\hat{\pi}$, rather than the actual 210 accidents, $\hat{\lambda}$. The index of effectiveness, $\hat{\theta}$, was 0.68, and represents an estimated reduction of 88 accidents on the roadway sections due to the installation of rumble strips. As previously mentioned, the variance, $V\hat{a}r\{\hat{\pi}(j)\}$, was very high, a drawback for the C-G method.

**Table 32**
**Statistical Results for 11 Roadway Sections**

| Statistic | Value | Explanation |
|---|---|---|
| Variance | 0.024 | |
| $\hat{\lambda}$ | 210 | Expected number of accidents to occur in the "after" period |
| $\hat{r}_c$ | 1.10 | Comparison ratio of expected "after" accidents to "before" accidents |
| $\hat{\pi}$ | 298.42 | The expected number of accidents for rumble strips sections in the "after" period if rumble strips were not installed |
| $V\hat{a}r\{\hat{\lambda}\}$ | 210 | Expected variance of the number of expected accidents |
| $V\hat{a}r\{\hat{\pi}(j)\}$ | 3106.12 | Expected variance of the expected number of accidents for rumble strip sections had rumble strips not been installed |
| $\hat{\delta}$ | 88.42 | Reduction in the "after" period of the expected number of accidents for the rumble strip sections |
| $\hat{\theta}$ | 0.68 | Index of Effectiveness or the ratio of safety for the rumble strip sections to what would be without the treatment |
| $\hat{\sigma}\{\hat{\delta}\}$ | 57.58 | Standard deviation of the reduction in the "after" period for rumble strip sections |
| $\hat{\sigma}\{\hat{\theta}\}$ | 0.13 | Standard deviation of the Index of Effectiveness |

From the statistical analysis, it is evident even a small number of accidents can achieve a satisfactory results. For the pooled data, for sections 1, 2 and 7, the results showed a reduction of 21 accidents, nearly a 30% decrease, due to the installation of rumble strips. However, by using a larger number of accidents, statistical precision for a safety treatment can be attained. The statistical results for the accident data for the 11 sections showed a reduction of 88 accidents, or 32% decrease in accidents. To achieve greater statistical precision, it is recommended that a significant amount accident data be collected.

## Summary of Statistical Analysis

The statistical analysis attempted to determine the expected number of accidents in the "after" period if rumble strips were not installed. There were 11 rumble strip sections, and 11 matching comparison sections. The Comparison Group (C-G) method was then used whereby an 'odds' ratio was calculated to determine the expected number of accidents in absence of rumble strips. Table 26 shows the mean values of the 'odds' ratio for each of the 11 rumble strip sections. The mean value of the 'odds' ratio should be less than 1 (<1), indicating a safety benefit. Of the 11 sections, only three of the 11 sections did not satisfy this requirement. In order to increase the precision of safety estimation, data were pooled for 3 of the 11 study sections. It should be recognized that each of the 11 sections has a unique combination of external characteristics. A separate examination of each section would reveal the safety effects from rumble strips for each individual site. Further statistical analysis was performed on the pooled data for these three sections. Table 29 shows the results, including an index of effectiveness, or a safety measure of rumble strips. From the analysis, the index of effectiveness had a value of 0.71, and it was found that there would be 21 less fixed-object, single-vehicle, run-off-the-road accidents than if rumble strips had not been installed.

The statistical analysis for the compiled accident data for the 11 rumble strip sections and their respective comparison sections resulted in an index of effectiveness, $\hat{\theta}$, of 0.68. The results also showed that there would have been 88 "rumble strip related" accidents if rumble strips were not installed. From these statistical procedures, it is evident that rumble strips affect safety by a reduction of accidents.

## Conclusion and Further Study Recommendations

Rumble strips are a corrective measure to alert inattentive drivers of approaching hazards. Across the U.S., inattentive driving has led to an escalation of accidents. The documented success regarding accident mitigation from rumble strips differs by geographic location, rumble strip design, placement and installation methods. However, there is a general consensus among transportation agencies about the positive safety benefits gained from the installation of rumble strips.

This research attempted to measure the safety benefits achieved from rumble strips along roadways in Connecticut. For this study, safety benefits are considered a reduction in single-vehicle, fixed object, run-off-the-road accidents. From the results of the data description, the number of "rumble strip related" (single vehicle, fixed object, run-off-the road) accidents decreased as well as the number of "asleep" and injury/fatal accidents. The study incorporated a methodology that uses comparative sections to predict the "what if" scenario of the number of accidents that would have occurred if rumble strips had not been installed. The statistical analysis used the comparison sections and calculated an index of effectiveness based on accident data for the rumble strip and comparison sections. For this study, the statistical results showed an index of effectiveness that reflected a decrease in "rumble strip related" accidents for the collected accident data.

This study used the Comparison Group methodology to predict rumble strip accidents, without reference to causal factors such as driver behavior, accident reporting, and traffic counts. Hauer (1997) recommends accounting for factors such as traffic through the incorporation of average daily traffic (ADT) data in the statistical analysis. Inclusion of this data in the comparison ratio would represent realistic operating conditions along roadways. This would require available and reliable ADT data for those sections of roadway in the "before" and "after" periods. However, the ADT data is not always available. Future research should attempt to account for ADT in future rumble strip studies. Connecticut continues to install rumble strips along roadways, and continued observation of the accident data will reflect the impacts on roadway safety.

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# Appendix A

## List of 300 Shoulder Miles on 73 Sections of Limited-Access Highway, installed in 1995

| ID | Route | Dir | Shoulder | To | From | Location Description |
|---|---|---|---|---|---|---|
| 1 | 6 | E | right | 88.53 | 92.80 | .55 mile east of Hop River Overpass |
| 2 | 6 | E | left | 88.09 | 89.95 | US 6 underpass (Boston Post Road) |
| 3 | 6 | E | left | 90.64 | 90.80 | .18 mile east of Mansfield Ave underpass |
| 4 | 6 | E | right | 87.85 | 92.61 | Begin Route 6 as mainline |
| 5 | 6 | E | left | 87.85 | 92.61 | .11 mile west of Hop River overpass |
| 6 | 7 | N | right | 0.40 | 3.81 | I-95 overpass |
| 7 | 7 | N | right | 25.74 | 29.85 | Federal Road overpass |
| 8 | 7 | N | left | 0.40 | 3.94 | I-95 overpass |
| 9 | 7 | N | left | 25.74 | 29.64 | Federal Road overpass |
| 10 | 7 | S | right | 25.74 | 29.25 | Federal Road overpass |
| 11 | 7 | S | right | 0.00 | 3.81 | End of ramp to I-95 Southbound |
| 12 | 7 | S | left | 25.74 | 29.49 | Federal Road overpass |
| 13 | 7 | S | left | 0.33 | 3.81 | I-95 overpass |
| 14 | 8 | N | right | 19.28 | 22.20 | .33 mile north of entrance from Route 67 (past Exit 22) |
| 15 | 8 | N | right | 23.67 | 25.14 | 1.47 mile north of entrance from SR 852 |
| 16 | 8 | N | right | 42.64 | 49.25 | .16 mile north of entrance to rest area |
| 17 | 8 | N | right | 49.71 | 50.11 | .52 mile north of entrance from Harwinton Ave |
| 18 | 8 | N | right | 53.41 | 54.92 | 1.43 mile north of entrance from Kennedy Drive (exit 45) |
| 19 | 8 | N | right | 57.65 | 58.44 | .56 mile north of Greenwoods Rd underpass |
| 20 | 8 | N | left | 19.28 | 25.14 | .33 mile north of entrance from Route 67 (past Exit 22) |
| 21 | 8 | N | left | 40.38 | 58.44 | .88 mile north of entrance from Route 67 (past Exit 22) |
| 22 | 8 | S | right | 19.28 | 20.65 | .12 mile south of SR 721 underpass |
| 23 | 8 | S | right | 21.02 | 21.41 | 1.30 mile south of exit to SR 852 |
| 24 | 8 | S | right | 22.15 | 25.14 | .18 mile south of exit to SR 852 (Exit 24) |
| 25 | 8 | S | right | 31.26 | 34.07 | .07 Mile South of Route 73 overpass |
| 26 | 8 | S | right | 34.84 | 43.09 | .57 mile south of Echo Lake Rd overpass |
| 27 | 8 | S | right | 45.01 | 47.60 | .06 mile south of Conrail & Naugatuck Rv overpass |
| 28 | 8 | S | right | 48.13 | 51.76 | .84 mile south of entrance from Harwinton Ave |
| 29 | 8 | S | right | 54.50 | 55.84 | .18mile south of Greenwoods Rd underpass |
| 30 | 8 | S | right | 57.80 | 58.29 | .49 mile wouth of beginning of expressway |
| 31 | 8 | S | left | 31.26 | 58.29 | .99 mile south of entrance from Huntingdon Ave |
| 32 | 8 | S | left | 19.28 | 25.14 | .12 mile south of SR 721 (N. Main St.) underpass |
| 33 | 9 | N | right | 0.23 | 3.91 | I-95 underpass |
| 34 | 9 | N | right | 24.47 | 27.43 | .01 mile north of Middletown town line sign |
| 35 | 9 | N | right | 37.49 | 39.93 | .07 mile north of Bass Brook overpass |
| 36 | 9 | N | left | 0.42 | 3.91 | Exit from I-95 southbound |
| 37 | 9 | N | left | 24.47 | 27.43 | Middletown town line sign |

| ID | Route | Dir | Shoulder | To | From | Location Description |
|---:|---:|---|---|---:|---:|---|
| 38 | 9 | N | left | 37.40 | 39.93 | .07 mile north of Bass Brook overpass |
| 39 | 9 | S | right | 0.23 | 3.91 | I-95 underpass |
| 40 | 9 | S | right | 24.47 | 29.10 | .03 mile south of Middletown-Cromwell TL sign |
| 41 | 9 | S | right | 37.49 | 40.71 | Entrance from Route 175 (Exit 29) |
| 42 | 9 | S | left | 0.27 | 3.91 | .09 mile south of entrance to I-95 SB |
| 43 | 9 | S | left | 24.47 | 29.10 | .03 mile south of Middletown-Cromwell TL sign |
| 44 | 9 | S | left | 37.49 | 40.71 | Entrance from Route 175 (Exit 29) |
| 45 | 11 | N | right | 10.38 | 17.80 | Entrance from Route 82 |
| 46 | 11 | N | left | 10.38 | 17.80 | Entrance from Route 82 |
| 47 | 11 | S | right | 10.38 | 17.80 | .05 mile north of exit to Route 82 |
| 48 | 11 | S | left | 10.38 | 17.80 | .05 mile north of exit to Route 82 |
| 49 | 15 | N | right | 50.20 | 66.86 | Route 10 overpass (Exit 60) |
| 50 | 15 | S | right | 50.20 | 63.87 | Route 10 overpass (Exit 60) |
| 51 | 15 | S | right | 65.41 | 66.86 | .04 mile north of Baldwin Ave underpass |
| 52 | 20 | E | right | 30.35 | 31.52 | .21 mile west of entrance from Old County Road |
| 53 | 20 | E | left | 30.56 | 31.52 | Entrance from Old County Road |
| 54 | 20 | W | right | 30.35 | 31.52 | .63 mile west of entrance from I-91 SB |
| 55 | 20 | W | left | 30.56 | 31.52 | .42 mile west of entrance from I-91 SB |
| 56 | 40 | N | right | 0.57 | 1.36 | Entrance from I-91 SB |
| 57 | 40 | N | left | 0.57 | 1.36 | Entrance from I-91 SB |
| 58 | 40 | S | right | 0.53 | 0.80 | I-91 overpass |
| 59 | 40 | S | left | 0.53 | 0.80 | I-91 overpass |
| 60 | 72 | N | right | 0.00 | 3.20 | Junction northbound Route 9 |
| 61 | 72 | N | right | 3.72 | 4.54 | I-84 overlap ends |
| 62 | 72 | N | left | 0.00 | 3.20 | Junction northbound Route 9 |
| 63 | 72 | N | left | 3.72 | 4.54 | I-84 overlap ends |
| 64 | 72 | S | right | 0.31 | 3.11 | Route 71 underpass |
| 65 | 72 | S | right | 3.72 | 4.54 | I-84 overlap begins |
| 66 | 72 | S | left | 0.31 | 3.11 | Route 71 underpass |
| 67 | 72 | S | left | 3.72 | 4.54 | I-84 overlap begins |
| 68 | 693 | N | right | 0.00 | 1.41 | Junction Route 32 northbound |
| 69 | 693 | N | left | 0.00 | 0.96 | Junction Route 32 northbound |
| 70 | 693 | N | left | 1.05 | 1.23 | .73 mile north of end of Route 32 overpass |
| 71 | 693 | N | left | 1.25 | 1.41 | Junction I-395 |
| 72 | 693 | S | right | 0.00 | 1.41 | Junction Route 32 northbound |
| 73 | 693 | S | left | 0.00 | 1.41 | Junction Route 32 northbound |

