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Decision Support System to Rank and Evaluate Crash Attenuators

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DECISION SUPPORT SYSTEM TO RANK AND EVALUATE CRASH ATTENUATORS

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ABSTRACT

Understanding the behavior and performance of roadside safety devices, such as guardrails, concrete barriers, end terminals, and crash attenuators, is of great importance to improving the safety of roadways and intersections. Crash attenuators have saved numerous lives by reducing the severity of vehicle crashes. However, while a great deal of crash test data exists on barriers and end terminals, information on their performance under field conditions is limited. Because of a variety of reasons described in more detail below, the field performance of barriers and attenuators can vary drastically from their behavior during crash tests.

Four research objectives were established for this project. They are as follows:

1) Develop a database system.
2) Design and implement a framework for a Decision Support System (D.S.S.).
3) Input the appropriate data from FDOT into the database.
4) Use the D.S.S. and data to rank and evaluate attenuators.

The D.S.S. is a computer program, based on a decision tree, which recommends an action that best meets a set of prioritized goals. The designer specifies goals, measures (criteria by which the goals can be quantified), and alternates (different ways in which the goal can be met). Weights are used to prioritize or indicate the relative importance of each goal and measure. They are also used to indicate the degree to which each alternate meets the objectives.

A series of graphs were developed to explain and compute the relationship between each D.S.S. site criteria and the relevant site characteristics; these graphs are known as the importance functions. The importance functions range from zero (meaning that the site characteristic is not relevant at all for the given value of the D.S.S. criteria) to one (meaning that the site characteristic is very important for the given value of the D.S.S. criteria). In some cases, the graphs were developed based on numeric evidence found through researching accident reports, roadway design and attenuator selection standards, and other relevant literature. For relationships where numeric values could not be found, common sense was used to develop the graph.

Based on the test cases included in Chapter 5 and other test cases that were run, the Decision Support System does work and recommends different attenuators to meet different site characteristics and/or situations. It was determined that the Decision Support System results are more sensitive to changes in the objective weights and test standards and not so sensitive to changes in the site characteristics. The only time there were significant changes in the recommendations based on site characteristics is when the type of site was drastically changed. In the case of a mild site, based on the current setup, the recommendation could be that an attenuator may not be needed. Therefore, the importance functions should be fine-tuned to help in different recommendations.

Another recommendation is that more data needs to be added to the database. This could help give better or more accurate recommendations, since the recommendations are based on historical performance data. More historical data is required on attenuators that meet the

NCHRP-350 standards. As with any program that gives results based on its database, the more data that is available the more accurate the results will be.

CHAPTER 1
INTRODUCTION AND PROBLEM STATEMENT

1.1 Introduction

Attenuators are used to prevent a vehicle from making contact with a fixed object. They slow an impacting vehicle down to decrease the severity of an impact or even prevent the impact altogether. Attenuators also prevent traffic from entering work zone areas, provide protection for workers in these work zone areas, and separate two-way traffic. They are used throughout the state on many different types of roadways. Their main uses are on interstate highways, freeways, and toll roads. Many different types and designs are used depending on the size or type of object that needs to be protected. Although attenuators can be used as end treatments for longitudinal barriers, such as guardrails and concrete barriers, they are generally treated as separate classes of roadside safety structures.

Attenuators, also known as crash cushions, lessen impacts in one of two ways, either by absorbing kinetic energy or by transferring momentum. In the first type plastics, foam, metal or other types of deforming materials are used in attenuators to absorb the kinetic energy of a moving vehicle. Some of the kinetic energy is also dissipated by the part of the car being crushed. These types of attenuators are usually called compression attenuators. They need a rigid backup to resist a vehicle's impact.

The transfer of momentum is the second way an attenuator slows down an impacting vehicle. The momentum is transferred to an expendable mass that is in the vehicle's traveled way. The expendable mass usually consists of barrels filled with sand. Lighter barrels are placed to the front of the array and heavier barrels to the rear, so that the vehicle is gradually slowed to a stop. These types of attenuators do not need a rigid backup because the kinetic energy is not absorbed, but is transferred to the other masses. Another name for these types of attenuators is inertial barriers.

Compression attenuators also have stiff fender panels or guide wires along their length to deflect side impacts. Attenuators with this property are known as re-directive attenuators. Redirection is an important property because vehicles impacting the side of an attenuator cannot take advantage of the entire length of the cushion to slow it down. As a result, unless properly redirected, the vehicle may penetrate into the cushion and strike the fixed object at a high rate of speed, a phenomenon known as pocketing, or snag its wheels or fenders on parts of the attenuator, leading to high deceleration rates. Inertial barriers rarely provide redirection.

To lessen the effect of an angled impact on the nose of an attenuator, many are designed to break away, allowing the vehicle to pass through without excessive deceleration due to the impact. This property is known as gating. While gating is preferred to excessive decelerations, the highway designer must ensure that the clear zone behind the attenuator is of sufficient length and width to prevent secondary collisions with other vehicles, construction equipment, pedestrians, or structures.

1.2 Problem Statement/Needs

Understanding the behavior and performance of roadside safety devices, such as guardrails, concrete barriers, end terminals, and crash attenuators, is of great importance to improving the safety of roadways and intersections. Crash attenuators have saved numerous lives by reducing the severity of vehicle crashes. However, while a great deal of crash test data exists on barriers and end terminals, information on their performance under field conditions is limited. Because of a variety of reasons described in more detail below, the field performance of barriers and attenuators can vary drastically from their behavior during crash tests.

Before the acceptance of any roadside safety device, including crash attenuators, evaluation tests must be conducted to ensure that it meets minimum safety standards. The most recent specification in use in the United States is "Recommended Procedures for the Safety Performance Evaluation of Highway Features," Report 350 of the National Cooperative Highway Research Program described in more detail in the next chapter. NCHRP crash test specifications are accepted by all state transportation departments [1]; however, roadway projects completed prior to the acceptance of a new standard are generally brought up to code only when major renovation is required. Therefore, while NCHRP 350 is the current standard, many devices in use today were installed prior to its adoption, and only meet the less stringent provisions of NCHRP 230 [2] or an even older standard.

The crash tests required by NCHRP 350 and other standard specifications attempt to show that a roadside safety device will protect vehicle occupants under expected service conditions. In general, the tests are intended to replicate a maximum credible vehicle impact, and require the device to meet specific criteria regarding deceleration forces and change in vehicular velocity. However, these tests are based on idealized installations and carefully controlled impacts, which may be very different from service conditions. Test impacts occur at a constant speed on flat, smooth surfaces with no braking or turning of the vehicle wheels. Factors, which affect the *in-situ* performance of roadside safety devices include, but are not limited to, the following:

- Vehicle impact conditions, which exceed those in the standard due to increased speed limits, wet roadways, larger vehicles, and unanticipated impact angles and positions.
- Driver action, such as applying brakes and turning of the steering wheel in an attempt to avoid the attenuator.
- Variations in roadway and roadside surfaces, including potholes, curbs, drainage structures, changes in grade, embankment slopes, etc.
- Multiple car accidents, including hits after the safety device has been damaged.
- Improper installation, lack of routine maintenance, delays in repair after an impact or other damage.
- Deterioration due to age and exposure to weather, support settlement, vandalism and other causes.

To correctly assess the field performance of crash attenuators, it is necessary to understand the effect of driver action, road conditions, maintenance history, and other field characteristics on their behavior and operation. In addition, to select the most cost-effective attenuator system for a given situation, designers need to know the relative in-service performance of the different systems under the environment in consideration. While the crash test standards provide a service rating for each attenuator system based on the maximum design speed at which it can be used, they provide no information that can be used in comparing two evenly rated systems against one another.

Aside from preventing a vehicle from impacting a fixed obstacle, vehicle crashes with an attenuator can have many different outcomes. Outcomes that need to be reduced or prevented are rebounding, pocketing, snagging of wheels or fenders, high redirect angles, rollovers, and gating. A particular outcome can be more or less important depending on the design situation or needs of the engineer. For instance, the importance of preventing rebounding, high redirect angles, and/or gating is largely dependent on the clearances around the attenuator. Therefore, decisions about attenuator selection and use need to be based on the site the attenuator is going to be placed at. From test data and accident records, we can see how the different attenuators react to different situations. Further, in selecting attenuators, one needs to consider whether cost is more important than performance and safety. For example, the Fitch and Energite sand barrels are inexpensive, but they have poor redirection and allow pocketing whereas the G-R-E-A-T attenuator performs very well under side impacts, but is more expensive to install. Also, the repair cost becomes a factor. The number of employees required to do a repair is different for each attenuator, as well as the amount and cost of equipment and parts needed to do the repair.

One way to address some of these problems is to create a computer system that will aid engineers in selecting, ranking, and evaluating attenuators. One model of a computer system would consist of a database and a Decision Support System (D.S.S.). A D.S.S. is a computer program that recommends an action that will best meet a set of prioritized goals. In this case, the D.S.S. would rank attenuators based on field crash performance and life-cycle costs. This information will give the engineer an opportunity to see which attenuators are best suited for a particular site. The database provides a uniform mechanism for storing and analyzing data and supports decision making by providing historical data to the D.S.S. The field performance data would include accident, inspection, repair, and cost data obtained from different FDOT districts throughout Florida.

CHAPTER 2
BACKGROUND AND RELATED RESEARCH

2.1 Types of Attenuators

There are many different types of attenuators that are in use today. This section lists some of those and briefly describes those in use in Florida. Although the category of attenuators includes gravel beds, truck-mounted attenuators and vehicle arresting barriers, we are only concerned with compression cushions and inertial barriers as described in the previous chapter. In the following list, attenuators that are used primarily as end treatments are separated out. This was done because in Florida, end treatments are not included in the attenuators inventory database. Therefore, they are excluded from the research described herein.

- Sand Barrel
  - Energite Barrels
  - Fitch Barrels
- Compression Cushions
  - REACT 350 (Reusable Energy Absorbing Crash Terminal)
  - Guardrail Energy Absorbing Terminal (G-R-E-A-T)
  - G-R-E-A-T CZ
  - Hi-Dro Cell
  - Hex-Foam Sandwich
  - Connecticut Impact Attenuation System (CIAS)
  - Bullnose Attenuator
  - CAT
  - Low Maintenance Attenuator (LMA)
  - Advance Dynamic Impact Extension Module (ADIEM)
  - QUADGUARD
- End Treatments
  - Sentre
  - Trend
  - Brakemaster
  - Triton Barrier

The following are descriptions of the most common attenuators that are being used in Florida today.

2.1.1 Energite and Fitch Barrel Attenuator Systems

Energite Sand Barrels and Fitch Barrels are two types of sand filled containers used in Florida. The main difference is that the Energite Sand Barrels are of one-piece construction and come in two different sizes, whereas the Fitch Barrel system consists of two components that are put together to form a barrel. Only one size barrel is available. Different sand weights are accommodated in both barrel systems by raising or lowering the internal platform. Typical sand barrel weights are shown in Table 2.1. In states where freezing occurs, rock salt is added to the sand to help prevent any freezing due to moisture in the sand. The Energite Sand Barrel is manufactured by Energy Absorption Systems and the Roadway Safety Service manufactures Fitch Sand Barrels.

Fitch Sand Barrels can be interchanged in an array with the Energite Sand Barrels. Both of these systems are very easy to install and remove and can be configured to meet a variety of needs. Configurations can be designed to meet NCHRP 350 standards [1]. They are also very convenient to store since they can be stacked inside of one another. Figure 2.1 and 2.2 are pictures of both the Energite and Fitch Sand Barrels. The key benefit of either sand barrel system is their low installation and replacement cost. However, one major drawback is that they do not have the re-directive features of most compression cushions and have to be set up in wide arrays to protect most hazards. As a result, they are difficult to place where space is limited. Another drawback is that when impacted, debris may scatter everywhere causing clean up to be a problem.

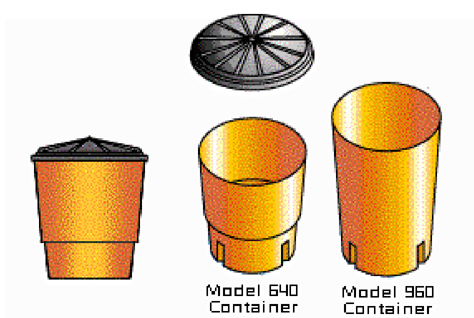


Figure 2.1: Energite Barrel Attenuator

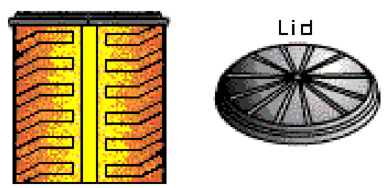


Figure 2.2: Fitch Barrel Attenuator

Table 2.1: Nominal Sand Masses for Typical Sand Barrel Arrays

Nominal Mass	
kg	**lbs**
90	200
180	400
320	700
640	1400
960	2100

2.1.2 G-R-E-A-T and G-R-E-A-T CZ Attenuator System

The GuardRail Energy Absorbing Terminal (G-R-E-A-T) system was designed specifically to protect the ends of median barriers and other narrow fixed objects. Some of these objects include:

- Bridge Pillars
- Center Piers
- Light Poles
- Butterfly Signs
- Double Faced Guardrail Ends
- Gore Areas

The G-R-E-A-T attenuator is a compression cushion that absorbs and dissipates the kinetic energy of impacting vehicles. It absorbs the kinetic energy through dense foam cartridges with the trade name Hex-Foam. The Hex-Foam cartridges are held in place by steel frames, which retract backwards when it is hit end-on. Cables and leg pins restrain the unit when hit from the side. When a side impact occurs, the system will redirect the vehicle. The G-R-E-A-T attenuator has many different lengths ranging from one bay to twelve bays and three different widths. The width of the system that is required depends on the width of the hazard. The longer systems absorb more energy and therefore, are suitable for roads with higher design speeds.