# Appendix B

## Accident Data for 3-Year Before/After Analysis

| Before Rumble Strip Installation | | | | | | | After Rumble Strip Installation | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Section Number** | **Total Accidents 1993-94** | **Rumble Strip Related Accidents 1993-94** | **Total Accidents 1994-95** | **Rumble Strip Related Accidents 1994-95** | **Total Accidents 1995-96** | **Rumble Strip Related Accidents 1995-96** | **Total Accidents 1996-97** | **Rumble Strip Related Accidents 1996-97** | **Total Accidents 1997-98** | **Rumble Strip Related Accidents 1997-98** | **Total Accidents 1998-99** | **Rumble Strip Related Accidents 1998-99** |
| **1** | 28 | 1 | 29 | 2 | 27 | 0 | 18 | 1 | 19 | 0 | 18 | 0 |
| **2** | 2 | 0 | 5 | 1 | 7 | 1 | 7 | 0 | 5 | 0 | 4 | 1 |
| **3** | 30 | 1 | 14 | 1 | 14 | 0 | 10 | 1 | 12 | 0 | 9 | 1 |
| **4** | 22 | 1 | 29 | 3 | 29 | 2 | 20 | 0 | 23 | 0 | 19 | 0 |
| **5** | 30 | 0 | 29 | 2 | 29 | 1 | 20 | 1 | 23 | 4 | 19 | 1 |
| **6** | 79 | 0 | 19 | 0 | 88 | 2 | 102 | 1 | 92 | 2 | 77 | 0 |
| **7** | 31 | 0 | 32 | 3 | 28 | 2 | 45 | 0 | 31 | 0 | 20 | 1 |
| **8** | 80 | 1 | 19 | 0 | 89 | 3 | 106 | 3 | 94 | 3 | 78 | 0 |
| **9** | 28 | 0 | 31 | 3 | 26 | 0 | 38 | 0 | 24 | 3 | 16 | 1 |
| **10** | 27 | 1 | 25 | 1 | 23 | 2 | 33 | 2 | 21 | 0 | 16 | 0 |
| **11** | 85 | 3 | 62 | 1 | 93 | 0 | 109 | 3 | 96 | 2 | 81 | 1 |
| **12** | 28 | 0 | 26 | 0 | 23 | 0 | 35 | 0 | 24 | 1 | 16 | 0 |
| **13** | 79 | 1 | 59 | 1 | 88 | 3 | 102 | 1 | 92 | 3 | 77 | 1 |
| **14** | 15 | 1 | 26 | 1 | 17 | 1 | 16 | 0 | 10 | 0 | 22 | 1 |
| **15** | 21 | 0 | 6 | 1 | 20 | 2 | 16 | 0 | 24 | 0 | 15 | 1 |
| **16** | 54 | 3 | 64 | 3 | 44 | 2 | 43 | 3 | 49 | 6 | 69 | 5 |
| **17** | 3 | 0 | 2 | 0 | 9 | 0 | 3 | 0 | 6 | 0 | 9 | 0 |
| **18** | 1 | 0 | 6 | 0 | 13 | 1 | 3 | 0 | 4 | 0 | 6 | 0 |
| **19** | 8 | 5 | 1 | 0 | 9 | 1 | 8 | 3 | 3 | 0 | 9 | 1 |
| **20** | 55 | 2 | 43 | 4 | 46 | 7 | 48 | 3 | 54 | 4 | 57 | 8 |
| **21** | 112 | 11 | 125 | 23 | 135 | 16 | 109 | 12 | 114 | 23 | 149 | 18 |
| **22** | 6 | 0 | 8 | 2 | 8 | 2 | 7 | 3 | 3 | 1 | 11 | 0 |
| **23** | 1 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 4 | 0 | 2 | 0 |
| **24** | 40 | 2 | 29 | 0 | 31 | 0 | 33 | 1 | 46 | 1 | 36 | 2 |
| **25** | 51 | 3 | 39 | 2 | 43 | 1 | 41 | 1 | 34 | 1 | 45 | 1 |
| **26** | 66 | 5 | 51 | 1 | 64 | 4 | 67 | 2 | 65 | 1 | 61 | 2 |

| Before Rumble Strip Installation | | | | | | | After Rumble Strip Installation | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Section Number** | **Total Accidents 1993-94** | **Rumble Strip Related Accidents 1993-94** | **Total Accidents 1994-95** | **Rumble Strip Related Accidents 1994-95** | **Total Accidents 1995-96** | **Rumble Strip Related Accidents 1995-96** | **Total Accidents 1996-97** | **Rumble Strip Related Accidents 1996-97** | **Total Accidents 1997-98** | **Rumble Strip Related Accidents 1997-98** | **Total Accidents 1998-99** | **Rumble Strip Related Accidents 1998-99** |
| **27** | 30 | 5 | 44 | 3 | 24 | 1 | 22 | 1 | 29 | 2 | 36 | 1 |
| **28** | 21 | 2 | 28 | 3 | 43 | 2 | 31 | 3 | 29 | 2 | 34 | 4 |
| **29** | 7 | 0 | 13 | 2 | 14 | 5 | 14 | 2 | 15 | 2 | 4 | 0 |
| **30** | 5 | 0 | 0 | 0 | 8 | 0 | 3 | 0 | 3 | 1 | 7 | 0 |
| **31** | 227 | 19 | 206 | 27 | 229 | 22 | 206 | 23 | 210 | 25 | 251 | 27 |
| **32** | 55 | 6 | 55 | 4 | 46 | 2 | 48 | 1 | 54 | 5 | 8 | 3 |
| **33** | 22 | 2 | 26 | 1 | 21 | 1 | 16 | 0 | 25 | 2 | 24 | 4 |
| **34** | 44 | 3 | 43 | 3 | 40 | 6 | 46 | 7 | 27 | 0 | 45 | 5 |
| **35** | 41 | 0 | 53 | 5 | 63 | 3 | 59 | 0 | 66 | 0 | 79 | 2 |
| **36** | 22 | 2 | 10 | 0 | 20 | 1 | 13 | 0 | 18 | 1 | 21 | 0 |
| **37** | 44 | 1 | 43 | 10 | 40 | 3 | 46 | 5 | 27 | 6 | 45 | 9 |
| **38** | 41 | 0 | 53 | 0 | 63 | 0 | 59 | 2 | 66 | 2 | 79 | 0 |
| **39** | 22 | 0 | 26 | 5 | 21 | 3 | 16 | 2 | 25 | 2 | 24 | 3 |
| **40** | 73 | 7 | 80 | 8 | 78 | 5 | 84 | 5 | 79 | 5 | 89 | 2 |
| **41** | 45 | 0 | 56 | 3 | 68 | 2 | 72 | 0 | 69 | 3 | 24 | 2 |
| **42** | 22 | 2 | 26 | 3 | 21 | 1 | 16 | 2 | 25 | 1 | 24 | 2 |
| **43** | 73 | 6 | 92 | 6 | 78 | 4 | 84 | 9 | 79 | 9 | 89 | 6 |
| **44** | 45 | 1 | 56 | 2 | 68 | 2 | 72 | 2 | 69 | 1 | 86 | 2 |
| **45** | 12 | 2 | 14 | 1 | 16 | 0 | 13 | 1 | 10 | 3 | 13 | 1 |
| **46** | 12 | 1 | 14 | 0 | 16 | 1 | 13 | 1 | 10 | 1 | 13 | 1 |
| **47** | 12 | 1 | 14 | 3 | 16 | 0 | 13 | 1 | 10 | 0 | 13 | 1 |
| **48** | 12 | 2 | 14 | 5 | 16 | 3 | 13 | 2 | 10 | 1 | 13 | 2 |
| **49** | 373 | 28 | 442 | 23 | 562 | 23 | 454 | 16 | 409 | 9 | 417 | 20 |
| **50** | 403 | 14 | 394 | 12 | 510 | 13 | 400 | 3 | 369 | 8 | 377 | 9 |
| **51** | 6 | 0 | 2 | 0 | 7 | 2 | 4 | 0 | 6 | 0 | 7 | 0 |
| **52** | 8 | 1 | 9 | 0 | 13 | 2 | 19 | 0 | 8 | 0 | 15 | 1 |

| Before Rumble Strip Installation | | | | | | | After Rumble Strip Installation | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Section Number** | **Total Accidents 1993-94** | **Rumble Strip Related Accidents 1993-94** | **Total Accidents 1994-95** | **Rumble Strip Related Accidents 1994-95** | **Total Accidents 1995-96** | **Rumble Strip Related Accidents 1995-96** | **Total Accidents 1996-97** | **Rumble Strip Related Accidents 1996-97** | **Total Accidents 1997-98** | **Rumble Strip Related Accidents 1997-98** | **Total Accidents 1998-99** | **Rumble Strip Related Accidents 1998-99** |
| **53** | 6 | 0 | 5 | 1 | 6 | 2 | 15 | 1 | 8 | 3 | 11 | 0 |
| **54** | 8 | 1 | 9 | 3 | 13 | 0 | 19 | 1 | 8 | 1 | 15 | 0 |
| **55** | 6 | 0 | 5 | 0 | 6 | 2 | 15 | 2 | 8 | 0 | 11 | 1 |
| **56** | 6 | 0 | 7 | 0 | 17 | 0 | 10 | 0 | 11 | 1 | 9 | 0 |
| **57** | 6 | 0 | 7 | 1 | 17 | 1 | 10 | 0 | 11 | 0 | 9 | 2 |
| **58** | 1 | 0 | 1 | 0 | 4 | 1 | 3 | 0 | 6 | 0 | 2 | 0 |
| **59** | 1 | 0 | 1 | 0 | 4 | 1 | 3 | 0 | 6 | 0 | 2 | 0 |
| **60** | 112 | 2 | 65 | 6 | 89 | 2 | 102 | 0 | 95 | 8 | 91 | 8 |
| **61** | 16 | 2 | 14 | 0 | 11 | 0 | 8 | 0 | 10 | 1 | 12 | 0 |
| **62** | 112 | 6 | 65 | 4 | 89 | 2 | 102 | 0 | 95 | 6 | 91 | 8 |
| **63** | 16 | 0 | 14 | 2 | 11 | 0 | 8 | 0 | 10 | 0 | 12 | 2 |
| **64** | 98 | 1 | 55 | 2 | 80 | 6 | 86 | 2 | 83 | 5 | 78 | 3 |
| **65** | 16 | 3 | 14 | 1 | 11 | 0 | 8 | 0 | 10 | 0 | 12 | 0 |
| **66** | 98 | 4 | 91 | 4 | 80 | 6 | 86 | 5 | 83 | 3 | 78 | 2 |
| **67** | 16 | 3 | 14 | 5 | 11 | 1 | 8 | 2 | 10 | 0 | 12 | 2 |
| **68** | 10 | 0 | 12 | 3 | 15 | 1 | 12 | 2 | 12 | 1 | 7 | 1 |
| **69** | 6 | 0 | 12 | 1 | 9 | 0 | 10 | 1 | 7 | 0 | 4 | 0 |
| **70** | 1 | 0 | 0 | 0 | 1 | 0 | 2 | 0 | 1 | 0 | 0 | 0 |
| **71** | 3 | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 4 | 0 | 3 | 0 |
| **72** | 10 | 0 | 12 | 0 | 15 | 1 | 12 | 0 | 12 | 1 | 7 | 3 |
| **73** | 10 | 1 | 12 | 2 | 15 | 1 | 12 | 1 | 12 | 3 | 7 | 0 |
| **Total** | **3217** | **169** | **3007** | **219** | **3615** | **187** | **3406** | **146** | **3221** | **179** | **3251** | **185** |

# Appendix C

## List of Limited-Access Highway Sections with Minimum 3-Feet Shoulder, installed in 1995

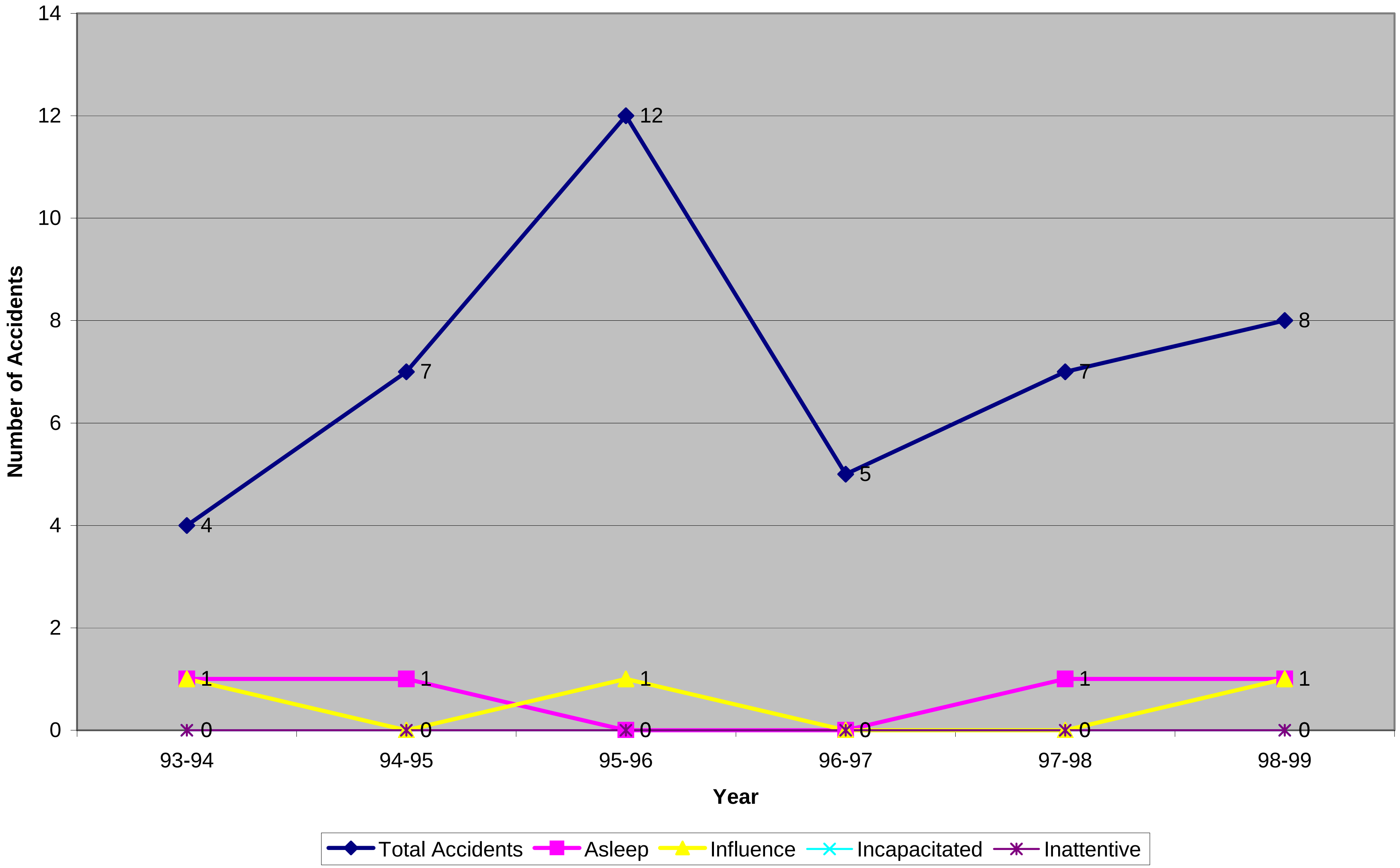
## Limited-access highway locations for installation of rumble strips

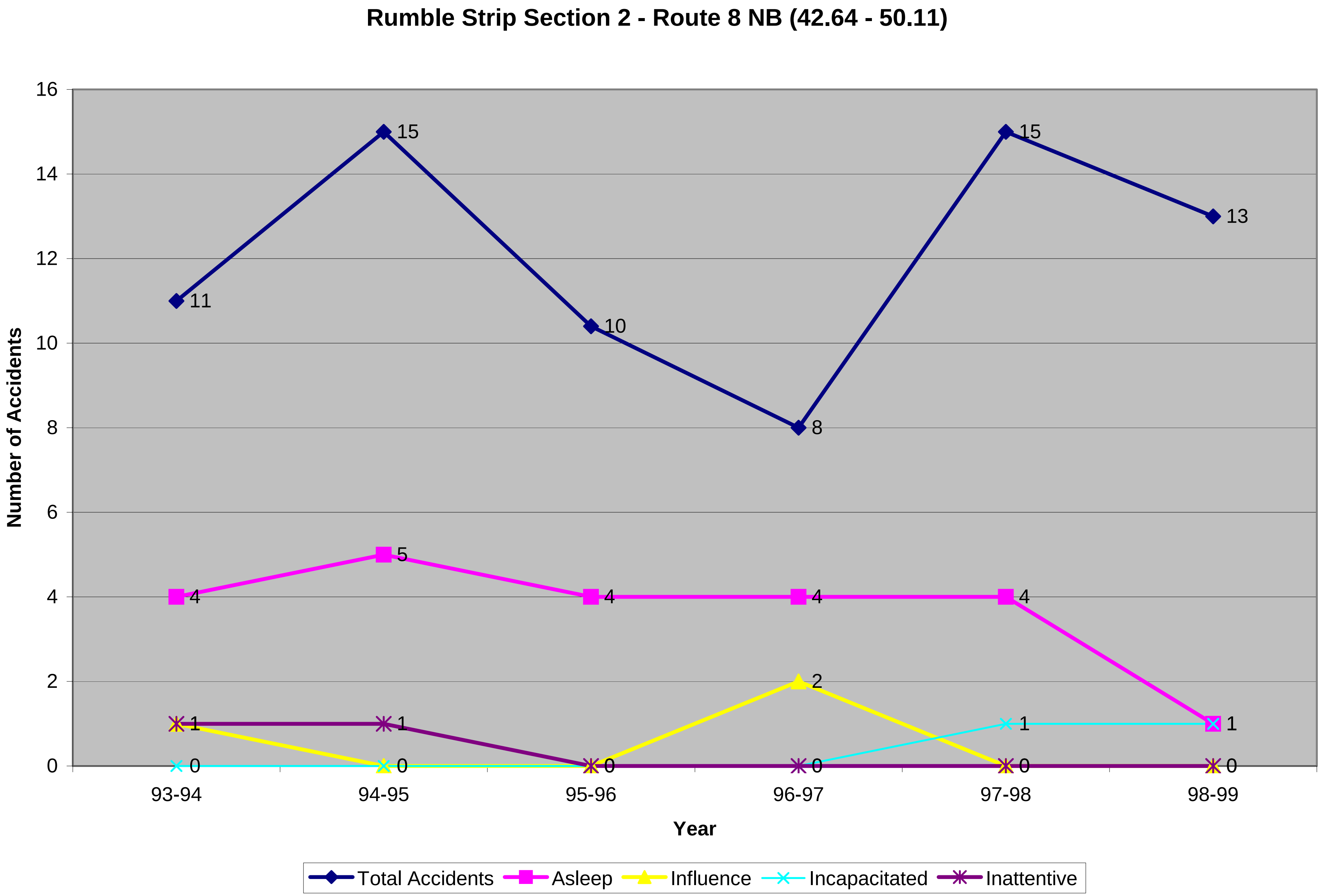
| Route | Begin Mile | Begin km | Begin Description | Begin Town | End Mile | End km | End Description | End Town | Length(miles) | Length(km) |
|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 0.00 | 0.00 | Columbus Blvd. | Hartford | 38.15 | 61.40 | Route 169 | Norwich | 38.15 | 61.40 |
| 6 | 87.81 | 141.32 | Route 66 | Columbia | 92.87 | 149.46 | Route 66 | Windham | 5.06 | 8.14 |
| 7 | 0.00 | 0.00 | I-95 | Norwalk | 3.92 | 6.31 | Gristmill Road | Norwalk | 3.92 | 6.31 |
|  | 20.00 | 32.19 | Begin Expressway | Danbury | 21.56 | 34.70 | Begin I-84 overlap | Danbury | 1.56 | 2.51 |
|  | 25.21 | 40.57 | End I-84 overlap | Danbury | 29.91 | 48.14 | US 202 | Brookfield | 4.70 | 7.57 |
| 8 | 0.00 | 0.00 | I-95 | Bridgeport | 58.29 | 93.81 | US 44 | Winchester | 58.29 | 93.81 |
| 9 | 0.00 | 0.00 | I-95 | Old Saybrook | 40.89 | 65.81 | I-84 | West Hartford | 40.89 | 65.81 |
| 11 | 10.12 | 16.29 | Route 82 | Salem | 17.80 | 28.65 | Route 2 | Colchester | 7.68 | 12.36 |
| 15 | 37.62 | 60.54 | Housatonic River | Milford | 66.86 | 107.60 | Berlin Turnpike | Meriden | 29.24 | 47.06 |
|  | 77.94 | 125.43 | Rt. 314 | Wethersfield | 83.53 | 134.43 | I-84 | East Hartford | 5.59 | 9.00 |
| 20 | 27.72 | 44.61 | Bradley Connector | Windsor Locks | 31.56 | 50.79 | I-91 | Windsor | 3.84 | 6.18 |
| 25 | 3.75 | 6.04 | End Rt. 8 overlap | Bridgeport | 9.87 | 15.88 | Route 111 | Trumbull | 6.12 | 9.84 |
| 40 | 0.00 | 0.00 | I-91 | North Haven | 3.08 | 4.96 | Route 10 | Hamden | 3.08 | 4.96 |
| 72 | 0.00 | 0.00 | Route 9 | New Britain | 3.20 | 5.15 | Begin I-84 overlap | Plainville | 3.20 | 5.15 |
|  | 3.72 | 5.99 | End I-84 overlap | Plainville | 6.33 | 10.19 | Route 372 | Plainville | 2.61 | 4.20 |
| I-84 | 0.00 | 0.00 | N.Y. state line | Danbury | 97.9 | 157.55 | Mass. State Line | Union | 97.90 | 157.55 |
| I-91 | 0.00 | 0.00 | I-95 | New Haven | 58.00 | 93.34 | Mass. State Line | Enfield | 58.00 | 93.34 |
| I-95 | 0.00 | 0.00 | N.Y. state line | Greenwich | 111.57 | 179.55 | R.I. State Line | N. Stonington | 111.57 | 179.55 |
| I-291 | 0.00 | 0.00 | I-91 | Windsor | 6.40 | 10.30 | I-84 | Manchester | 6.40 | 10.30 |
| I-384 | 0.00 | 0.00 | I-84 | East Hartford | 8.53 | 13.73 | US 6 & US 44 | Bolton | 8.53 | 13.73 |
| I-395 | 0.00 | 0.00 | I-95 | East Lyme | 54.69 | 88.02 | Mass. State Line | Thompson | 54.69 | 88.02 |
| I-691 | 0.00 | 0.00 | Route 66 | Meriden | 8.92 | 14.36 | I-84 | Cheshire | 8.92 | 14.36 |
| 693 | 0.00 | 0.00 | Route 32 | Waterford | 1.41 | 2.27 | I-395 | Montville | 1.41 | 2.27 |
| 695 | 0.00 | 0.00 | I-395 | Plainfield | 4.49 | 7.23 | R.I. State Line | Killingly | 4.49 | 7.23 |
| 796 | 0.00 | 0.00 | US 1 | Milford | 2.88 | 4.63 | Route 15 | Milford | 2.88 | 4.63 |

# Appendix D

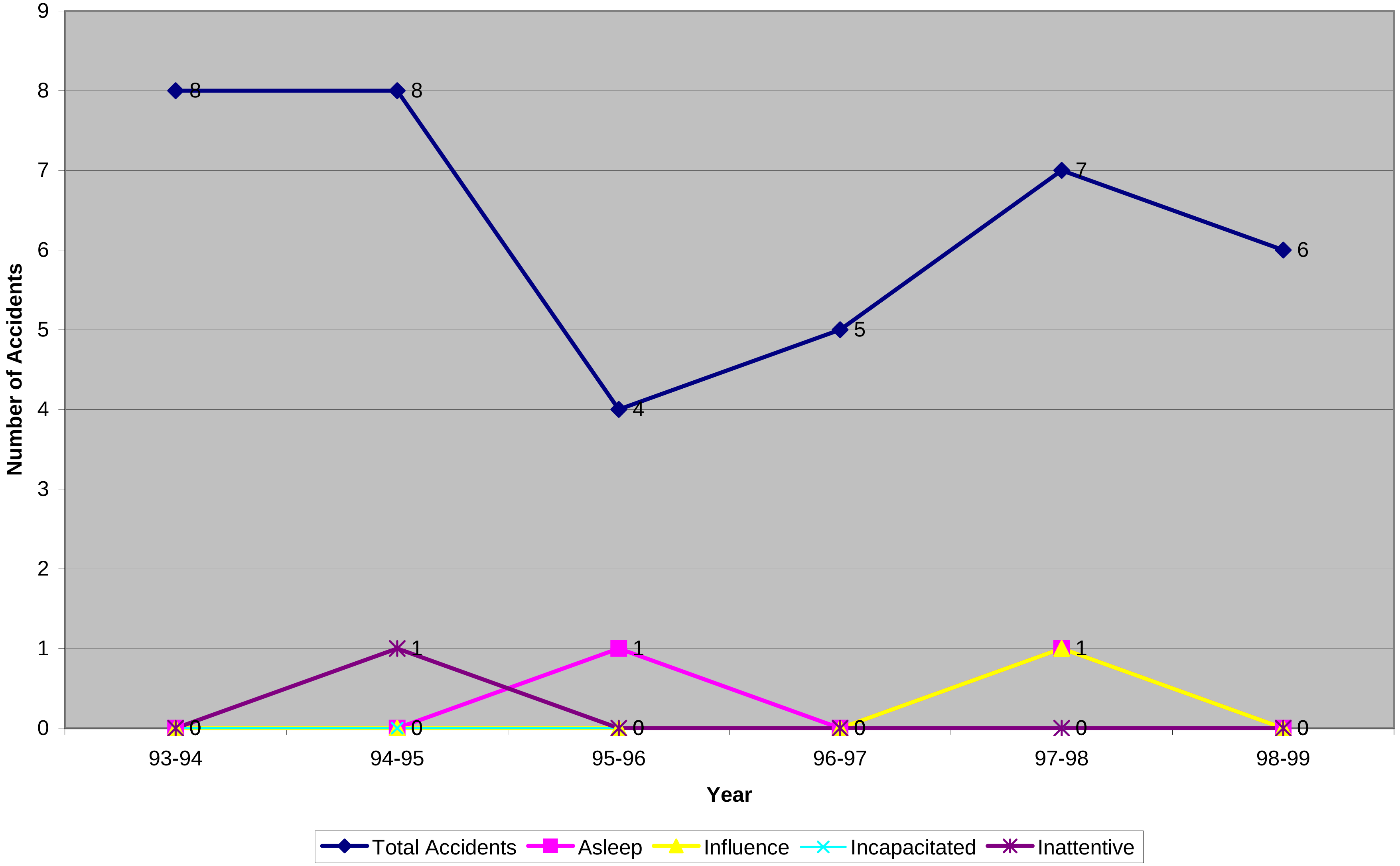
## Graphical Display of Accidents on 11 Rumble Strip Sections