The G-R-E-A-T CZ system is intended for temporary installation in construction work zones. It is different from the G-R-E-A-T system because it has an integral platform, backup structure, and anchor system instead of a separate backup structure. It can be moved fully assembled from one location to the next. It comes in two lengths and two widths. It should be located on a smooth surface for anchoring with either bolts or pins. This system is also designed to redirect an impacting vehicle. Some benefits of these systems are the ease of repair, diversity of different configurations, and performance of the attenuator. The only drawback is the durability of the foam cartridges in certain weather conditions. In very hot climates, the cartridges may deteriorate. Energy Absorption Systems is the manufacturer of both of these systems. As G-R-E-A-T systems do not meet NCHRP 350 standards, the compliant QuadGuard attenuator, also a product of Energy Absorption Systems, is slowly replacing them at the time of writing [1]. Figure 2.3 is a picture of the G-R-E-A-T System.

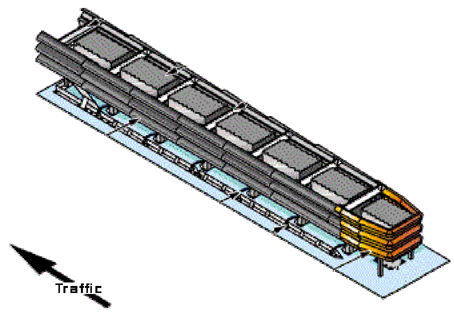


Figure 2.3: G-R-E-A-T Attenuator

2.1.3 Hi-Dro Sandwich Attenuator System

The Hi-Dro Sandwich System dissipates the kinetic energy of a crash by discharging water from plastic tubes and by the transfer of energy from the vehicle to the expelled water. The plastic tubes are arranged in bays separated by diaphragms. A rigid backup structure is required for this system. Vertically and laterally, steel cables support it and it is free to collapse backward at impact. An advantage of this system is that there is very little debris after impact except for water. Another advantage is that the system is easy to repair if involved in an accident. Many times immediately after an accident the attenuator can be pulled back out into place. Then, the cells can be replaced or filled with water, if needed. A disadvantage is that the expelled water could cause skidding and decrease traction. In addition, a major drawback is that water can evaporate during hot weather or leak out of small punctures in the tubes. This means that maintenance is high on this attenuator. To prevent freezing, the tubes are sometimes filled with a liquid calcium chloride solution.

This system is designed to redirect a vehicle if it is hit from the side. The redirection of a vehicle is caused through fender panels attached to the side of the barrier. As with most of the attenuators, Energy Absorption Systems is the manufacturer of this attenuator. Figure 2.4 is a picture of a Hi-Dro Sandwich attenuator.

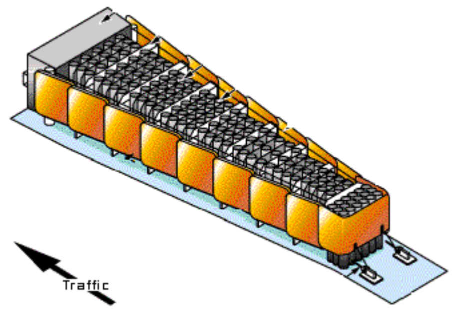


Figure 2.4: Hi-Dro Sandwich System

2.1.4 Hi-Dro Cell Cluster

The Hi-Dro Cell Cluster system uses the same tubes as the Hi-Dro Sandwich system. These tubes are filled with water and held together in a cluster by a flexible "safety belt." Backup structures are required for this system. The system is used for areas where the speed limit is 70 km (45 mph) or less. One advantage of this system is that it can be arranged in various patterns to fit the object being shielded. Another advantage is that the system can be used in very small places where many of the other attenuators will not fit. However, because there are no fender panels, an impact toward the rear of the system may allow the vehicle to hit the back up structure. Similar to the Hi-Dro Sandwich, the Hi-Dro Cell Cluster attenuator has a high maintenance rate due to the water filled tubes. Some applications include shielding gore areas, bridge piers, or abutments, traffic control devices, and tollbooths. The Hi-Dro Cell Cluster is manufactured by Energy Absorption Systems.

2.1.5 Hex-Foam Sandwich

The Hex-Foam Sandwich is used to protect wide hazards and is very effective at high accident frequency locations. This is because it is relatively inexpensive to repair, which is a major advantage. Another advantage is that it can be used for head on or side impacts. It dissipates the kinetic energy of an impacting vehicle primarily through the crushing of expandable cartridges containing Hex-Foam. When hit, the cartridges crush, the unit collapses from front to rear, and the front of the vehicle crushes as impact forces build up. This system uses telescoping panels for side impacts. During side impacts, the system redirects the vehicle safely. The system can easily be pulled out and reused. The only parts that need replacement in a normal impact are the foam cartridges. The system is available in three different widths and nine different lengths. It can accommodate speeds varied from 65-120 km (40-70 mph). The Hex-Foam Sandwich is manufactured by Energy Absorption Systems. Figure 2.5 is a picture of the Hex-Foam Sandwich attenuation system.

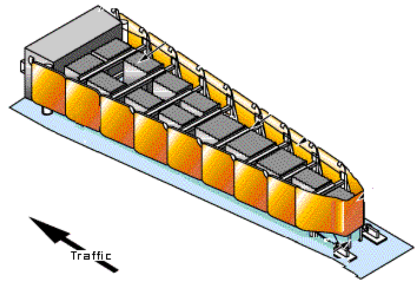


Figure 2.5: Hex-Foam Sandwich

2.1.6 Low Maintenance Attenuator (LMA)

The LMA system is designed to protect narrow obstacles in locations where a high frequency of impacts occur. It is considered to be low maintenance because it has highly reusable parts. The system has twelve modular bays, which consist of triple corrugated steel diaphragms and three-beam fender panels. It also has a reusable nose section. The backward crushing of the guardrail and compression of the elastometric cylinders absorb the kinetic energy when hit head-on. Restraining chains and cables are used for longitudinal stiffness and side impacts. The system can easily be pulled back out to its original length and repaired by a two-person crew in about an hour. Unlike foam cushions, the elastometric cylinders recover their original shape when expanded. The Low Maintenance Attenuator is manufactured by Energy Absorption Systems.

2.1.7 REACT 350

The REACT 350 system consists of high density polyethylene cylinders along with a cable system that are designed to attenuate head on hits and redirect severe angle hits. As its name indicates, the REACT 350 meets NCHRP 350 standards [1]. REACT stands for Reusable Energy Absorbing Crash Terminal, indicating that each attenuator maintains 90% of its initial deceleration capabilities after an impact, so it can be reused for many impacts. The system is designed to expand back to its original length after a hit with no repair required. For severe hits, an over-stretching is sometimes required to obtain the original shape. This results in greatly decreased repair costs. However, some concerns have been raised over the possibility of excessive rebound of vehicles back into travel lanes. Three different models of the REACT 350 are available depending on the design speed of the road where it is to be placed. The systems are self-contained and can be used for both permanent and temporary applications. A benefit of the low speed attenuator is that is comes completely assembled, meaning that the contractor has to spend very little time at the site for installation, making it safer for traffic and workers. The only maintenance required is regular visual inspections. Roadway Safety Service manufactures the REACT 350. Figure 2.6 is a picture of the REACT 350 attenuation system.

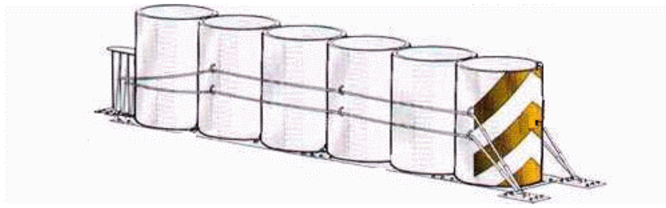


Figure 2.6: REACT 350

2.2 Reference Materials

This section includes descriptions and explanations of the National Cooperative Highway Research Program, AASHTO Roadside Design Guide, and Safety Needs Analysis Program. These references describe the testing and use of attenuator systems and provided much of the needed background information used in developing the database and decision support system. A brief review of decision methodologies is also provided.

2.2.1 NCHRP Report 350

The National Cooperative Highway Research Program (NCHRP) produces crash test standards and protocols for various types of roadside safety structures. The most recent guide is Report 350 titled "Recommended Procedures for the Safety Performance Evaluation of Highway Features" [1]. This report contains recommended procedures for safety performance evaluation of highway features, including crash cushions, longitudinal barriers, break-away or yielding supports for signs and luminaries, breakaway utility poles, truck mounted attenuators, and work zone traffic control devices. The report gives standards and guidelines that each attenuator is required to pass in order to be used on our highways and freeways.

The first NCHRP specification for crash tests was the Highway Research Correlation Services Circular 482, written in 1962. It was a one-page document that specified vehicle masses, impact speeds, and impact angles for different crash tests. In 1973, a project headed by the NCHRP was begun to address questions that the Circular 482 did not cover. A new report by NCHRP was devised and written. This new report was published in 1974 as NCHRP Report 153 and was sixteen pages long. It was based on technical input from over seventy individuals and agencies. Later revisions included minor changes requiring modified treatment of particular problem areas and major changes that were required were testing with trucks and buses, re-evaluating criteria for impact severity, and looking at special highway appurtenances such as construction barriers. These new changes were implemented and published in 1978 as the Transportation Research Circular 191.

The NCHRP then reviewed and revised the Circular 191 to include current technology. This report was published in 1980 as NCHRP Report 230 [2]. This was used for full-scale crash testing for highway appurtenances in the United States. In 1989, a research team began investigating new technology, new barriers that were being designed, and new criteria needed for crash testing. After years of research the team came up with a draft of the new report. This draft was sent to one hundred individuals for comments. The comments were reviewed and where necessary, changes were made. This new report was published as NCHRP Report 350 [1].

NCHRP Report 350 is used to present guidelines for crash testing of permanent and temporary highway safety features and recommends evaluation criteria to get test results. These guidelines and evaluation criteria incorporate current technology and knowledge of professionals in the field of roadside safety design. The guidelines and criteria provide a platform on which researchers and agencies can compare impact performance of safety features, guidance for new safety features, and a way for agencies to formulate performance specifications for safety features.

NCHRP 350 highly recommends uniform testing of all roadside safety devices so highway engineers can have a good foundation to compare product performances. The NCHRP 350 helps in the selection of a safety feature by grouping safety devices into product types. These groups are based on crash performance characteristics. Also, there are many test levels that are based on the design speed of the product being tested.

As of May 1994, all newly designed attenuator products must meet the approval of the NCHRP 350 requirements. In addition, all existing attenuators and crash cushions were be re-tested to make sure that they meet the NCHRP 350 requirements by August 1998. Only attenuators meeting the NCHRP 350 requirements can be purchased using Federal funds, however, attenuators presently in use that do not meet the NCHRP 350 standards do not have to be replaced.

NCHRP 350 addresses three different vehicle types or weight classes in the test procedures. These test vehicles and their description is as follows:

- 700C and 820C vehicles (small compact cars)
- 2000P vehicle (high center of gravity pickup truck)
- 8000S, 36000V and 36000T vehicles (heavy trucks)

The 820C vehicle (1800 lbs.) is a good comparison for the passenger cars on the lower end of the spectrum in terms of mass. The vehicle that the NCHRP 350 recommends is the Ford Festiva. The 2000P (4409 lbs.) pickup truck represents utility vehicles and mini vans, which have a high center of gravity. NCHRP 350 recommends a ¾ ton pickup truck. The other three test vehicles (8000S, 36000V, and 36000T) are used for crash test evaluation of longitudinal barriers.

The NCHRP 350 evaluates the performance of highway safety devices based on three criteria. These criteria are structural adequacy, occupant risk, and vehicle trajectory. These three criteria are called Performance Evaluation Criteria.

Structural adequacy is a factor that assesses the safety device from a structural and mechanical aspect. If an impact occurs, the vehicle should not penetrate, under-ride, or over-ride the attenuator. If there are support posts or transition areas, they should not cause snagging. Factors that should be checked include the stiffness, deformation, yielding, fracture, and energy absorption or dissipation of the device.

Occupant risk is a criterion that evaluates the risk of the occupant injury during an impact with an attenuator. This is very hard to quantify because it involves very important, but varied factors of the occupant, such as, physiology, size, seating position, attitude, and restraint. There are several other occupant risk criteria which include:

- Debris does not penetrate occupant compartment.
- Debris does not block driver's vision or cause the driver to loose control of the vehicle.