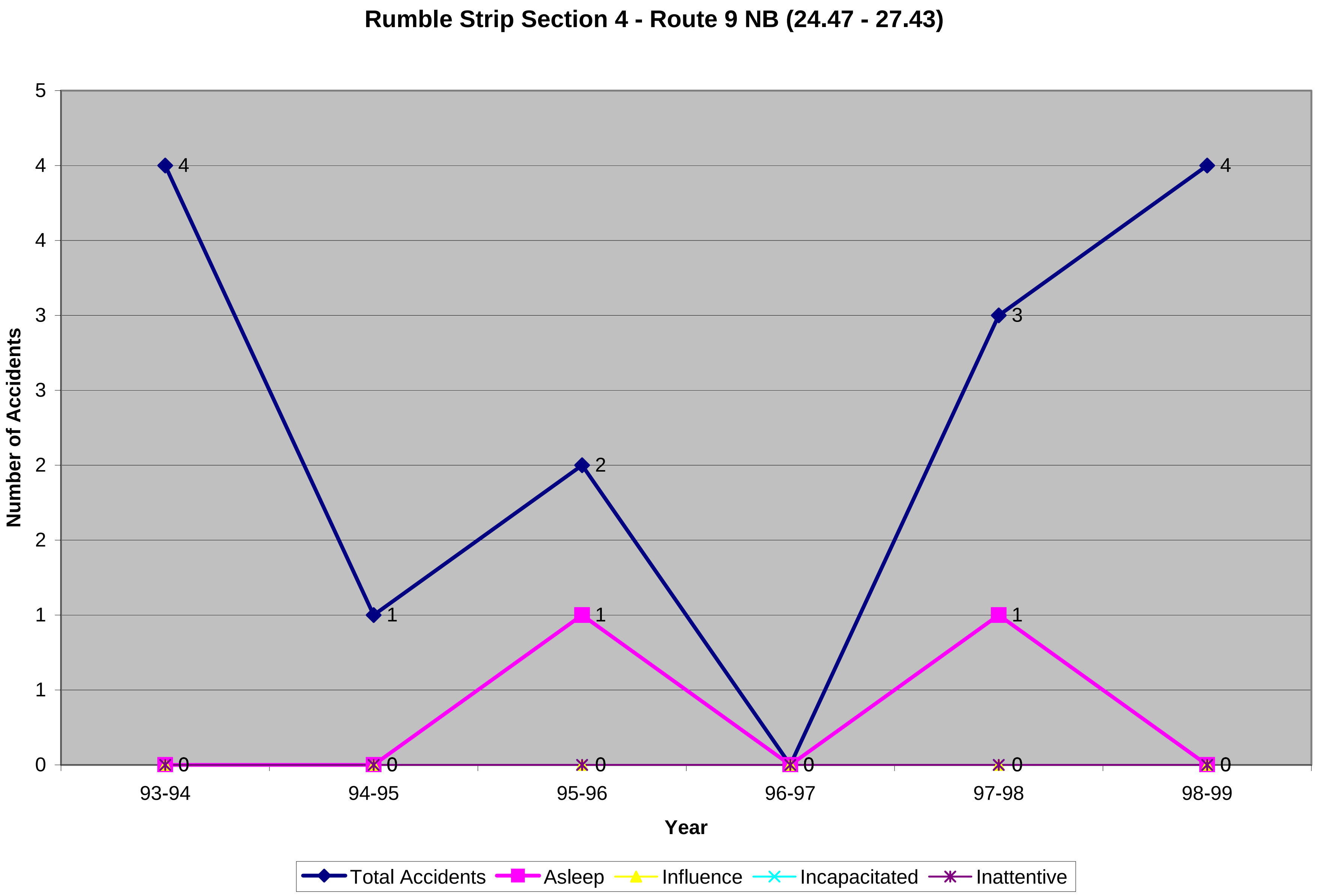
## Rumble Strip Section 1 - Route 8 NB (19.28 - 25.14)



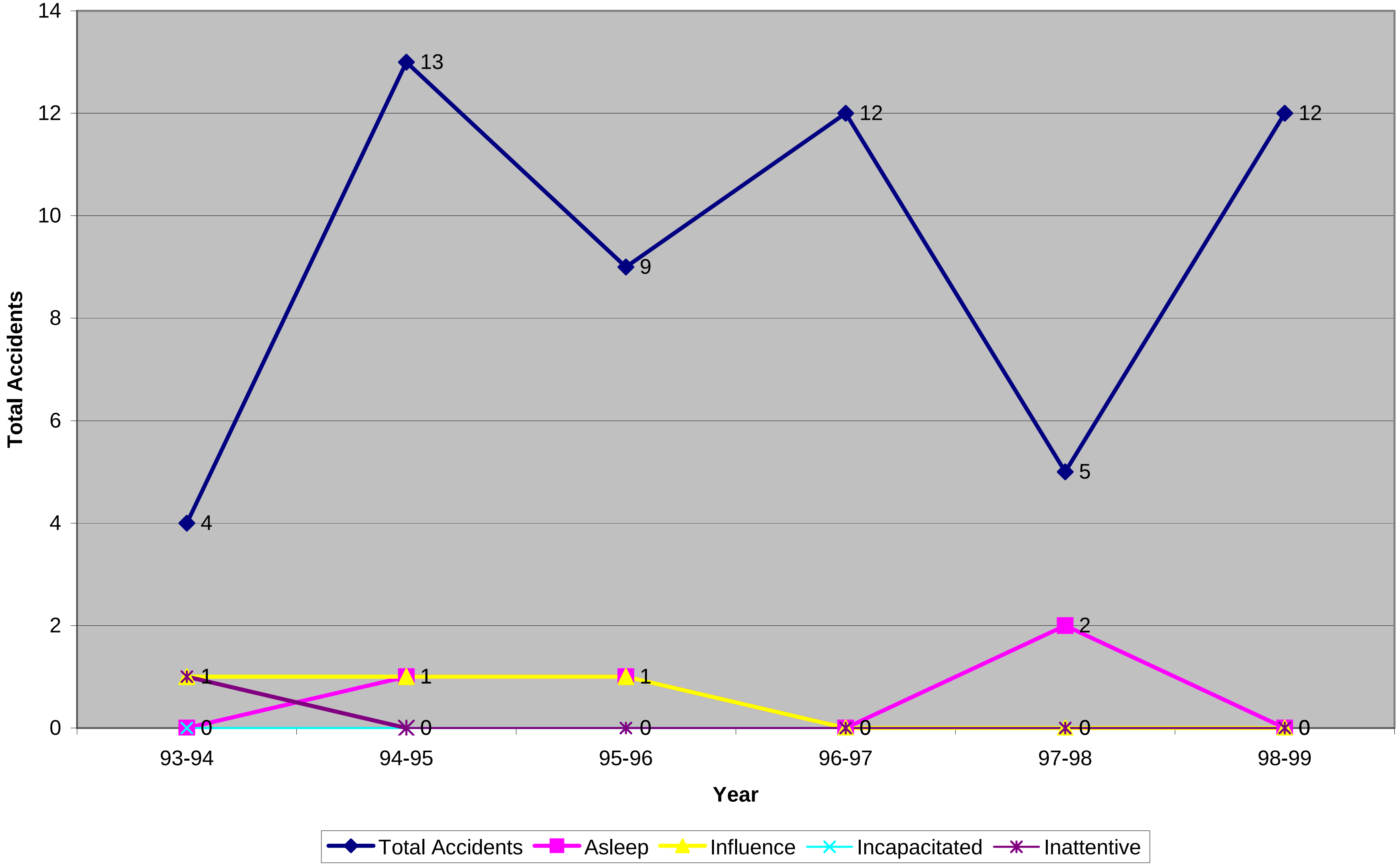

Rumble Strip Section 2 - Route 8 NB (42.64 - 50.11)
Number of Accidents
16
14
12
10
8
6
4
2
0
11
15
10
8
15
13
4
5
4
4
4
1
1
1
0
0
0
2
0
0
1
1
0
0
0
0
93-94
94-95
95-96
96-97
97-98
98-99
Year
Total Accidents
Asleep
Influence
Incapacitated
Inattentive

## Rumble Strip Section 3 - Route 8 SB (19.28 - 25.14)

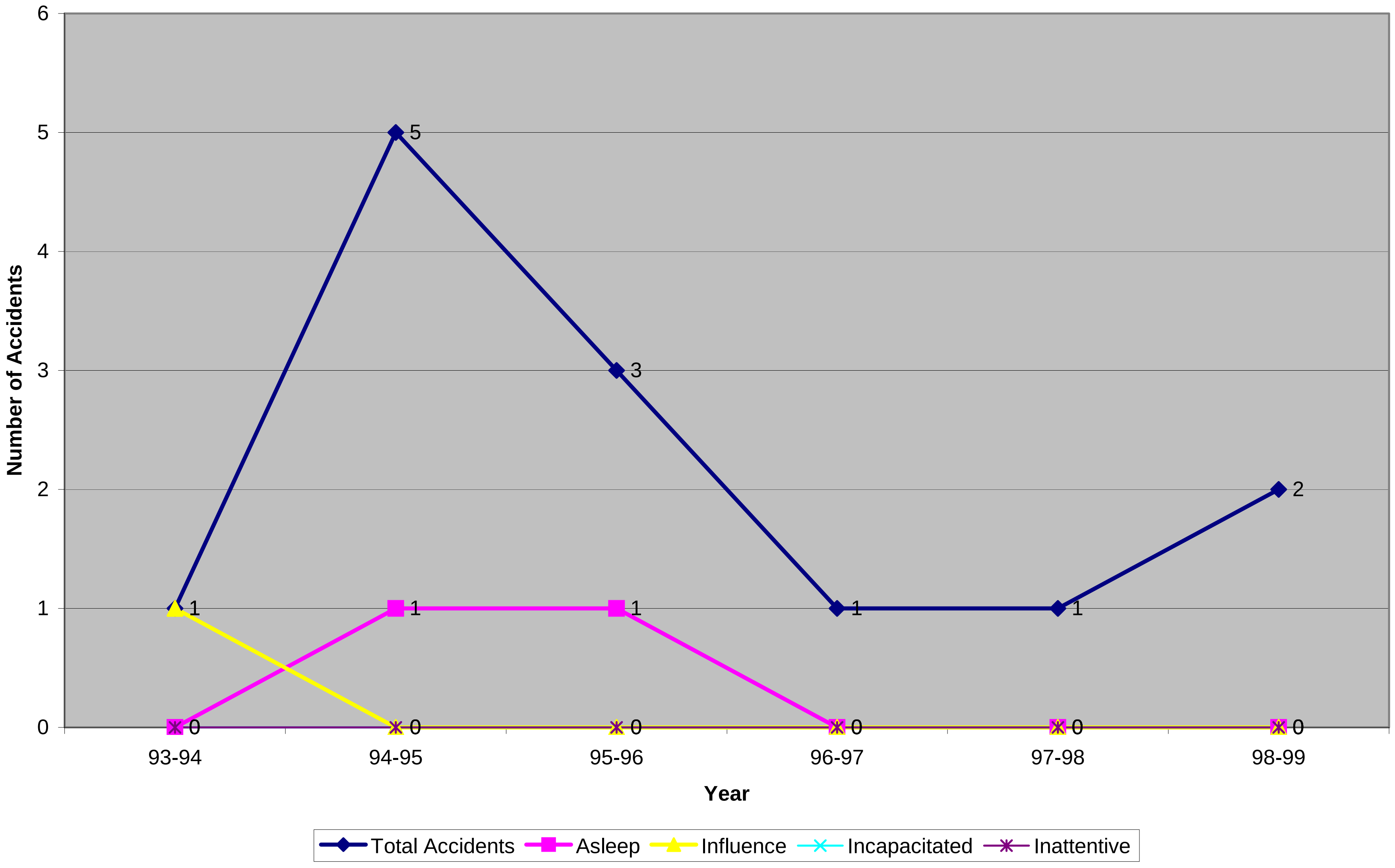


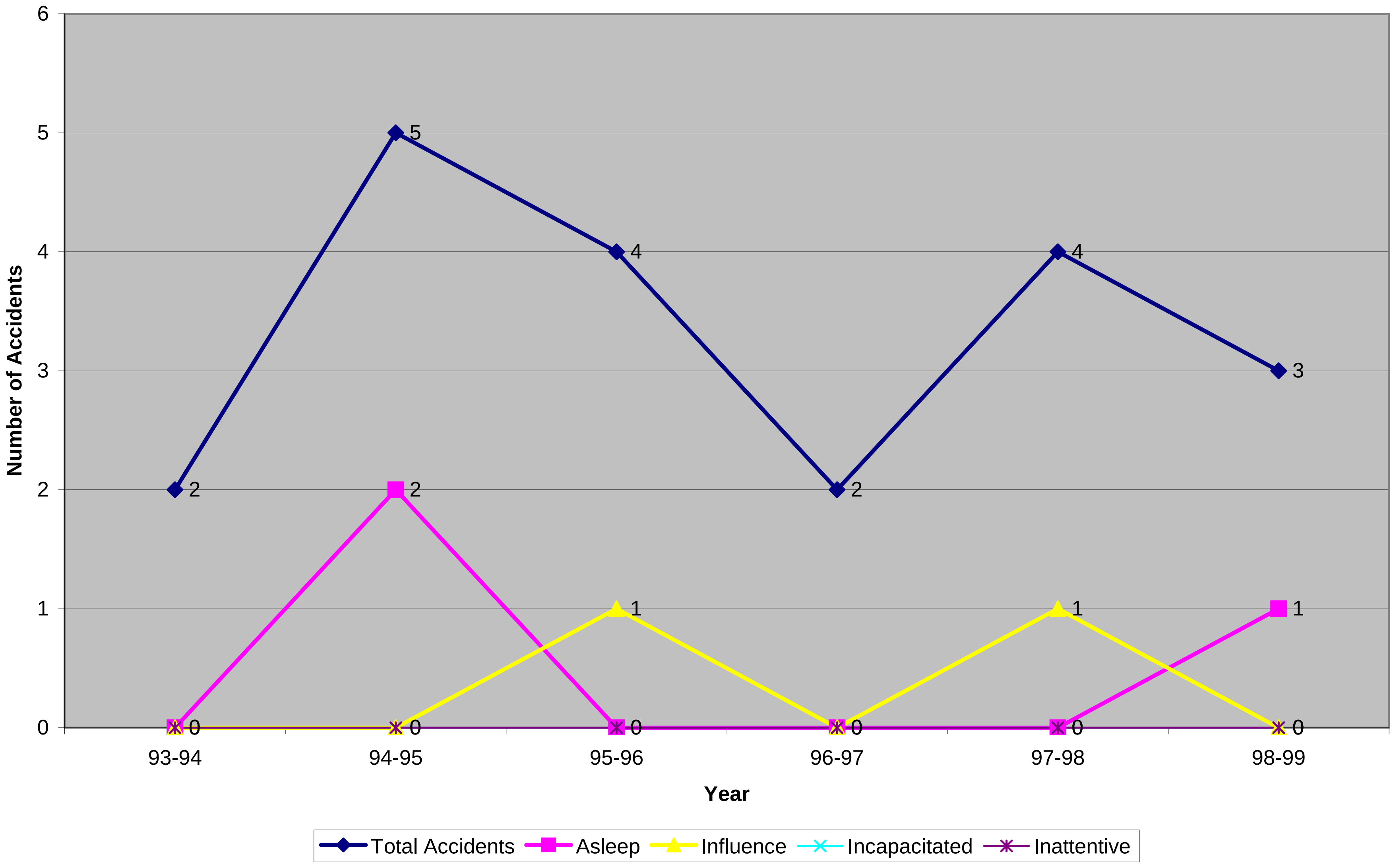

Rumble Strip Section 4 - Route 9 NB (24.47 - 27.43)