- Debris should not present a hazard to other traffic, pedestrians, or workers that might be present in a work zone.
- Vehicle should remain upright during and after the impact.

Vehicle trajectory is the third criterion, for which it evaluates the post impact behavior of the test vehicle and is a measure of the risk of the test vehicle causing a subsequent multi-vehicle accident or impacting other fixed objects. Factors of vehicle trajectory are as follows:

- After an impact, the vehicle's trajectory does not interfere with adjacent traffic lanes.
- If pocketing or snagging occurs, it does not cause occupant velocities or ride-down accelerations in the longitudinal direction to exceed the specified limits.
- The exit angle is less than 60% of the impact angle.

Vehicle trajectory behind the device is acceptable for gating and non-re-directive devices.

2.2.2 AASHTO Roadside Design Guide

The American Association of State Highway and Transportation Officials (AASHTO) has devised a guide for roadside design called the Roadside Design Guide (RDG) [3]. The RDG was developed in metric units and presents a synthesis of current information and operating practices for roadside safety. The roadside can be defined as the area beyond the driving lanes and shoulder of the roadway. The main focus of the RDG is safety treatments including, attenuators, that will minimize the likelihood of serious injuries if a driver runs off the road.

It is very important to note that the RDG is strictly a guide and not a code or standard for design. It should only be used as a resource that highway agencies could develop standards or policies. The RDG uses design speed as the basic speed parameter. However, in some cases roadway conditions may not allow the driver to drive as fast as the design speed or some drivers may go much faster than the design speed. Since these situations might occur and often times do occur, the highway engineer should consider the speed at which encroachments are most likely to occur when selecting an appropriate design standard or feature.

The RDG provides a brief description of how attenuators work and summarizes the key features of many common attenuators. The RDG also discusses placement, use, and maintenance issues. The RDG recommends the following criteria for the selection of attenuators.

- Performance Capability
- Deflection
- Site conditions
- Compatibility
- Cost
- Maintenance (routine, collision, materials storage, simplicity)
- Aesthetics
- Field Experience

Placement recommendations are considered after it has been determined that an attenuator is needed. The layout required could be determined by four major factors: lateral offset from the edge of the traveled way, terrain effects, flare rate, and length of need. These factors are interrelated so that the design engineer can make a compromise for a final design if needed.

2.2.2.1 Lateral Offset

The rule of thumb for the placement of an attenuator is that it should be placed as far from the traveled way as permitted. This will give motorists a better chance at regaining control without causing an impact. The shy line offset is the distance from the edge of the traveled way, beyond which a roadside object will not be seen as an obstacle, which could result in the motorist reducing speed or changing the vehicles position on the roadway. Table 2.2 shows the design speed and related shy line offset.

Table 2.2: Suggested Shy Line Offset Values

Design Speed (km/h)	Shy Line Offset (m)
130	3.7
120	3.2
110	2.8
100	2.4
90	2.2
80	2
70	1.7
60	1.4
50	1.1

2.2.2.2 Terrain Effects

The best results of an impact usually occur when all the wheels of the vehicle are touching the ground and its suspension is not compressed or extended. The terrain conditions between the traveled way and attenuator have a great effect on the performance of the attenuator. Two important features are curbs and slopes. If a vehicle comes across one of these features, it might over-ride the attenuator or under-ride the attenuator if there is a downhill slope. A vehicle, which under-rides the attenuator, risks the chance of snagging the wheels or fenders.

2.2.2.3 Flare Rate

If a roadside barrier is not parallel to the edge of the traveled way, then it is considered flared. The reason to flare the barrier is to minimize the driver’s reaction to an obstacle near the road by gradually introducing a parallel installation. A disadvantage of flaring a barrier is that the greater the flare rate, the higher the angle at which the barrier can be hit. When the angle of impact is increased, the severity of the accident increases. The same general effect and guidelines would occur with an attenuator. Table 2.3 shows flare rates for barrier design.

Table 2.3: Suggested Flare Rates for Attenuator Design

Design Speed (km/h)	Flare Rate for attenuator inside shy line	Flare Rate for attenuator beyond shy line	
110	30:1	20:1	15:1
100	26:1	18:1	14:1
90	24:1	16:1	12:1
80	21:1	14:1	11:1
70	18:1	12:1	10:1
60	16:1	10:1	8:1
50	13:1	8:1	7:1

2.2.2.4 Length of Need

Length of need is the amount of attenuator that is needed to prevent the vehicle from impacting the obstacle or embankment. If the vehicle hits the attenuator before the length of need, then it is ok if it gates or breaks away. If the vehicle impacts behind the length of need, then it shouldn't break through because it won't have a sufficient run out length to stop. The variables of length of need are run out length and lateral extent of the area concern. Run out Length is the distance a vehicle needs to come to a stop if it has left the roadway. Run out Length is measured from the upstream extent of the obstruction along the road to the point where it is believed that the vehicle had left the road. Depending on the operating speed and tire friction, the distances will be different. Table 2.4 shows suggested run out lengths.

Table 2.4: Suggested Run-out Lengths for Attenuator Design

Design Speed (km/h)	Traffic Volume (ADT)			
	Over 6000	2000-6000	800-2000	Under 800
	Runout Length (m)	Runout Length (m)	Runout Length (m)	Runout Length (m)
110	145	135	120	110
100	130	120	105	100
90	110	105	95	85
80	100	90	80	75
70	80	75	65	60
60	70	60	55	50
50	50	50	45	40

Lateral Extent of the Area of Concern is described as the distance from the traveled way to the far side of the fixed object or to the outside edge of the clear zone of an embankment or a fixed object that extends beyond the clear zone. The clear zone is the distance from the through traveled way to the clear run out. The lateral extent of the area of concern length is an important part of design. When this length and the run out length are determined, then the proper length of attenuator can be selected.

2.2.2.5 Attenuator Maintenance

Maintenance is broken up into three categories, which are routine maintenance, collision maintenance, and material and storage requirements. Routine maintenance may include filling tubes with water, replacing diaphragms, painting, tightening nuts and bolts, or just cleaning the surrounding area. Collision maintenance includes any type of repair or adjustment that the attenuator may need. These repairs or adjustments are needed due to a vehicle impact. Material and storage requirements are very important when selecting an attenuator. It is preferable that the parts are readily available and easy to store. It is very important to consider the need for spare parts since the storage requirements increase as the number of parts in the attenuator increases.

2.2.3 Safety Needs Analysis Program (SNAP)

The Safety Needs Analysis Program is a program that can be downloaded from the Energy Absorption Systems web site [4]. The program provides overviews of the different attenuators that Energy Absorption manufactures, NCHRP Report 350, Energy Absorption Systems itself, and illustrations of sites where attenuators might be used. For attenuator systems, the program provides a description, characteristics, and siting recommendations. The software has an interactive program called Site Considerations, which allows you to input different data about a given site and identifies the types of attenuators, which are suitable for that site. This is similar to what we are trying to accomplish, but with a few key differences. One difference is that they do not consider other attenuators on the market and only briefly consider repair costs, maintenance costs, and other life cycle performance issues. Further, if more than one type of attenuator is suitable, it does not offer further recommendations or rankings of the models. These factors are very important to the engineer when making a decision. In general, however, this program is very informative and gives users a basis for what attenuators are, how they work, and which ones should be used at certain locations.

2.2.4 Decision Methodologies

Much research has been done in the area of decision support systems. A number of approaches exist for making decisions, such as Analytic Hierarchy Process (AHP), Author Co-citation Analysis (ACA), Analytic Network Process (ANP), Neural Network Process (NNP) and Agglomerative Hierarchical Clustering (AHC) methods.

The Analytic Hierarchy Process (AHP), developed by Thomas L. Saaty, is one of the more popular approaches. AHP is used for prioritization in decision-making; it is a means of doing pairwise comparison of alternatives under quantitative or qualitative criteria. Recent research in this area has ranged from medical diagnosis [16] to sizing naval fleets [17]. AHP was developed in the 1970's. It is the basis of the Expert Choice software [18], developed in 1983. Expert Choice is software that utilizes the AHP in structuring a decision into smaller parts. This software breaks down the decision making from the goal to objective, then sub-objectives down to the alternative courses of action. The user makes pairwise comparison judgments through the hierarchy to achieve overall priorities for the alternatives. The AHP and Expert Choice can be used to predict likely outcomes, plan projected and desired futures, and facilitate group decision-making as well as much more. The approach used in this study is loosely based on the AHP method as implemented in the Expert Choice software, except that importance functions are used to obtain criteria scores rather than pairwise comparison.

The OC1 (Oblique Classifier 1) method [14] is a decision tree induction system designed for applications where the instances have numeric (continuous) feature values. OC1 builds decision trees that contain linear combinations of one or more attributes at each internal node; these trees then partition the space of examples with both oblique and axis-parallel hyperplanes. OC1 has been used for classification of data representing diverse problem domains, including astronomy, DNA sequence analysis, and others.

Note that an alternate definition of a decision tree is as a representation of a decision procedure for determining a class label to associate with a given example. At each internal node of the tree, there is a test (question), and a branch corresponding to each of the possible outcomes of the test. At each leaf node, there is a class label (answer). With this formulation, the decision tree is used to solve problems that can be cast in terms of producing a single answer in the form of a class name. Based on answers to the questions at the decision nodes, one can find the appropriate leaf and the answer it contains [15]. An example of this type of decision tree would be answering questions about a patient's symptoms (questions) to provide a medical diagnosis (class label).

2.3 Related Research

This section describes four different studies of in-service attenuator performance. In general, the studies involve a limited number of installations and infrequent impacts. Although impact performance, installation cost, and repair cost were typically considered, a thorough study of life cycle costs was not performed. In addition, no efforts were made to develop procedures or software systems to evaluate or rank different attenuator systems.

2.3.1 North Carolina Department of Transportation

In this study, the Department of Transportation was comparing the Guard Rail Energy Absorption Terminal (G-R-E-A-T) to other attenuation devices used in North Carolina [5]. They were testing the effectiveness of the G-R-E-A-T in reducing the severity of injuries and property damage. They installed more than eighty systems (G-R-E-A-T's and other types of attenuators) throughout the state.

During the study period, the researchers found that nineteen impacts were recorded in police reports involving ten of the installations. However, none of the impacts involved installations of the G-R-E-A-T attenuator. Information that was available about unreported impacts with the G.R.E.A.T. system gave them reason to believe the attenuator was performing adequately in reducing impact severity.

This research is related to our research in that they are investigating the performance of impact attenuators. However, they did not do any research on ranking the attenuators nor did they investigate life cycle costs: rather they compared performance of the G-R-E-A-T to the types currently in use.

2.3.2 Connecticut Department of Transportation Projects

2.3.2.1 **Narrow Connecticut Impact-Attenuation System**

In this study, Connecticut was testing out a new device, known as the Narrow Connecticut Impact-Attenuation System (NCIAS) [6]. As part of the research project they designed, field evaluated and crash tested this device. It has eight steel cylinders connected in a single row, which are used as the energy absorbing material. This device is mainly used for narrow rigid roadside features.

This research is mildly relevant to ours, in that they were testing the performance of a new attenuator. While this is very important, we were more concerned with attenuators that are in use and have experienced impacts, rather than the design and implements of a new system.

2.3.2.2 **Connecticut Impact-Attenuation System**

This research and documentation was for an attenuator known as the Connecticut Impact-Attenuation System (CIAS) [7]. It was installed at four high hazard locations and tested over a three-year period. The main advantage of this attenuator is the ease of installation. It can sustain a number of hit and run impacts before it needs to be replaced or repaired.

This research is comparable to our research since they were evaluating impacts that had occurred with this attenuator. Unfortunately, they were more concerned with hit and run incidents instead of actual reported impacts. Our research involves incidents such as the hit and run impacts as well as the reported impacts.

2.3.2.3 **Tire and Sand**

This next study by Connecticut was concerning another attenuator they designed and tested [8]. It involved using old tires stacked up on their side. The tires were filled with sand and supports made out of fifty-five gallon drums were used. After reviewing accident reports they found that the performance was satisfactory in decelerating errant vehicles and that the installation and repair costs were much lower than most proprietary systems.

This system is similar to sand barrel systems. Sand barrels are used a great deal throughout Florida for construction zones. Again, this study is similar to ours because they are evaluating an attenuation system based on actual impacts and not controlled environments. However, they are only looking at a few types of attenuators in a limited number of crashes.

Further, they only consider installation and repair cost, neglecting deterioration and maintenance costs.

CHAPTER 3
GOALS/OBJECTIVES

3.1 Goals/Objectives

Four research objectives were established for this project. They are as follows:

1) Develop a database system.
2) Design and implement a framework for a Decision Support System (D.S.S.).
3) Input the appropriate data from FDOT into the database.
4) Use the D.S.S. and data to rank and evaluate attenuators.

The first objective of our research was to develop a database schema. The schema or structure of the database includes catalog data, site characteristics, accident/impact data, and repair/maintenance inspection data.

The D.S.S. (decision support system) was designed to use some of the key data items from the database. To evaluate and rank attenuators the ranking is reflective of goals and measures in the areas of safety, convenience, and cost. Measures are criteria, such as frontal capacity, tendency to snag wheel, or repair cost, by which the goals can be quantified, and alternates are the different attenuator types, such as, sand barrels, G-R-E-A-T, Hi-Dro Cell, HexFoam, Hi-Dro Sandwich, and Fitch barrels, which could be used at a site. Weights are used to prioritize or indicate the relative importance of each goal and measure. The weights vary based on the site characteristics, e.g. speed limit, roadway condition, and clearances. The overall score for an alternate indicates the degree to which each alternate meets the objectives.

The data in the database is taken from a variety of sources at the Florida Department of Transportation. Repair, inspection, and maintenance reports, and cost data were obtained along with crash records extracted from FDOT databases and paper reports. Finally, the D.S.S. was used to analyze this data for the types of attenuators in Florida and draw conclusions regarding their suitability for various uses and their life-cycle costs.

CHAPTER 4
APPROACH/METHODS

To develop the computerized information system for crash attenuators, four steps were completed.

1) Develop a database system.
2) Design and implement a framework for a Decision Support System (D.S.S.).
3) Input the appropriate data from FDOT into the database.
4) Use the D.S.S. and data to rank and evaluate attenuators.

This chapter describes the approach taken to implement each step. Because the primary contribution of this author to the overall research project was the development of the D.S.S., step three is described in more detail than the other steps.

4.1 Developing the Database

The database contains four basic categories of historical performance data on crash attenuators: catalog data, site and installation data, inspection and maintenance data, and accident and incident data. Data analysis is supplied to the user in the form of standard reports describing the performance of different attenuators under a variety of site or crash conditions. The database also supplies data to an integrated decision support system program, which ranks attenuators based on their relative performance in three areas: safety, cost, and convenience.

The computer system was implemented on an intranet platform, which provides a familiar, user-friendly interface and accessibility from remote users running a number of hardware platforms. An intranet can be defined as the application of Internet technology to an organization's internal information needs. With an intranet platform, users within the organization can quickly access the database and application programs via hard-wired computer terminals. Users outside the organization with sufficient security privileges can access the system through an Internet gateway by way of the main organizational server. Public information about the project, including member profiles, contact information, and progress statements are provided by means of an Internet home page.

All application programs, including the decision support system, were developed using the Oracle PL/SQL language. User interface screens are created “on the fly” with calls to a set of stored procedures from within the PL/SQL code. These stored procedures, along with a procedural gateway provided by Oracle, provide a framework for producing dynamic HTML pages using the data in the underlying database. To minimize typing by the end user, pull-down menus enable the user to select items from lists of attenuator types, site features, repair activities, etc. Another key benefit of the graphical interface is that incorrect and inconsistent data input is minimized.

The challenge in designing a database for any accident analysis system is that roadway geometries, environmental conditions, and accident characteristics are unique, with an infinite number of possible scenarios. An effective database design must be capable of describing the majority of these attributes without overburdening the system with unnecessary details. If the latter occurs, the system will be worthless, because data gatherers will tire of recording the excessive amount of data, leading to incomplete and inaccurate data, and engineers and researchers will be unable to draw conclusions or find trends in the data. Therefore, a key concern was identifying the most relevant parameters, and the most efficient ways of describing attenuators, their history, conditions during impacts, and their performance.

To fully address the needs of FDOT regarding attenuator installations, we considered data needs related to both construction zone attenuators and permanent roadside installations. With the exception that attenuators in construction zones are subject to frequent relocation and reconfiguration, the data needs of the two types of systems are no different. A status field is used to indicate whether the installation was permanent or temporary; a second field tracks whether a record is archival or for an attenuator currently in use.

The data required to fully describe an attenuator and any activity that it might undergo during its life cycle can be separated into four categories. The data categories can be described as moving from the most general (data about an attenuator type) to the most specific (data about a specific accident involving an attenuator of a specific type). These categories of data are listed and briefly described below. In addition, a specific example of how that data might be used is also included.

- **Catalog Data:** This data is descriptive information about the types of attenuators that are available from various manufacturers and suppliers. This data, which can be drawn from manufacturer's literature and FDOT specifications, includes model numbers and specifications, as well as design criteria and key features of different attenuator types. A database user might utilize this data to review the characteristics of an attenuator to be installed for a specific project.
- **Site and Installation Data:** This data set contains installation and site information about a specific attenuator in the FDOT inventory. The data describes the roadway geometry and features, including clearances, design speeds, etc. Data in this category is collected from existing FDOT records, as well as from site investigations, and can be placed into the database as soon as a site is identified. This information is used in conjunction with data from the other categories to evaluate the performance of various attenuators under a set of roadway and traffic conditions (e.g. high volume urban medians with clearance of less than 3 meters).
- **Accident and Incident Data:** This data set contains information about specific accidents and incidents involving an attenuator installation. The information includes driver and vehicle characteristics as well as the environment and traffic at the time of the accident. It also includes quantitative and qualitative data about the accident outcome, including damage to the vehicle and attenuator, injury to the vehicle occupants, and the overall performance of the attenuator. This information can be used to compare attenuator performance after undergoing impacts of various degrees of severity.
- **Repair and Maintenance Data:** This data describes the inspection, maintenance and impact repair history of a specific attenuator. The data includes the attenuator condition

after various FDOT mandated inspections and any deficiencies noted or repairs required at that time. It also includes data collected from other FDOT maintenance and repair reports, including impact repair activities. This information can be used to compare repair rates and costs among various attenuator systems under common installation and usage criteria.

In most cases, data would also be entered in the order of the above categories. Catalog data about an attenuator model can be placed in the database before any systems are installed (or documented in the database); likewise, data describing an installation and its site conditions can be entered before any accident or repair data is available. However, the data would be incomplete and unclear if accident data were entered without a corresponding site description.

Further, as additional research was completed, it was determined that some fields needed to be revised to provide more useful data. However, due to the problems mentioned previously, the researchers elected to focus on extracting data from existing sources rather than revising the forms and repeating the process.

4.2 Designing and Implementing the D.S.S.

This section describes the design and implementation of the D.S.S.. The D.S.S. is a computer program, based on a decision tree, which recommends an action that best meets a set of prioritized goals. The designer specifies goals, measures (criteria by which the goals can be quantified), and alternates (different ways in which the goal can be met). Weights are used to prioritize or indicate the relative importance of each goal and measure. They are also used to indicate the degree to which each alternate meets the objectives. For example, in the field of attenuators, design criteria, such as speed limit, traffic count, and clearances affect goals such as safety, cost, and conveniences. The alternates are the different attenuator choices (e.g. sand barrels, G-R-E-A-T, etc.), which could be used at a site.

The database will supply data to the D.S.S. in two ways. First, the site characteristics (e.g. clearances, speed limits, traffic volumes, etc.) will be used to determine the weights and measures for that site, e.g. on a high-speed site, rebound is an important parameter and in urban areas, vandalism is important. Depending on what features the engineer is looking for or what goal is deemed more important, the engineer can use the weights computed by the computer program based on the database data, or assign numbers to any or all of the weights. Second, historical data from the database will be used within the D.S.S. to ascertain the past performance of different types of attenuators at similar sites. The D.S.S. combines this information to provide a ranked listed of attenuators based on their expected performance under the input site conditions.

4.2.1 Example Decision Tree

The decision support system is based on a decision tree. To illustrate how a decision tree works, a simple example involving which new car to buy is provided. Basically, the top node on the tree is the overall objective function or goal, which, in this case, is which car to purchase. The nodes on the second level are the three measures or criteria on which the decision is based: Cost, Appearance and Durability. Those criteria could be broken into successive levels of sub-criteria, which would enable a more precise measurement and differentiation between different alternates. Weights are given to each criteria to indicate their importance in making the decision of whether to buy a car. Table 4.1 provides typical weights, which a person might place on the three criteria.

Table 4.1: Criteria and Weights for Choosing a New Car

Criteria		Weights
1	Cost	0.5
2	Appearance	0.4
3	Durability	0.1

The alternates in this example are the car models being considered. Table 4.2 lists four brands of cars as alternate choices, and provides a score or ranking for each alternate with respect to each criterion. The scores range from 1 to 10, with 1 being the worst and 10 being the best. In this example, the Yugo scores high on Cost, since it is inexpensive, yet low on Durability, since it does not have a proven track record. The Mercedes scores low on Cost, since it is an expensive vehicle, yet high on Appearance and Durability.

Table 4.2: Criteria Scores for Four Alternate Car Choices

Car		Cost	Appearance	Durability
1	(Yugo)	10 (cheap)	2 (gets you around)	2 (won't last)
2	(Honda)	4 (moderate)	6 (average)	7 (pretty good)
3	(Mercedes)	1 (expensive)	10 (impresses)	8 (even better)
4	(Ford/Chevy)	6 (low/moderate)	4 (dull)	4 (moderate)

From this example we can calculate how each brand of car will rank. For each criteria, the weight is multiplied by the corresponding score. The calculations are as follows:

Car 1 (Yugo) = (0.5)(10) + (0.4)(2) + (0.1)(2) = 6
Car 2 (Honda) = (0.5)(4) + (0.4)(6) + (0.1)(7) = 5.1
Car 3 (Mercedes) = (0.5)(1) + (0.4)(10) + (0.1)(8) = 5.3
Car 4 (Ford/Chevy) = (0.5)(6) + (0.4)(4) + (0.1)(4) = 5

A Yugo would be recommended in this example, based on the low weight given to durability and relatively low weight given to appearance. However, depending on the importance a person places on different criteria and how he evaluates the alternates' performance, the weights and rankings may be different and yield a different outcome.

4.2.2 Actual Decision Tree

The multi-criteria decision support system (D.S.S.) uses the historical data to rank attenuators based on they're past performance under specific site conditions. This application supports the design and selection of attenuators for new locations; it also can be used to analyze current placement recommendations for common scenarios. Use of the system will allow highway safety personnel to better understand the performance and applicability of various types of crash attenuators. Further, the research extends the concept of a decision hierarchy by using deterministic and heuristic importance functions to vary the weights to reflect changes in site conditions and using historical data from the relational database to determine the attenuators' performance for each criterion.

The tree structure, which is based on criteria established after careful review of relevant literature, including the AASHTO Roadside Design Guide [3] and the NCHRP crash test specifications in Report 350 [1], is shown in Figure 4.1. As before, the top node on the tree is the overall objective function or goal, which is used to evaluate an attenuator. The nodes on the second level are the three sub-goals or measures on which the decision is based: Safety, Cost, and Convenience. The third level of nodes is the criteria, which are used to measure the degree to which each attenuator achieves the respective goal. Some criteria are listed more than once because they affect the performance of the attenuator in more than one way. For instance, scattering debris represents a risk to the impacting vehicle because it can blind the driver; it also is a risk to others because it can decrease surface friction on the roadway near the attenuator. Weights are placed on each node in the tree to reflect the significance of that criteria or goal in ranking an attenuator's performance.

1. Safety: The first goal of the decision support system is to improve the safety of the attenuator site by providing adequate structural performance, and reducing the impact both to the impacting vehicle and to surrounding vehicles and pedestrians.
   - 1.1 Structural Adequacy: An attenuator with adequate structural performance will better protect the vehicle, its occupants and the fixed obstacle by preventing a direct impact.
     - 1.1.1 Ability to Stop Frontal Impacts/Capacity: Because an impact with the protected obstacle will most likely result in the most negative possible outcomes, an attenuator that can stop an impacting vehicle before it hits the fixed object is desirable.
     - 1.1.2 Ability to Redirect Side Impacts: An attenuator which can redirect side impacts is preferable to which allows gating, pocketing, snagging, and/or other undesirable behaviors, because the impact is less likely to result in high deceleration rates and occupant injury.
   - 1.2 Risk to Impacting Vehicle: In the event of an impact, an attenuator, which results in the best outcome for the impacting vehicle, is desirable.
     - 1.2.1 Acceptable Deceleration Characteristics: High vehicular deceleration rates are correlated to high rates of occupant injury and unpredictable trajectories.

1.2.1.1 Tendency to Snag: When a vehicle snags on an attenuator, high decelerations will occur, causing a higher likelihood of severe injuries as well as unpredictable vehicle trajectories.

1.2.1.2 Tendency to Pocket: The tendency of an attenuator to pocket can lead to high vehicle deceleration rates, which in turn leads to a high likelihood of severe injuries, as well as unpredictable vehicle trajectories.

1.2.2 Ability to Contain Debris: Pieces of debris, which fly or protrude from the attenuator after an accident, can result in potential injuries to the vehicle's occupants.

1.2.2.1 Tendency to Spear/Penetrate Occupant Compartment: When the impact leads to the creation of sharp edges and pointed debris on the attenuator, the passenger compartment may rupture, thus causing injuries to the occupants.

1.2.2.2 Tendency to Scatter Debris: Excessive scatter of debris may lead to loss of vehicular control by blinding the driver and/or reducing traction on the roadway. This increases the chances that the vehicle will be in a secondary accident.

1.2.3 Acceptable Post-Impact Trajectory: The post-impact trajectory of the impacting vehicle is very important in determining the ultimate safety of the vehicle's occupants, as well as occupants in other surrounding vehicles and pedestrians.

1.2.3.1 Tendency to Rollover: A rollover of the impacting vehicle will increase the chances of causing injuries to the occupants of the impacting vehicle.