## Rumble Strip Section 5 - Route 9 NB (24.47 - 27.43)



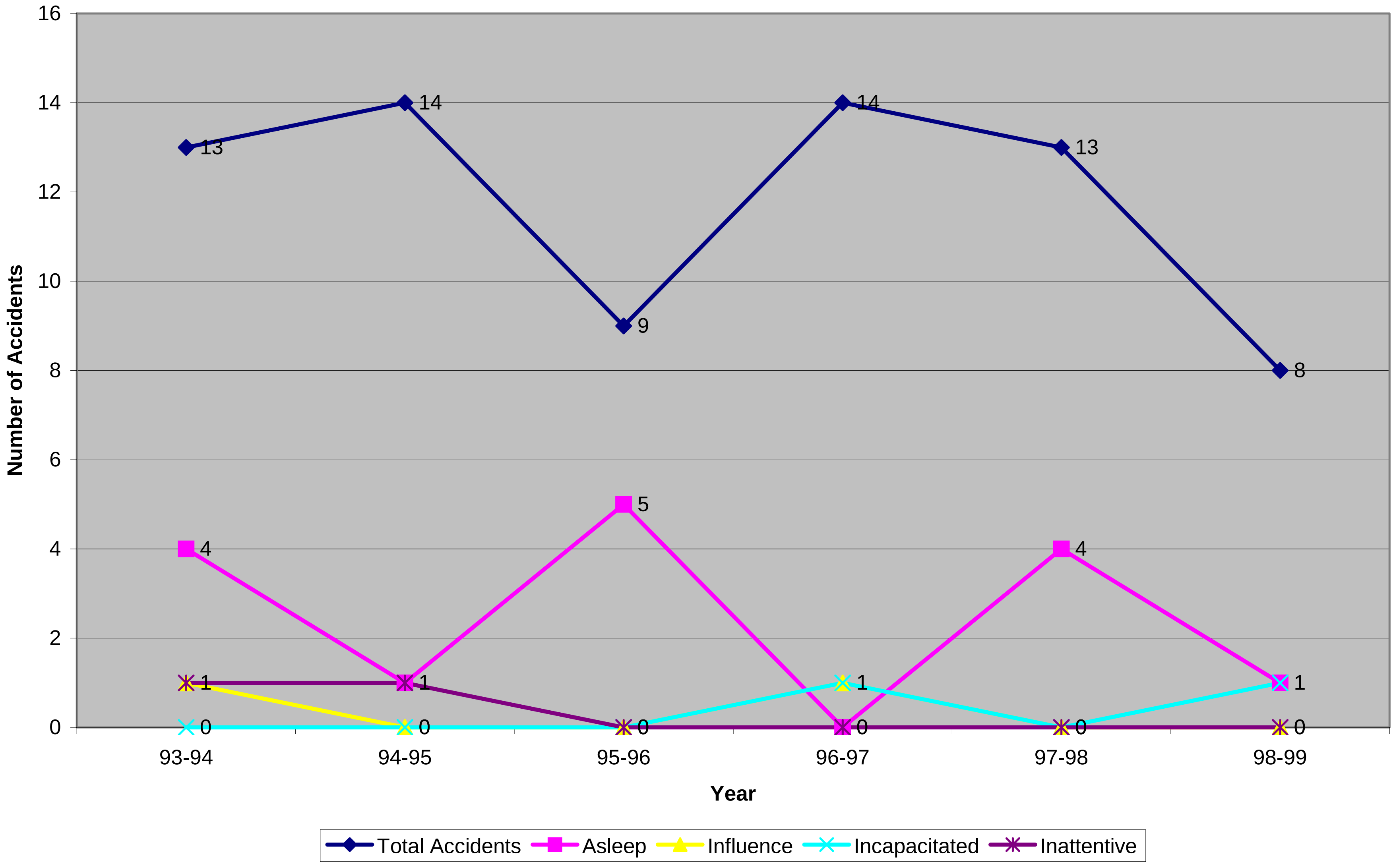
## Rumble Strip Section 6 - Route 9 NB (37.49 - 39.93)

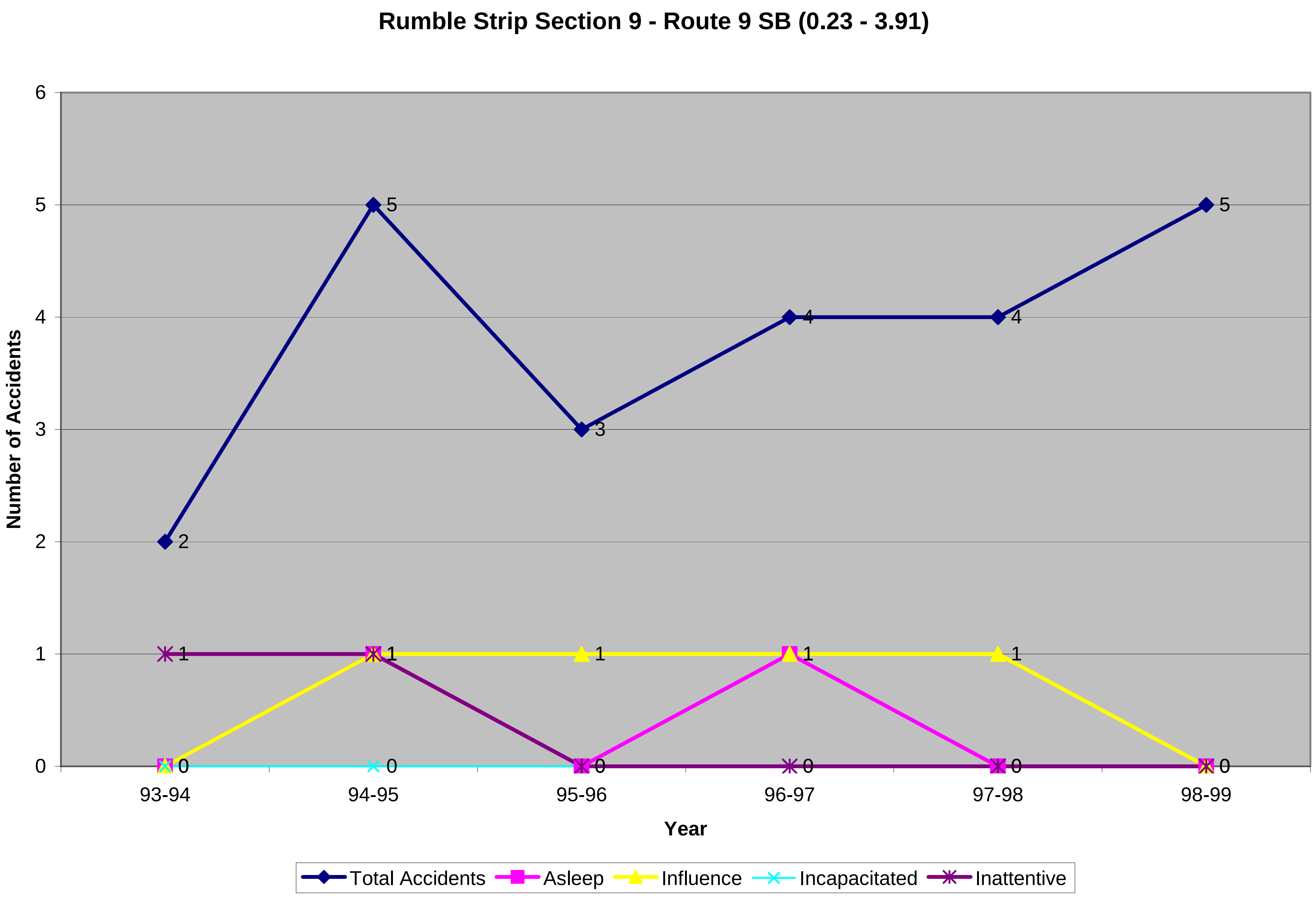




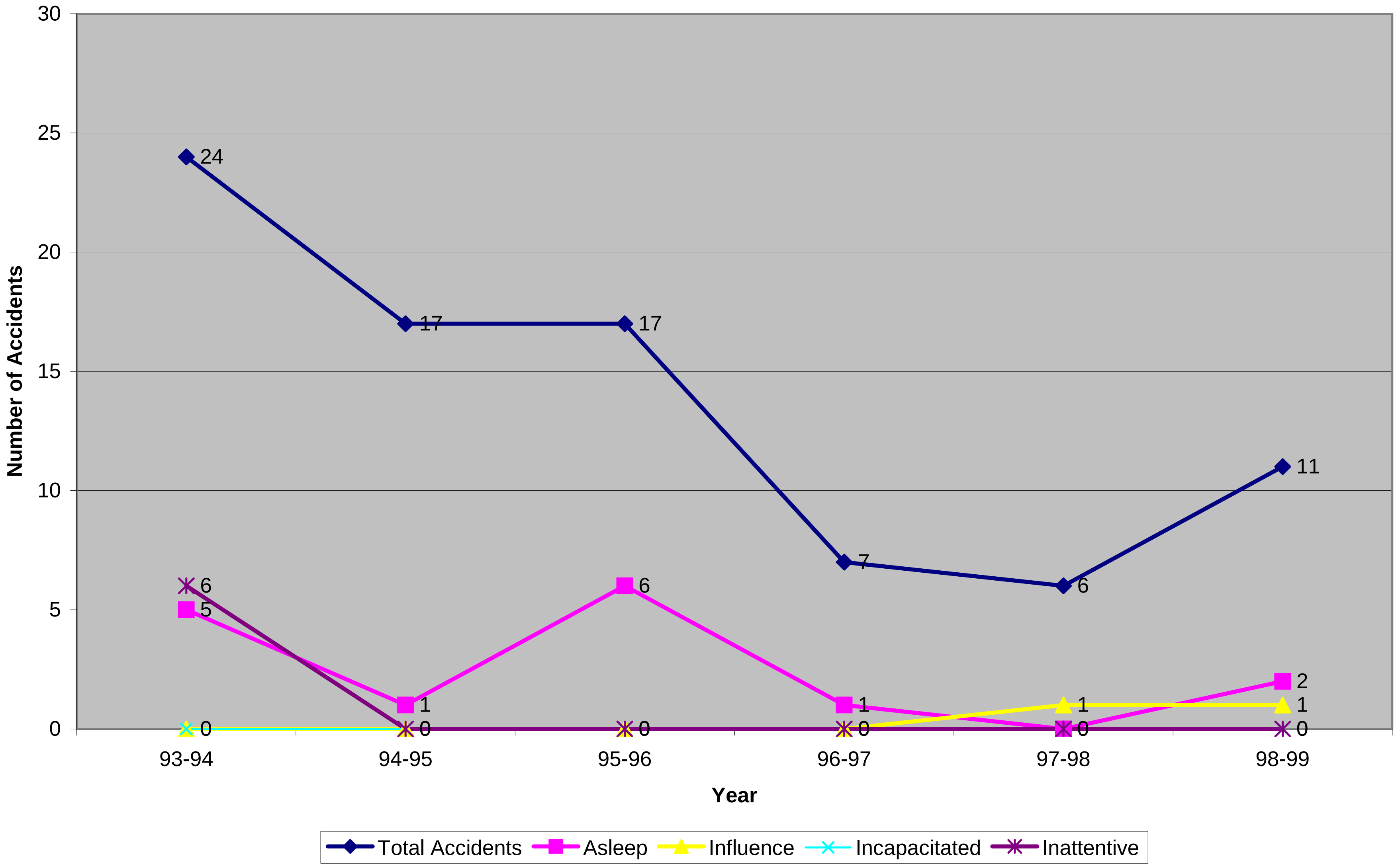
Rumble Strip Section 7 - Route 9 SB (37.49 - 40.71)