1.2.3.2 Tendency to Over-ride Cushion: An over-ride of the cushion can lead to the vehicle hitting the fixed object or moving to travel lanes in the opposite direction. This may cause additional injuries to the occupants of the impacting vehicle.

1.2.3.3 Tendency to Under-Ride Cushion: An under-ride of the cushion will lead to high deceleration, which in turn leads to a high likelihood of severe injuries.

1.2.4 Tendency to Deform Passenger Compartment: Larger amounts of vehicle damage and deformation, particularly to the passenger compartment, correlate to a higher incidence of occupant injuries.

1.2.5 Presence of Injuries: A system that results in less frequent and less severe injuries is obviously more desirable to the driving public.

1.2.5.1 Rate of Occupant Injury: An attenuator system which results in less frequent injuries are important for obvious reasons, because of the potential danger of frequent injuries.

1.2.5.2 Severity of Occupant Injury: An attenuator system which result in less severe injuries is important for obvious reasons, because of the potential danger of severe injuries.

1.3 <u>Risk to Others</u>: In the event of an attenuator impact, risk can occur to repair crews and to other vehicles, both during the crash and prior to the completion of the repair.

1.3.1 Risk During Crash: Drivers in adjacent lanes at the time of the crash can suffer severe risks, particularly in the event that the impacting vehicle has a poor post-impact trajectory.

1.3.2 Tendency to Rebound Backwards: A rebound backward from the cushion increases the chances that the vehicle will land in a travel lane and be hit by other vehicles that were following behind the original.

1.3.2.1 Tendency Toward Large Redirect Angle: Small redirect angles will reduce the possibility that the impacting vehicle will interfere with other travel lanes, while large redirect angles increase the chance of stopping in adjacent travel lanes.

1.3.2.2 Tendency to Gate: Gating will increase the possibility that the impacting vehicle will progress into the opposing traveling lanes, thus posing an increased risk to other road users.

1.3.2.3 Tendency to Scatter Debris: Flying debris will increase the chance of piercing other vehicles, blinding other drivers, and/or make other drivers swerve in an attempt to avoid the debris. This may cause an additional risk to other road users.

1.3.3 Risk After Crash: After a vehicle impact, risks to the safety of others on the road include risks to the repair crew and risks to other drivers due to the unprotected object.

1.3.3.1 Response Time: Response time is the time it takes for a crew to respond to an attenuator impact. The longer it takes for a crew to respond to their repair, the higher the likelihood that another vehicle may hit the unprotected object, adding a risk to other road users.

1.3.3.2 Repair Time: Repair time is the actual time it takes to restore the cushion to normal working order, once the repair has begun. During a repair, workers are exposed to a higher risk of being hit by an errant vehicle; thus the less time it takes to perform the actual repair the better.

1.4 <u>Geographical Considerations</u>: A cushion's susceptibility to vandalism or environmental deterioration can affect its safe performance. Both of these measures are highly correlated to geographical location.

1.4.1 Susceptibility to Vandalism: In the eventuality of vandalism, the fixed object remains unprotected or improperly unprotected, thus posing a safety concern. Vandalism is more likely to take place in urban areas than in rural areas.

1.4.2 Susceptibility to Environment: A susceptibility to environmental degradation can increase the need for and cost of maintaining an attenuator. In addition, the deterioration can severely decrease the impact performance of a cushion, if undetected and un-repaired.

2. Convenience: The second goal of the decision support system is to increase the convenience to construction workers and other roadway users when installing, repairing, and using crash attenuators.

2.1 <u>Installation Convenience</u>: A system, which is more difficult to install, can potentially result in inconveniences and travel delays to the driving public.

2.1.1 Installation Time: The longer the workers need to stay on the road installing the attenuator, the greater the need for more elaborate maintenance of traffic and the higher likelihood of inconvenience to the roadway users.

2.1.2 Installation Equipment: When heavy equipment is required to complete an installation, the operation of the highway may be obstructed, causing more inconvenience to other highway users.

2.2 <u>Repair Convenience</u>: A system that is more difficult to repair can potentially result in inconveniences and travel delays to the driving public, in addition to secondary effects on the safety and cost of the repair.

2.2.1 Repair Time: The longer the workers need to stay on the road conducting the repair, the greater the need for more elaborate maintenance of traffic and the higher likelihood of inconvenience to the roadway users.
2.2.2 Repair Equipment: When heavy equipment is required to complete a repair, the operation of the highway may be obstructed, causing more inconvenience to other highway users.
2.2.3 Inventory Requirements: Larger inventory required for installation and maintenance of a crash cushion result in larger storage requirements and make repairs more difficult and time-consuming.

2.3 <u>Portability</u>: At certain locations, such as in construction zones, portability may be a critical parameter. Some crash cushion systems are more portable than others.

3. Cost: The third goal of the decision support system is to reduce life-cycle costs when selecting attenuators. The rationale for this goal is self-explanatory.
   3.1 <u>Initial/Installation Cost</u>: A system with a high initial or installation cost requires a large initial investment, which may reduce the funding available for other aspects of a roadway project, or result in the use of fewer attenuators.
   3.2 <u>Maintenance Cost</u>: A system with high maintenance costs will require a high level of funding throughout its life cycle.
   3.3 <u>Repair Cost</u>: A system with high repair costs would be less desirable in a location with frequent impacts. This measure would be less important in a less impact-prone location.

4.2.3 <u>Relationship Between Criteria and Site Characteristics</u>

The previous section listed numerous criteria, which are important in evaluating the performance of an attenuator. However, certain criteria are more important sometimes and less important other times, depending largely on characteristics at the site where the attenuator has been or is to be placed. After researching accident reports, roadway design and attenuator selection standards, and other relevant literature, the following site characteristics were identified as having the largest effect on the suitability of an attenuator for a given site. These site characteristics are thus used to develop the weights for each of the end nodes on the D.S.S.:

- Design Speed
- Traffic Count
- Longitudinal Clearance
- Lateral Clearance to Traffic
- Width of Clear Zone
- Length of Clear Zone
- Work Zone Use
- Rigid Hazard
- Urban Location
- Climate
- Impact Frequency
- Pedestrian Use

Table 4.1 provides a matrix of the D.S.S. criteria and site characteristics. The boxes with an X inside indicate that there is a relationship between the intersecting D.S.S. criteria weight and the site characteristic, in other words, that the criteria becomes more or less important as the value of the site characteristic changes.

Table 4.3: D.S.S. Criteria and Site Characteristics Matrix

Criteria Number (End nodes only)	D.S.S. Criteria	Importance Functions (IF_{ij})												Consequences Exponent (n)
		Design Speed	**Traffic Count per Lane**	**Long. Clearance-Traffic**	**Lateral Clearance-Traffic**	**Width Clear Zone**	**Length Clear Zone**	**Work Zone Use**	**Rigid Hazard**	**Urban Loc.**	**Climate**	**Impact Frequency[1]**	**Pedestrian Use[2]**	
	1 SAFETY													
	1.1 Structural Adequacy													
1	1.1.1 Ability to stop frontal impacts/Capacity	X							X			X		3
2	1.1.2 Ability to redirect side impacts	X			X							X		3
	1.2 Risk to impacting vehicle													
	1.2.1 Acceptable deceleration characteristics													
3	1.2.1.1 Tendency to snag	X										X		2
4	1.2.1.2 Tendency to pocket	X							X			X		3
	1.2.2 Ability to contain debris													
5	1.2.2.1 Tendency to spear vehicle	X												2
6	1.2.2.2 Tendency to scatter debris	X										X		1
	1.2.3 Acceptable post-impact trajectory													
7	1.2.3.1 Tendency to rollover	X	X		X									2
8	1.2.3.2 Tendency to over-ride the attenuator	X				X								1
9	1.2.3.3 Tendency to under-ride the attenuator	X			X									2
10	*1.2.4 Tendency to deform the passenger compartment*	X												2
	1.2.5 Presence of injuries													
11	1.2.5.1 Rate of occupant injury	X												2
12	1.2.5.2 Severity of occupant injury	X												3
	1.3 Risk to others													
	1.3.1 *Risk during crash*													
13	1.3.1.1 Tendency to rebound backwards	X	X	X									X	3
14	1.3.1.2 Tendency toward large redirect angle	X	X		X								X	2
15	1.3.1.3 Tendency to gate	X	X			X	X						X	3
16	1.3.1.4 Tendency to scatter debris	X	X		X	X	X	X					X	1
	1.3.2 Risk after crash													
17	1.3.2.1 Response time							X	X			X		3
18	1.3.2.2 Repair time	X	X	X	X							X		2
	1.4 Geographical considerations													
19	1.4.1 Susceptibility to vandalism			X	X					X				1

[1] Derived quantity based on design speed, traffic count, and clear distance to traffic.
[2] Derived quantity based on urban location and road classification.

Table 4.3 Continued

Criteria Number (End nodes only)	D.S.S. Criteria	Importance Functions (IF_{ij})												Consequences Exponent (n)
		Design Speed	Traffic Count per Lane	Long. Clearance-Traffic	Lateral Clearance-Traffic	Width Clear Zone	Length Clear Zone	Work Zone Use	Rigid Hazard	Urban Loc.	Climate	Impact Frequency[1]	Pedestrian Use[2]	
20	1.4.2 Susceptibility to environment										X			0
	2 CONVENIENCE													
	2.1 Installation Convenience													
21	2.1.1 Installation time	X	X	X	X									0
22	2.1.2 Installation equipment			X	X	X	X							0
	2.2 Repair Convenience													
23	2.2.1 Repair time	X	X	X	X							X		0
24	2.2.2 Repair equipment			X	X	X	X					X		0
25	2.2.3 Inventory requirements											X		0
26	2.3 Portability							X				X		0
	3 COST													
27	3.1 Initial/Installation cost													1
28	3.2 Maintenance cost			X	X	X	X				X			1
29	3.3 Repair/replacement cost			X	X	X	X					X		1

[1] Derived quantity based on design speed, traffic count, and clear distance to traffic.
[2] Derived quantity based on urban location and road classification.

The relationships between the D.S.S. criteria weights and site characteristics are described in more detail in the following paragraphs. A graph was developed to explain and compute the relationship between each D.S.S. site criteria and the relevant site characteristics; these graphs are known as the importance functions. The importance functions range from zero (meaning that the site characteristic is not relevant at all for the given value of the D.S.S. criteria) to one (meaning that the site characteristic is very important for the given value of the D.S.S. criteria). In some cases, the graphs were developed based on numeric evidence found through researching accident reports, roadway design and attenuator selection standards, and other relevant literature. For relationships where numeric values could not be found, common sense was used to develop the graph.

Criteria 1.1.1 (The Ability to Stop Frontal Impacts/Capacity)

Through investigation of the aforementioned reference materials and other materials, three site characteristics were determined to be related to the ability to stop frontal impacts.

A) Design Speed
As the design speed of the roadway increases, the importance of providing sufficient frontal capacity increases. The following graph, shown in Figure 4.1, was developed using information provided in Index #435 of the Quadguard Roadway Design and Traffic Standards [9]. The ratio of the bays required for a given design speed to the total number of bays was used as the importance factor. That is, the smallest attenuator system protects against a 60 kph impact and the largest one is rated for a 110 kph impact; therefore, frontal capacity is more important at higher design speeds.

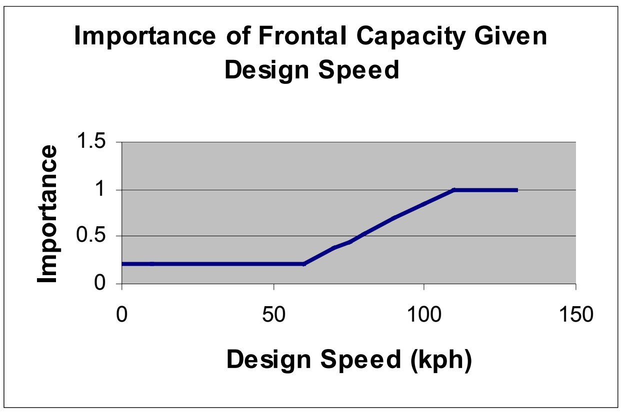


Figure 4.1: Importance of Frontal Capacity Given Design Speed

B) Hazard Rigidity
Although no specific reference materials were used to develop this function, common sense indicates that it is always important to stop frontal impacts to protect the motorist and hazard. This graph is shown in Figure 4.2. But, frontal capacity is more important if the hazard is rigid, e.g. a concrete barrier wall, and less important if the hazard is less rigid, e.g. a guardrail. However, since rigidity is not well defined, a simple yes/no value is assigned to this site characteristic.

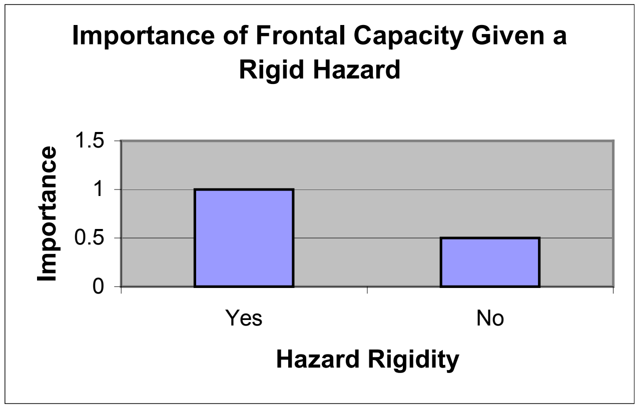


Figure 4.2: Importance of Frontal Capacity Given a Rigid Hazard

C) Impact Frequency

Impact Frequency is linearly related to the importance of an attenuator stopping frontal impacts. As the attenuator is impacted more often, the importance of stopping those impacts increases. No specific reference materials were found to develop this function. A graph representing this is shown in Figure 4.3.

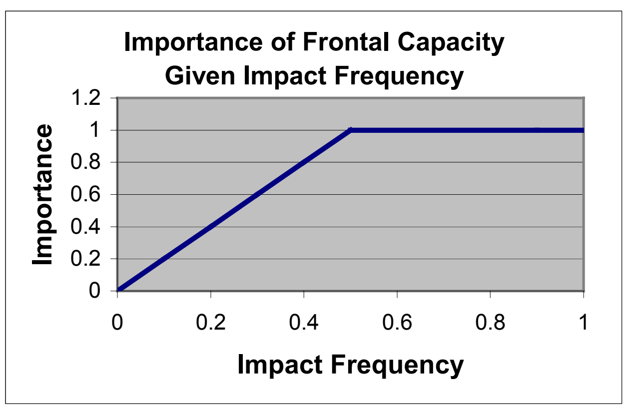


Figure 4.3: Importance of Frontal Capacity Given Impact Frequency

Criteria 1.1.2 (Ability to Redirect Side Impacts)

Through research of the following referenced materials and others, the three following site characteristics were found to be related to the ability to redirect side impacts.

A) Design Speed

As the design speed of the roadway increases, the importance of redirecting side impacts increases. The ability to redirect side impacts is important because we do not want the impacting vehicle to be redirected back into traffic. The graph in Figure 4.4 was developed using information found in NCHRP 350, Criteria "M" [1]. It states that the exit angle should be less than 60% of the impact angle. The acceptable ratio is exit angle divided by impact angle is less than or equal to 60%. According to NCHRP 350, attenuators did not adequately redirect vehicles at speeds of 80 kph and below. As a result, 80 kph was chosen as the cutoff where design speed was of minimal importance.

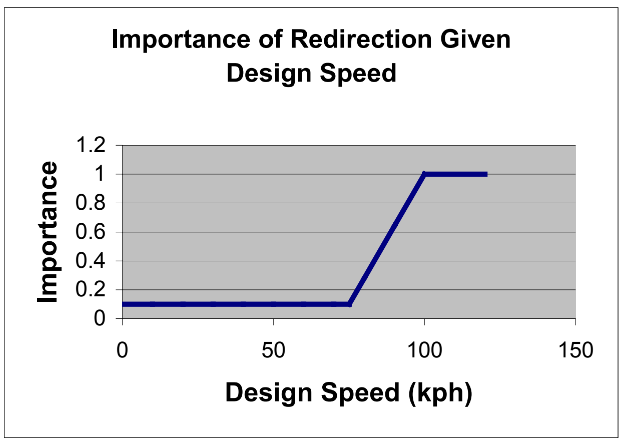


Figure 4.4: Importance of Redirection Given Design Speed

B) Lateral Clearance to Traffic

The lateral clearance to traffic is linearly related to the importance of redirecting a side impact. As the distance of lateral clearance increases, the importance of redirecting side impacts decreases. The graph shown in Figure 4.5 was loosely based on cutoffs used in the Energy Absorption Systems SNAP program [4].

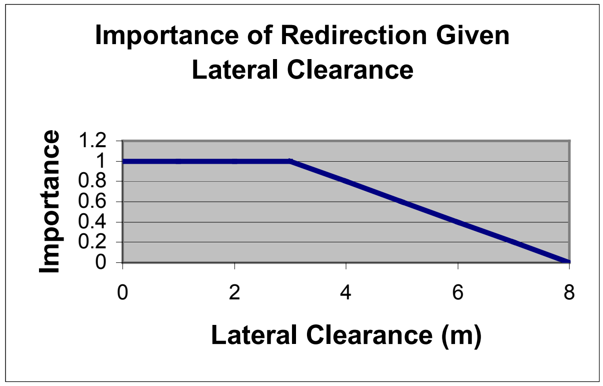


Figure 4.5: Importance or Redirection Given Lateral Clearance

C) Impact Frequency
Impact Frequency is linearly related to the importance of an attenuator to redirect side impacts. As the attenuator is impacted more often, the importance of redirecting side impacts increases. The following graph shown in Figure 4.6 represents this.

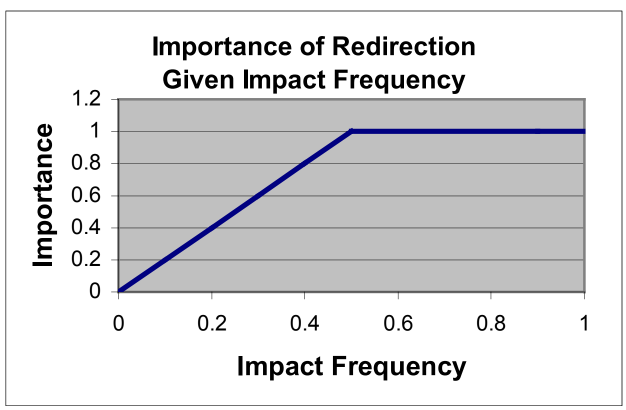


Figure 4.6: Importance or Redirection Given Impact Frequency

Criteria 1.2.1.1 (Tendency to Snag)

The tendency of a vehicle to snag on an attenuator is important because it can cause the vehicle to change direction and rollover, cause an abrupt stop, or snagging can lead to penetration of the occupant compartment. There are two site characteristics related to snagging. They are as follows.

A) Design Speed

The importance of design speed is linearly related to the tendency of an attenuator to snag the wheels or fenders. As the design speed of the roadway increases, the importance of not snagging the vehicle, which might cause sudden decelerations, increases. This graph is shown in Figure 4.7. This graph was developed using information found in Section 5.4 (Post Impact Vehicle Trajectory) of NCHRP 350 [1]. The cutoffs for design speed are loosely based on information found in a Transportation Research Record article [10]. Vehicles that snag while impacting an attenuator at higher speeds tend to have a higher rate of severe outcomes.

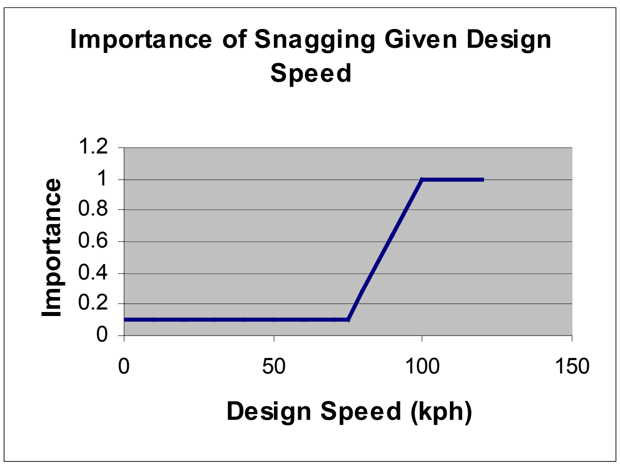


Figure 4.7: Importance of Snagging Given Design Speed

B) Impact Frequency

As the attenuator is impacted more frequently, the potential for negative consequences of a tendency to snag increases. A graph that represents this is shown in Figure 4.8. The cutoffs are based on common sense.

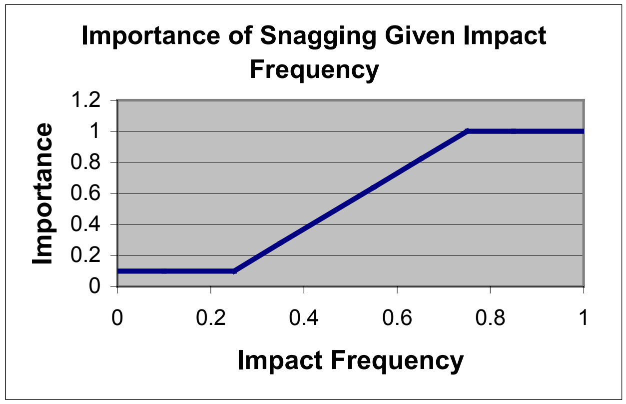


Figure 4.8: Importance of Snagging Given Impact Frequency

Criteria 1.2.1.2 (Tendency to Pocket)

As with snagging, the tendency of a vehicle to pocket is important because it may cause an abrupt stop. It may also allow the vehicle to come into contact with the rigid hazard or even allow the vehicle gate. The three following site characteristics are related to pocketing.

A) Design Speed

As the design speed of the roadway increases, the importance of the tendency of an attenuator to pocket increases. The graph shown in Figure 4.9 was determined from information found in Section 5.4 (Post Impact Vehicle Trajectory) of NCHRP 350 [1].

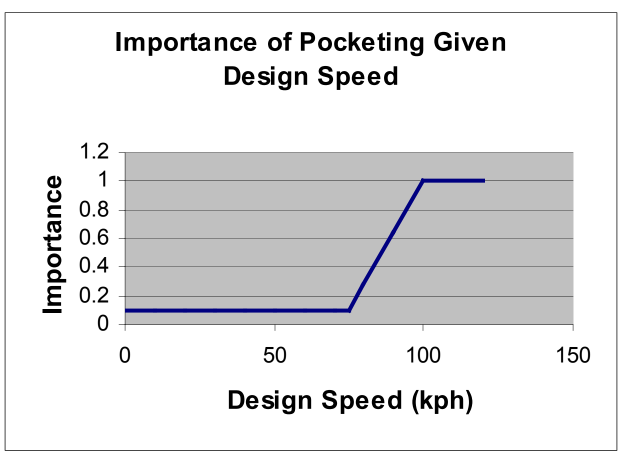


Figure 4.9: Importance or Pocketing Given Design Speed

The cutoffs for design speed are loosely based on information found in a Transportation Research Record article [10]. Vehicles traveling at high speeds have a greater chance of pocketing than vehicles traveling at slower speeds. These faster vehicles that tend to pocket have a more severe outcome.

B) Rigid Hazard

Although no specific reference materials were used to develop this function, common sense indicates that pocketing is more important when it involves a rigid hazard, because of the outcome that could occur to the motorist and hazard. This graph is shown in Figure 4.10.

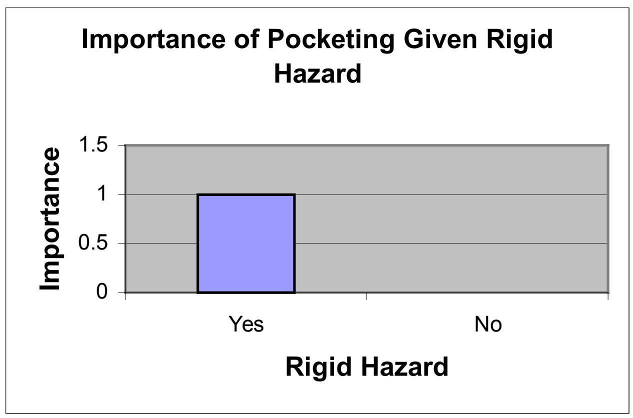


Figure 4.10: Importance of Pocketing Given Rigid Hazard

C) Impact Frequency

Although no specific reference materials were used to develop this function, common sense indicates that as the attenuator is impacted more often, the importance that the attenuator not pocket increases. If the attenuator is impacted more often, then this puts it at more risk of not performing the way it was designed to. This graph is shown in Figure 4.11.

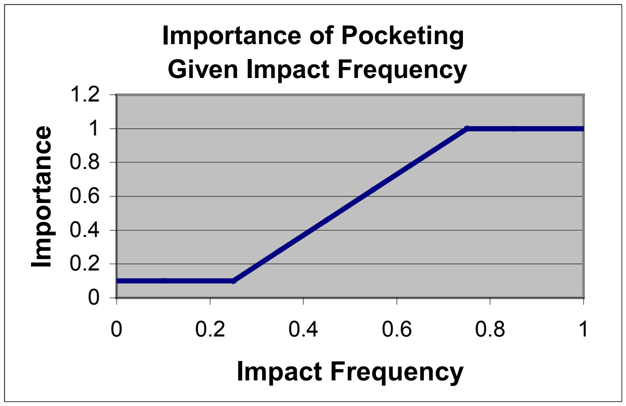


Figure 4.11: Importance of Pocketing Given Impact Frequency

Criteria 1.2.2.1 (Tendency to Spear/Penetrate Occupant Compartment)

Preventing spearing or penetrating the occupant compartment is very important. If this occurs, the risk of injury to the driver or passengers of the vehicle increases. Depending on where it occurs, the vehicle could catch on fire. Penetration will also cause an abrupt stop. The following site characteristic is related to spearing and penetrating.

A) Design Speed

The importance of the attenuator‘s tendency to spear or penetrate the occupant compartment increases with the design speed of the roadway, because of the potential for more negative consequences with a high-speed impact. This graph is shown in Figure 4.12.