**Rumble Strip Section 8 - Route 9 SB (24.47 - 29.10)**

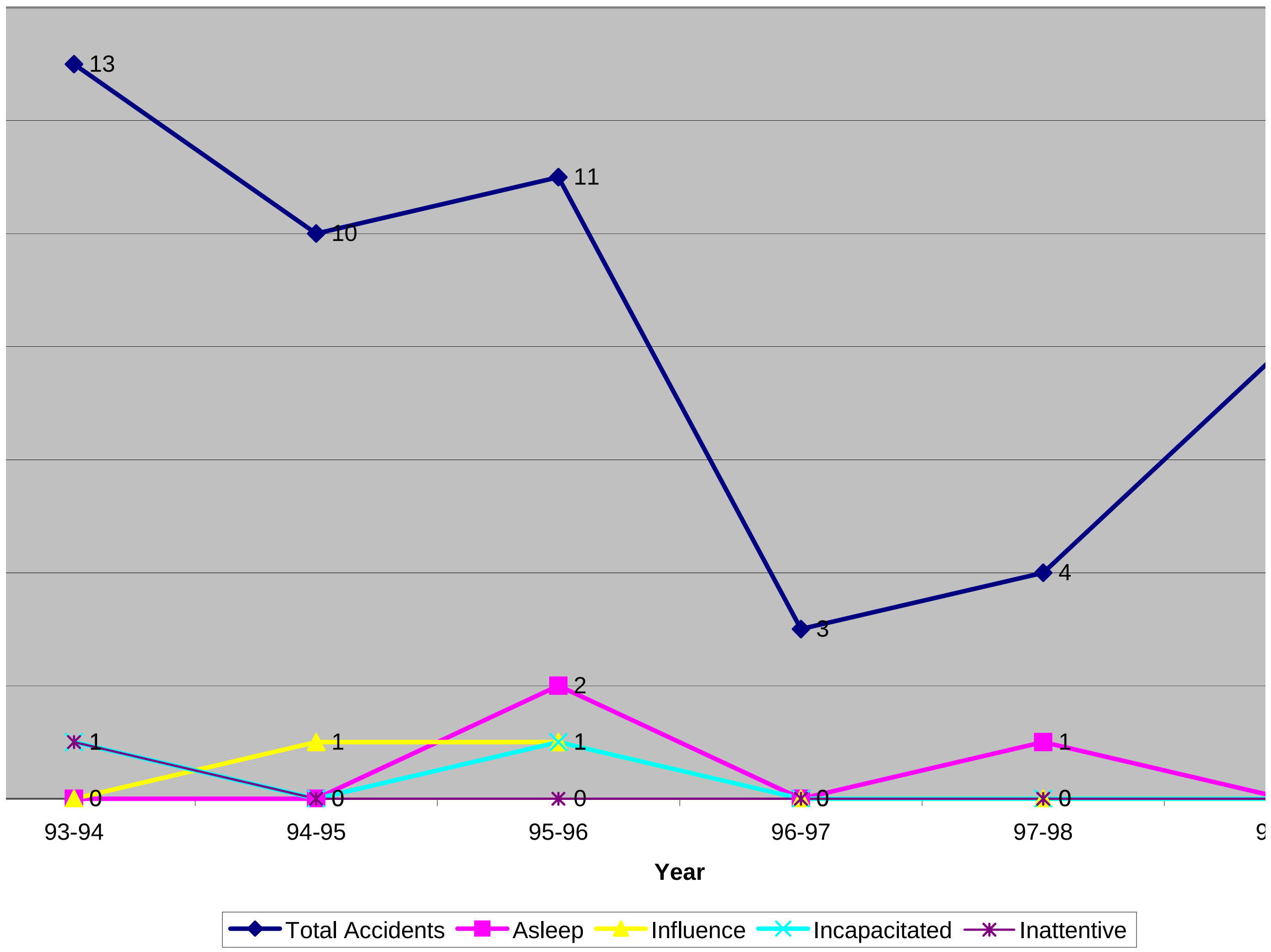



Rumble Strip Section 9 - Route 9 SB (0.23 - 3.91)
Number of Accidents
6
5
4
3
2
1
0
2
5
3
4
4
5
1
1
1
1
1
0
0
0
0
0
0
93-94
94-95
95-96
96-97
97-98
98-99
Year
Total Accidents
Asleep
Influence
Incapacitated
Inattentive

Rumble Strip Section 10 - Route 15 NB (50.20 - 59.72)



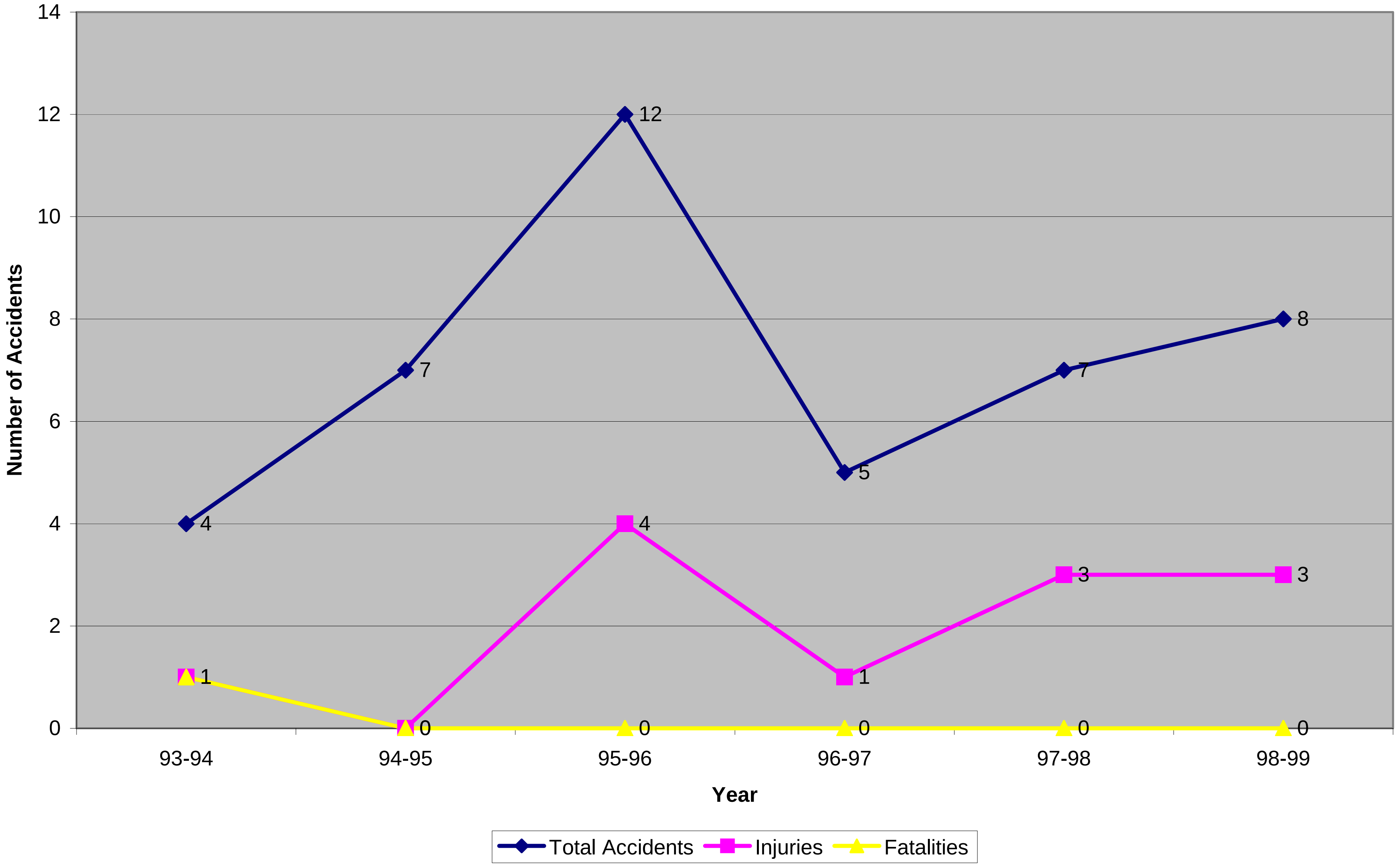
## Rumble Strip Section 11 - Route 15 SB (50.20 - 59.72)