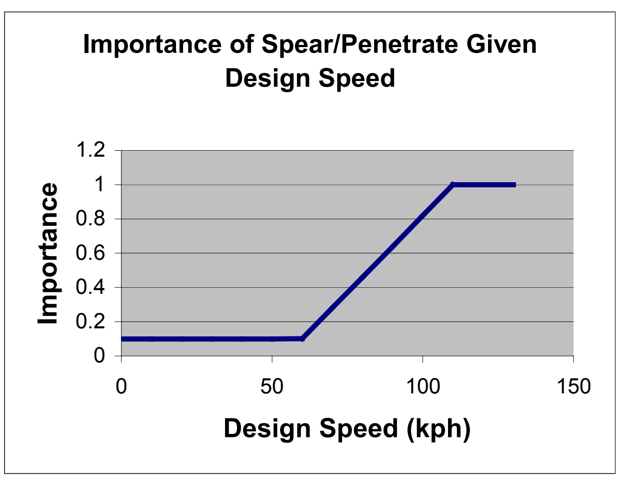


Figure 4.12: Importance of Spear/Penetrate Given Design Speed

On Florida interstates the minimum and maximum design speeds are 60 and 110 km/hr respectively. Because of this, 60 kph was chosen as the lower bound, where a tendency to spear is least important, and 110 was chosen as an upper bound, where a tendency to spear is most important. The importance factors are based in general on a spot speed type diagram. A spot speed diagram indicates that at higher posted speeds, there is a higher percentage rate for debris to penetrate or spear the occupant compartment and less of a percentage at slower speeds.

Criteria 1.2.2.2 (Tendency to Scatter Debris)

It is important that debris not be scattered following an attenuator impact because this will increase the risk of additional accidents and injuries to motorists or pedestrians. The following two site characteristics are related to scattering debris.

A) Design Speed

As the design speed of the roadway increases, the importance of using an attenuator that does not scatter debris increases. The graph shown in Figure 4.13 was determined using common sense. At any speed, an impact will have some sort of debris present; therefore, the importance of not scattering debris begins at zero when the design speed is zero. There will be much more debris at higher speed impacts; therefore, the importance increases linearly until a maximum speed of 110 kph is reached.

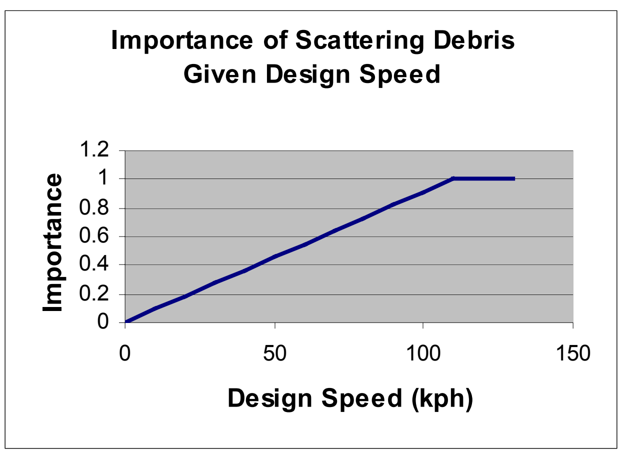


Figure 4.13: Importance of Scattering Debris Given Design Speed

B) Impact Frequency
As the attenuator is impacted more often, the importance of using an attenuator that contains debris increases. If the attenuator is impacted more often, then the potential negative consequences of not performing appropriately increase. The graph is shown in Figure 4.14.

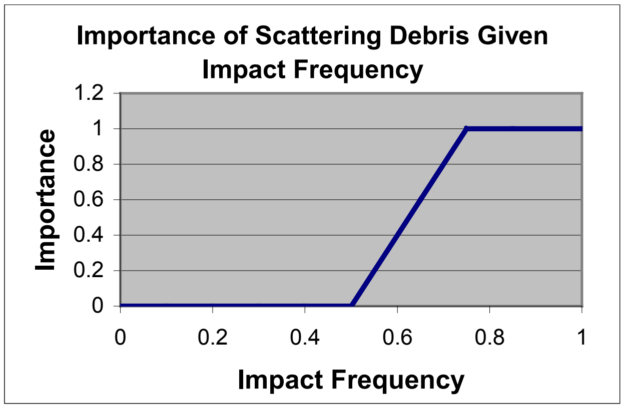


Figure 4.14: Importance of Scattering Debris Given Impact Frequency

Criteria 1.2.3.1 (Tendency to Rollover)

A rollover is very important to the passengers of the impacting vehicle. Severe injury can take place if a rollover occurs. Since a vehicle is not in control during a rollover, it puts the oncoming or passing traffic at great risk of causing a pile up collision. The site characteristics that are related to rollovers are as follows.

A) Design Speed
As the design speed of the roadway increases, the importance of the vehicle not to roll over increases. The cutoffs used in the graph shown in Figure 4.15 were based on information found in reference [11]. According to this document, guardrail accidents at speeds below 51.5 kph infrequently resulted in rollovers. Therefore, it was concluded that a tendency to rollover became less important at approximately 50 kph.

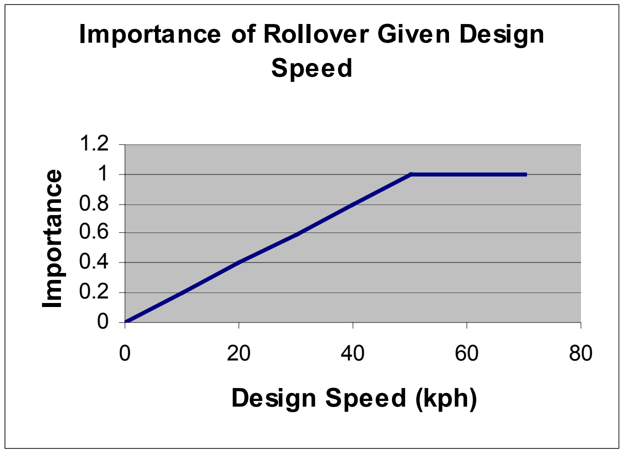


Figure 4.15: Importance of Rollover Given Design Speed

B) Traffic Count

The importance that the vehicles not roll over is linearly related to the traffic count. The cutoffs were taken from Figure 3.1 (Clear zone distance curves) of the Roadside Design Guide [3], where 25,000 vehicles per day is considered to be a high volume roadway, therefore because of the number of vehicles that will pass by the attenuator, it is of the highest importance that the attenuator not cause vehicle rollovers. The following graph shown in Figure 4.16 represents this.

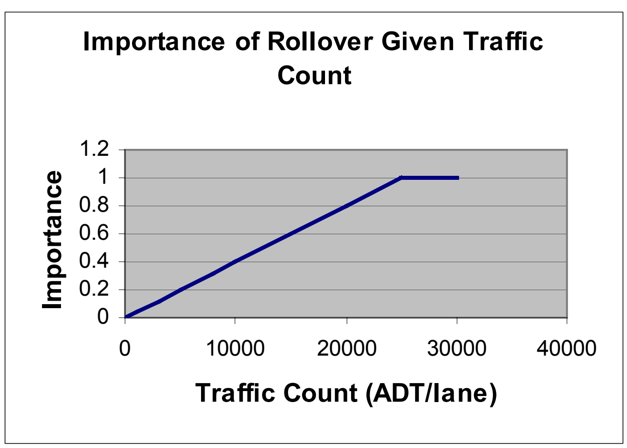


Figure 4.16: Importance of Rollover Given Traffic Count

C) Lateral Clearance To Traffic

As the amount of lateral clearance increases, the importance of not rolling over decreases. If a rollover occurs, the lateral clearance needs to be at least the length or width of the car, depending on how the car lands, to prevent intrusion into a travel lane. As a result, 8 meters was established as the lower limit, below which lateral clearance has maximum importance. The upper limit, above which lateral clearance has minimal importance, was based on recommendations provided in the Energy Absorption Systems SNAP program [4]; the lower limit is based on the size of a typical vehicle. The graph in Figure 4.17 represents this equation.

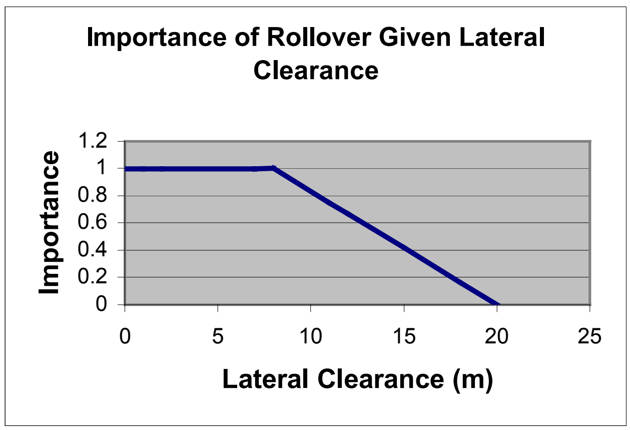


Figure 4.17: Importance of Rollover Given Lateral Clearance

Criteria 1.2.3.2 (Tendency to Over-Ride the Attenuator)

Over-riding an attenuator is when a vehicle impacts an attenuator and travels over it, possibly into oncoming traffic that might not see the accident occurring to react in time. Over-riding an attenuator is very important because it increases the possibility of head on collisions. The following are characteristics related to the tendency to over-ride the cushion.

A) Design Speed

As the design speed of the roadway increases, the importance a vehicle to not over-ride the attenuator increases. The graph shown in Figure 4.18 was based on the performance of a guardrail end terminal, which showed over-riding problems at approximately 100 kph [12].

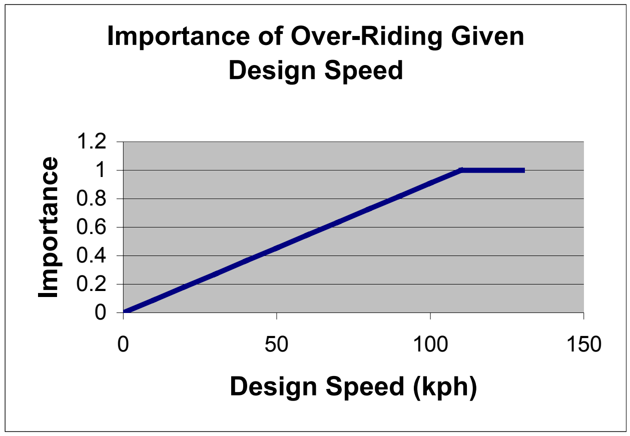


Figure 4.18: Importance or Over-Riding Given Design Speed

C) Width of Clear Zone

As the width of the clear zone increases, the importance of a vehicle not over-riding the attenuator decreases. If an impact occurs and there is sufficient clear zone width that the vehicle poses no risk to other vehicles, then potential negative consequences of a secondary impact are reduced. This graph is shown in Figure 4.19. The upper limit, above which over-riding has minimal importance, was based on a minimum clearance provided in the Energy Absorption Systems SNAP program [4]. The lower limit was loosely based on the maximum likely departure angle.

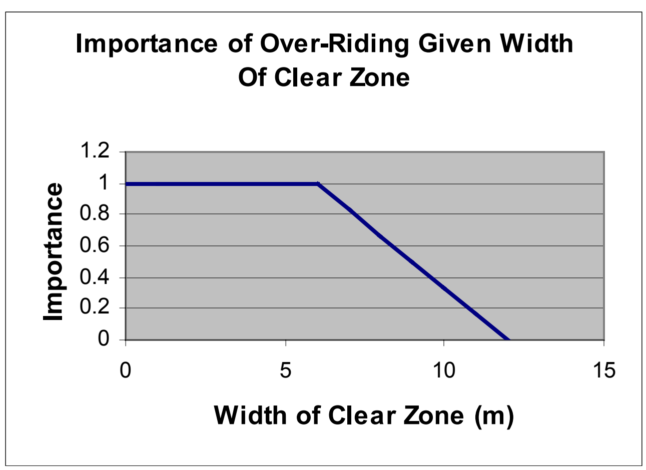


Figure 4.19: Importance of Over-Riding Given Width of Clear Zone

Criteria 1.2.3.3 (Tendency to Under-Ride the Attenuator)

Under-riding occurs when a vehicle impacts a cushion and is forced underneath the attenuator. This can be very dangerous for the occupants of the impacting car and any vehicles that are coming from behind the impacting car. The following characteristics are related to under-riding.

A) Design speed

As the design speed of the roadway increases, the importance of the vehicle to not under-ride the attenuator increases. The upper and lower limits were based on common sense. This graph is shown in Figure 4.20.