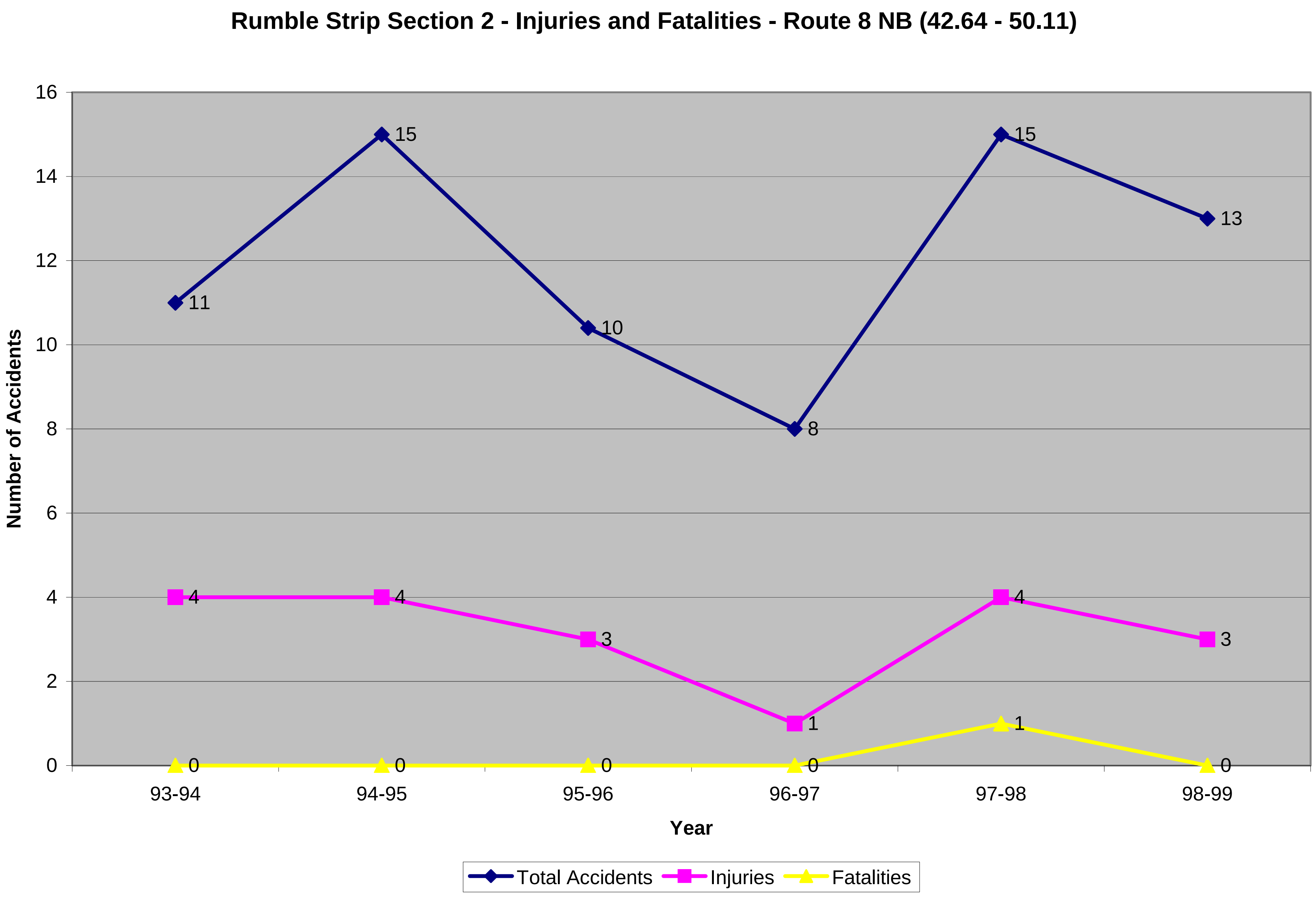


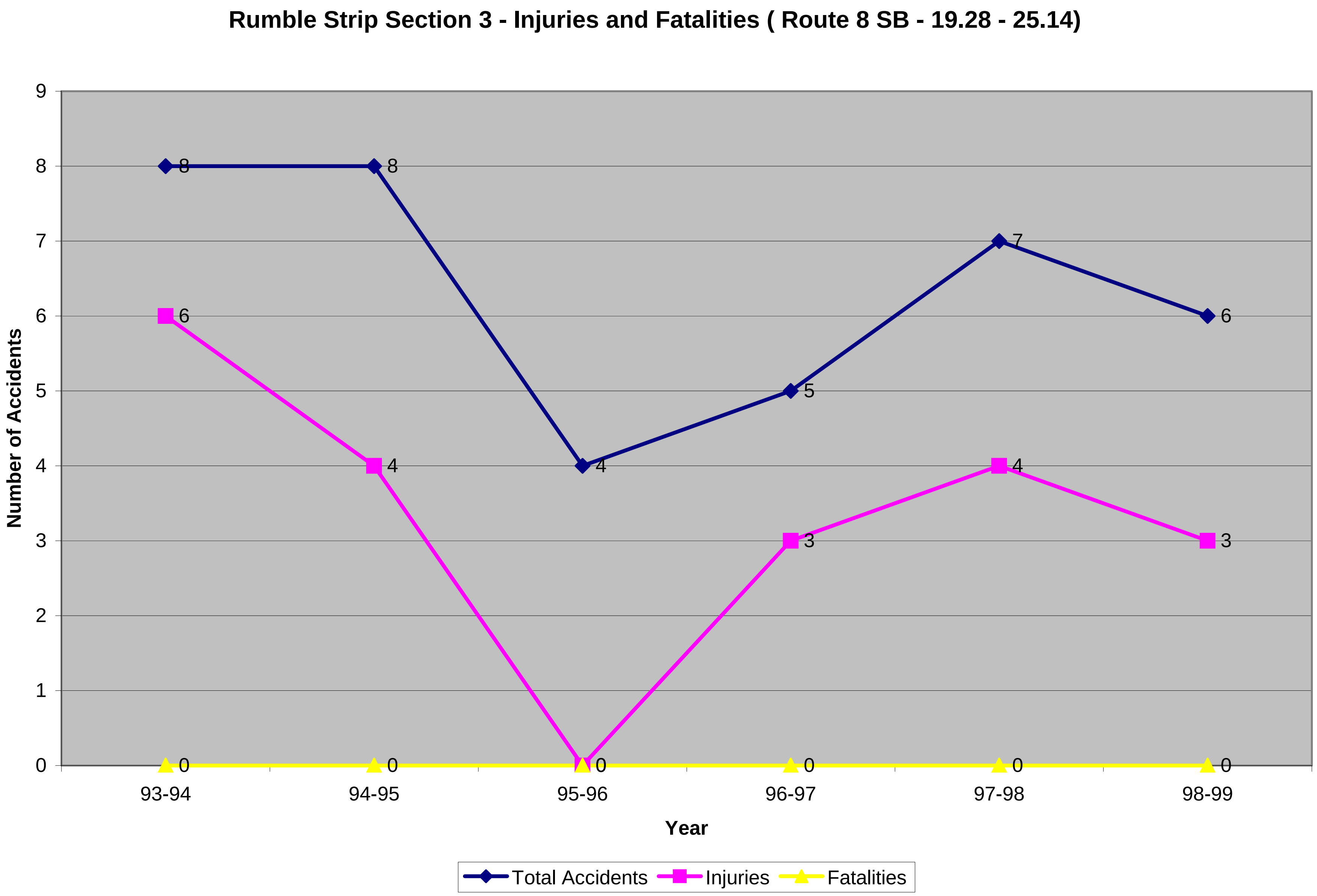
# Appendix E

## Graphical Display of Injury and Fatal Accidents

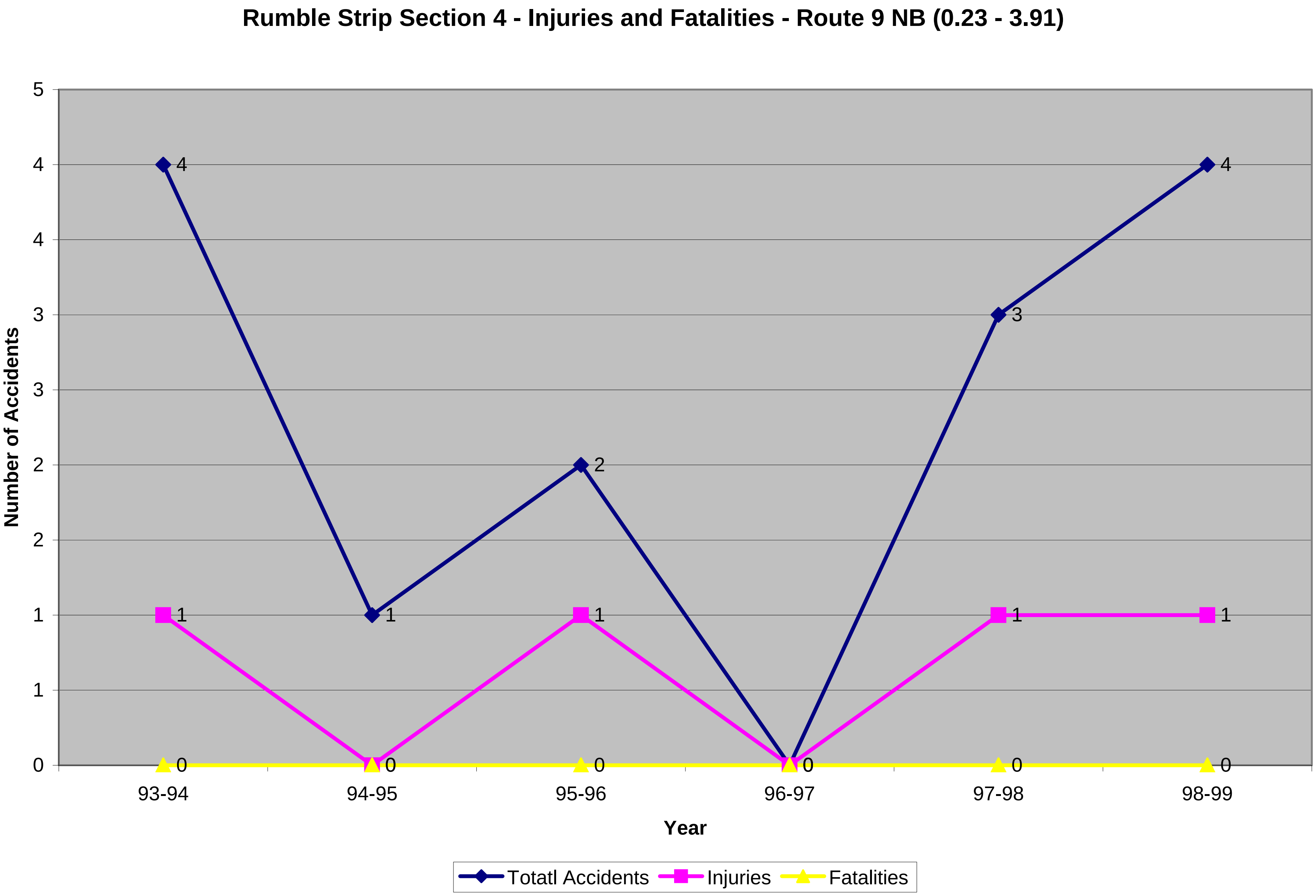
**Rumble Strip Section 1 - Injuries and Fatalities (Route 8 NB - 19.28 - 25.14)**



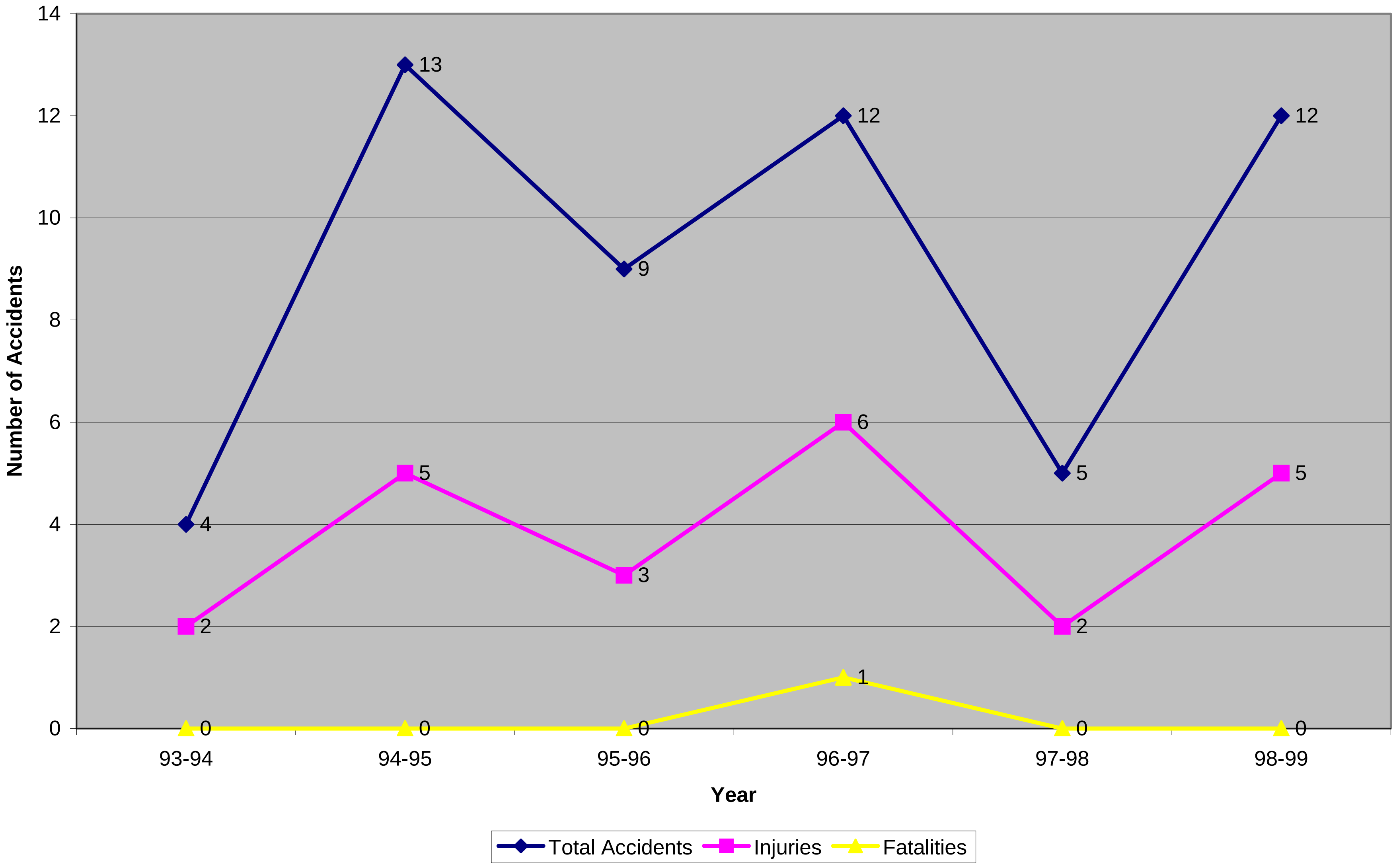
Rumble Strip Section 2 - Injuries and Fatalities - Route 8 NB (42.64 - 50.11)
Number of Accidents
16
14
12
10
8
6
4
2
0
Year
93-94
94-95
95-96
96-97
97-98
98-99
11
15
10
8
15
13
4
4
3
1
4
3
0
0
0
0
1
0
Total Accidents
Injuries
Fatalities



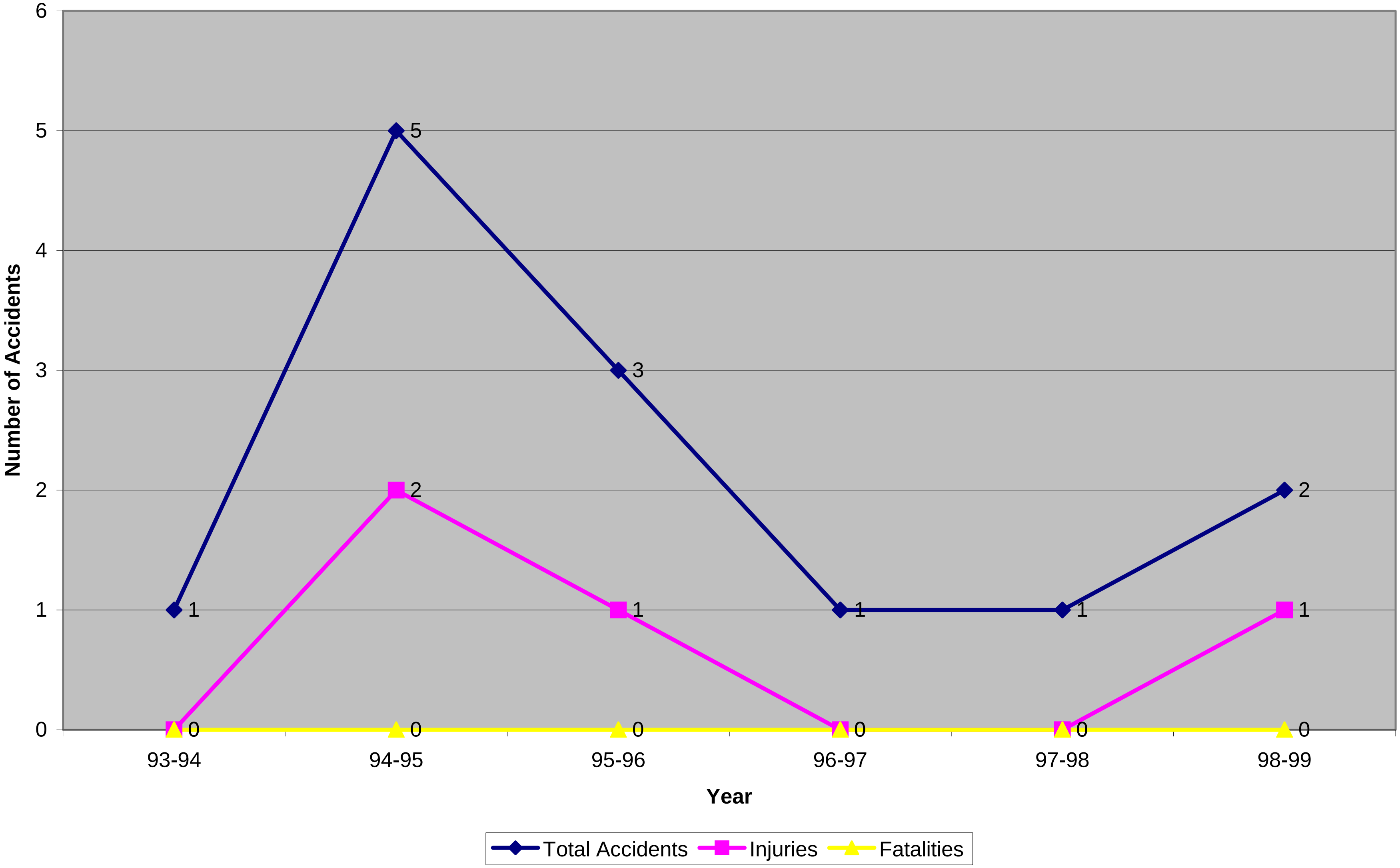
Rumble Strip Section 3 - Injuries and Fatalities ( Route 8 SB - 19.28 - 25.14)


Rumble Strip Section 4 - Injuries and Fatalities - Route 9 NB (0.23 - 3.91)
Number of Accidents
5
4
4
3
3
2
2
1
1
0
93-94
94-95
95-96
96-97
97-98
98-99
Year
4
1
2
0
3
4
1
0
1
0
1
1
0
0
0
0
0
0
Totatl Accidents
Injuries
Fatalities

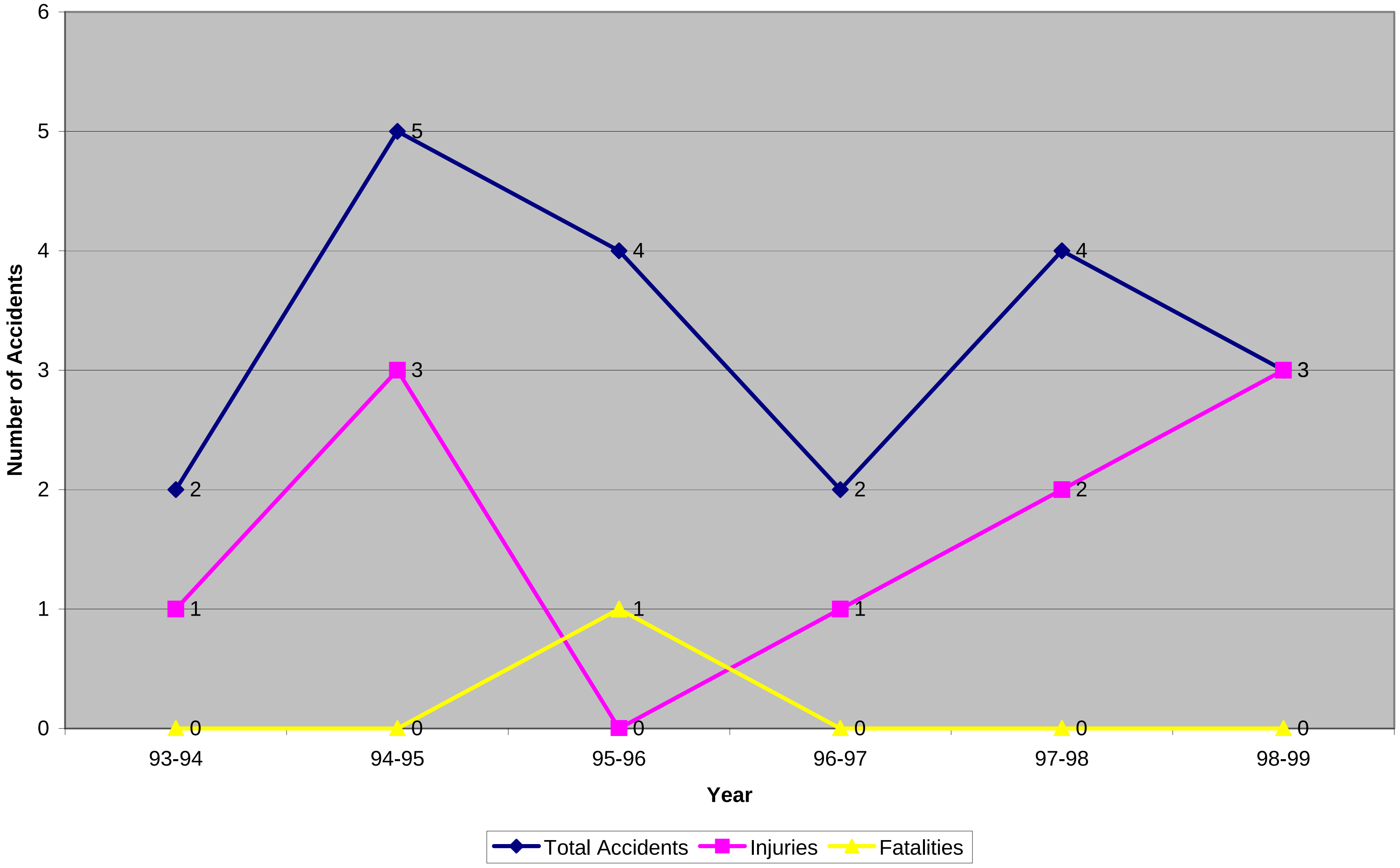
# Rumble Strip Section 5 - Injuries and Fatalities - Route 9 NB ( 24.47 - 27.43)



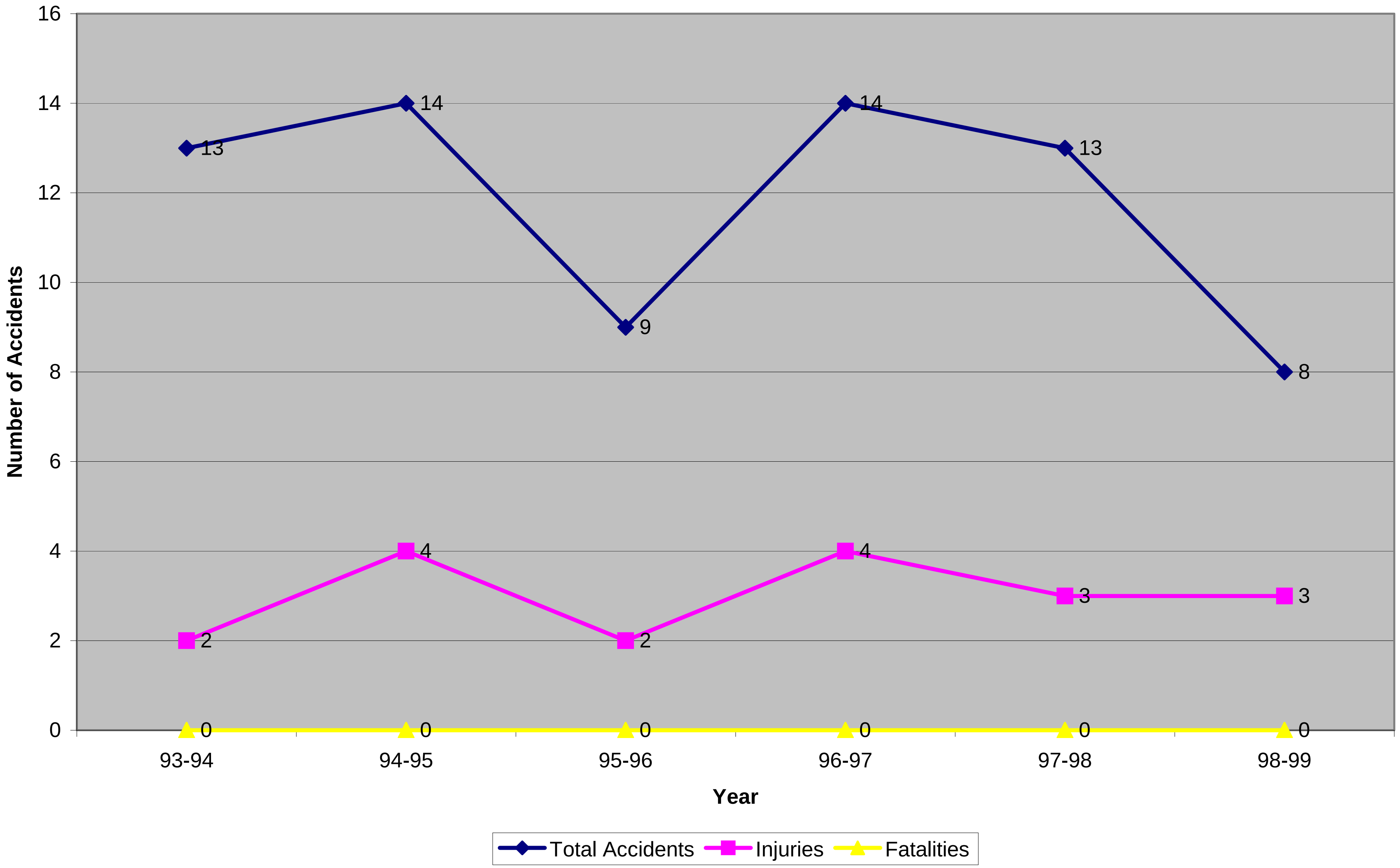
## Rumble Strip Section 6 - Injuries and Fatalities - Route 9 NB (37.49 - 39.93)



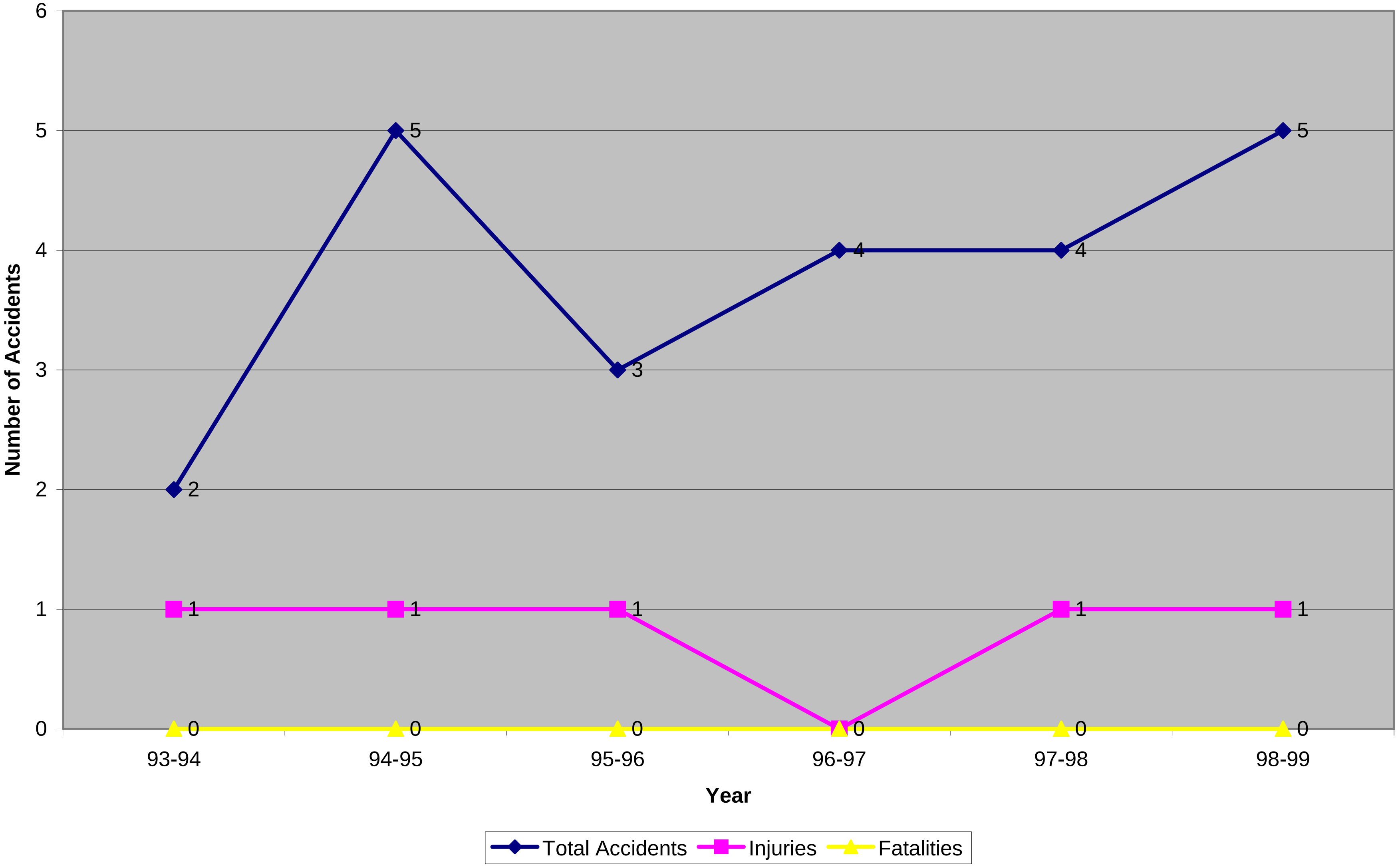
## Rumble Strip Section 7 - Route 9 SB (37.49 - 40.71)



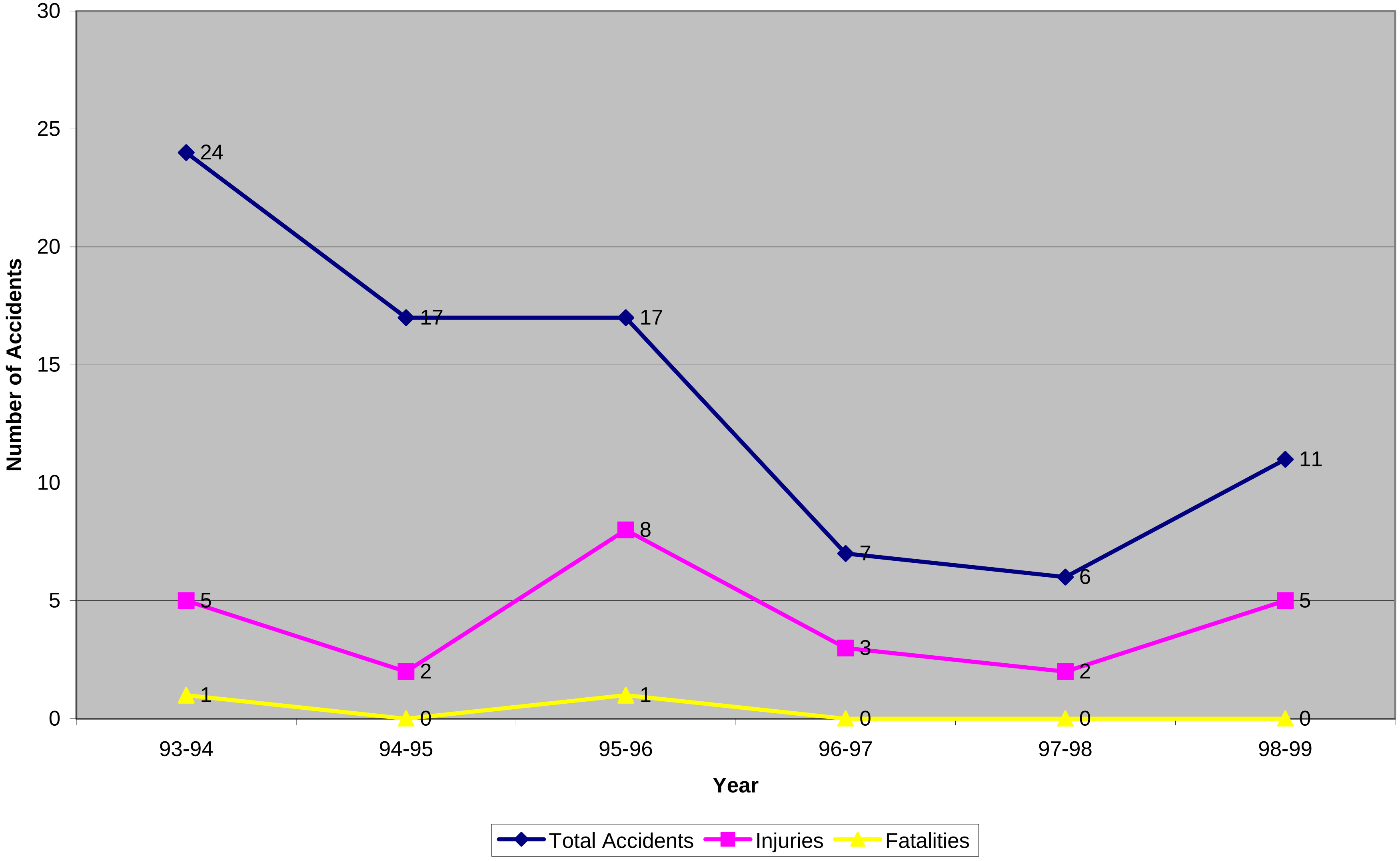
## Rumble Strip Section 8 - Injuries and Fatalities - Route 9 SB (24.47 - 29.10)



## Rumble Strip Section 9 - Injuries and Fatalities - Route 9 SB (0.23 - 3.91)



## Rumble Strip Section 10 - Injuries and Fatalities -Route 15 NB (50.20 - 59.72)



**Rumble Strip Section 11 - Injuries and Fatalities - Route 15 SB (50.20 - 59.72)**