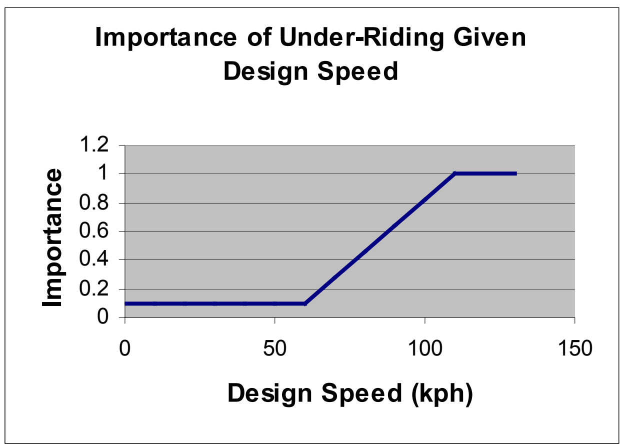


Figure 4.20: Importance of Under-Riding Given Design Speed

B) Lateral Clearance to Traffic

As the amount of lateral clearance increases, the importance that the vehicle does not under-ride the attenuator decreases. The graph is shown in Figure 4.21. When an attenuator is under-ran, the position of the car determines what space is required on either side of attenuator. The cutoffs are based on the width of a typical vehicle [1]. If the front corner of the vehicle under-rides the attenuator but the remainder of the vehicle doesn't pass underneath, a small lateral clearance means (less than 4 meters) that a secondary impact is more likely. A lateral clearance greater than about 5 meters makes this possibility more remote.

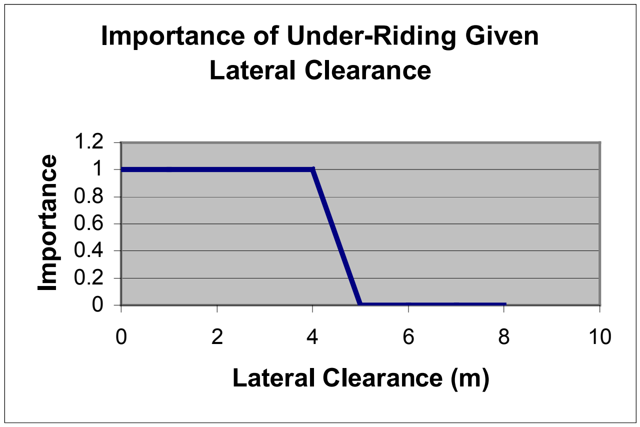


Figure 4.21: Importance of Under-Riding Given Lateral Clearance

Criteria 1.2.4 (Tendency to Deform the Passenger Compartment)

Deforming the passenger's compartment is very important because it puts the passengers at a higher risk of injury. The severity of the impact generally determines the extent of damage done to the vehicle. The following is the characteristic of deforming the passenger compartment.

A) Design Speed

The design speed is linearly related to importance of the tendency of a vehicle's passenger compartment to deform. The graph in Figure 4.22 was loosely based on cutoffs found in Table 5 of Appendix G of the NCHRP 350 [1]. The importance values are assumed.

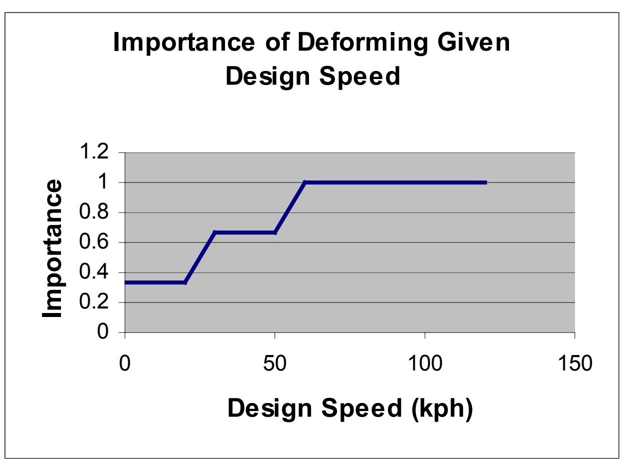


Figure 4.22: Importance of Deforming Given Design Speed

Most accidents occur at low speeds, but the more severe accidents occur at high speeds; therefore it is more important that the attenuator not tend to deform the passenger compartment.

Criteria 1.2.5.1 (Rate of Occupant Injury)

This criteria relates to the rate or frequency of occupant injuries, rather than the severity of injuries. The following characteristics are related to the rate of occupant injury.

A) Design Speed

The design speed is linearly related to the importance of the rate of occupant injury. As the design speed of the roadway increases, the importance of preventing occupant injury decreases. Because there are more accidents at slower speeds, the number of injuries is greater at the slower speeds rather than higher speeds. The graph shown in Figure 4.23 was based on information found in Appendix G of NCHRP 350, in Table 5 [1]. The importance of the rate of injury depends on the number of accidents. There are more accidents at lower speeds; therefore it is more important at lower design speeds that the attenuator has a low rate of occupant injuries.

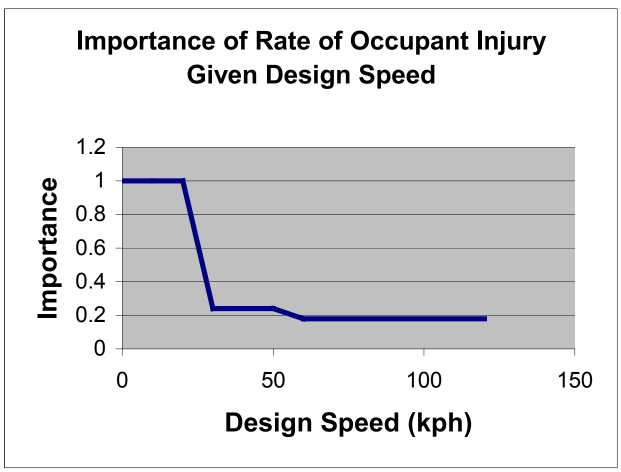


Figure 4.23: Importance of Rate of Occupant Injury Given Design Speed

Criteria 1.2.5.2 (Severity of Occupant Injury)

This criteria relates to the severity of occupant injuries, rather than the rate or frequency of injuries. The site characteristics related to severity of occupant injury are as follows.

A) Design Speed
The design speed is linearly related to the importance of severity of occupant injury. This is the exact opposite of the graph for rate of occupant injury. The severity of injury depends on the design speed as well, but the higher the speed of impact means the more severe the injuries will be. Figure 4.24 was based on the same data in NCHRP 350 [1]. Even though more accidents occur at low speeds, the more severe accidents occur at high speeds.

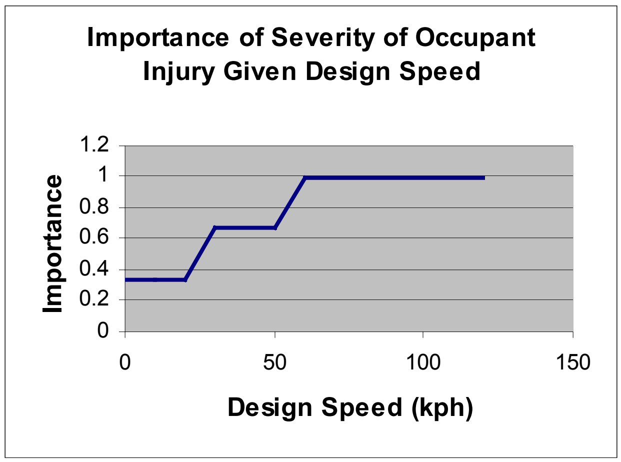


Figure 4.24: Importance of Severity of Occupant Injury Given Design Speed

Criteria 1.3.1.1 (Tendency to Rebound Backwards)

The tendency to rebound backwards is very important because it can put other motorists in harms way. The following characteristics are related to rebounding backwards.

A) Design Speed
The design speed is linearly related to the importance of the tendency of a vehicle to rebound backwards after hitting an attenuator. As the design speed of the roadway increases, the importance that a vehicle not rebound backwards increases. When a vehicle impacts an attenuator at slow speeds, the attenuator slows the car down with more efficiency. When the vehicle is traveling at higher speeds, it is difficult for the attenuator to operate the way it was designed. If the attenuator is hit head on, it can cause the vehicle to be shot backwards into traffic. This graph, based on common sense, is shown in Figure 4.25.

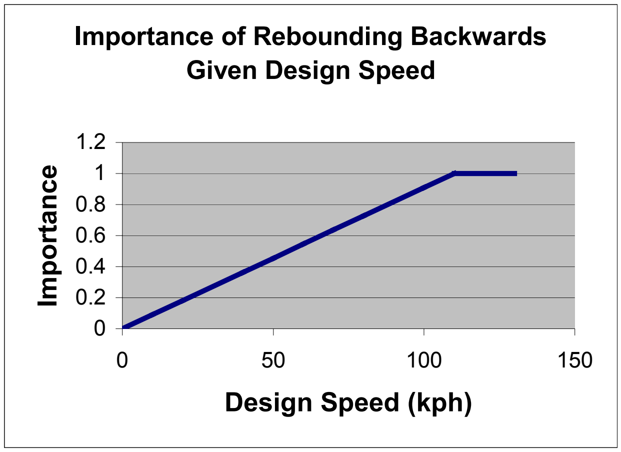


Figure 4.25: Importance of Rebounding Backwards Given Design Speed

B) Traffic Count

Traffic count is linearly related to the importance of the tendency of a vehicle to rebound backwards after hitting an attenuator. When there are more vehicles on the travel road, it is more important that a vehicle impacting an attenuator does not rebound backwards due to the possibility of impacting oncoming vehicles. The graph shown in Figure 4.26 was based on cutoffs in Roadside Design Guide Figure 3.1 for average daily traffic [3].

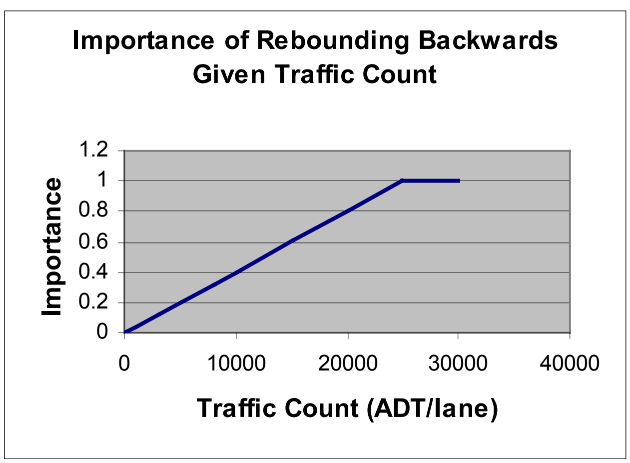


Figure 4.26: Importance of Rebounding Backwards Given Traffic Count

C) Longitudinal Clearance
The longitudinal clearance to traffic is linearly related to the importance of the tendency of a vehicle to rebound backwards after hitting an attenuator. As the amount of longitudinal clearance increases, the importance that the vehicle not rebound backwards decreases. The longitudinal clearance needs to be at least the length of a typical vehicle, to prevent intrusion into a travel lane upon rebound. As a result, 4 meters was established as the lower limit, below which lateral clearance has maximum importance. The upper limit, above which longitudinal clearance has minimal importance, was established heuristically. The graph is shown in Figure 4.27.

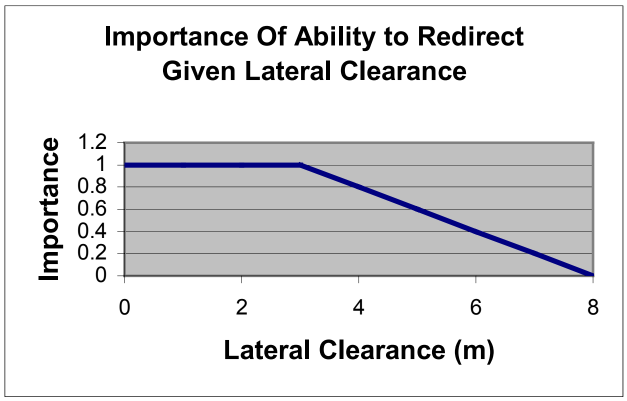


Figure 4.27: Importance of Ability to Redirect Given Lateral Clearance

D) Pedestrian Use
Pedestrian use is linearly related to the importance of the tendency of a vehicle to rebound backwards after hitting an attenuator. Rebounding backwards will always be important where pedestrians are present. The pedestrian use factor is a factor that indicates the likelihood that pedestrians will be present. It is based on the functional classification of the road, and whether the location is rural or urban. For instance, pedestrians are normally not present on interstates, unless in a construction zone. Pedestrians are found more frequently in urban locations. This graph is shown in Figure 4.28.

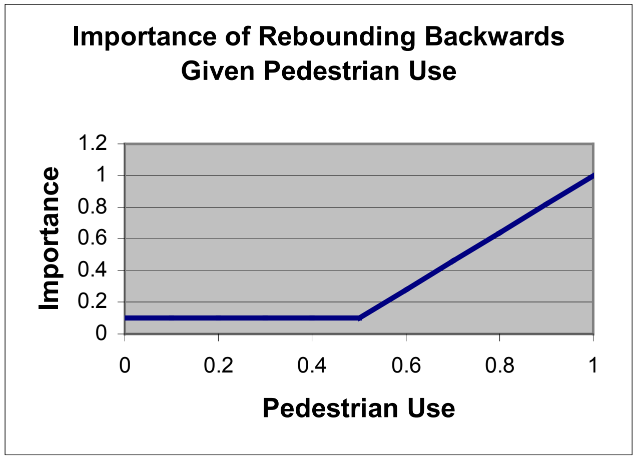


Figure 4.28: Importance of Rebounding Backwards Given Pedestrian Use

Criteria 1.3.1.2 (Tendency toward Large Redirect Angle)

Many attenuators are designed to redirect the vehicles, but a high redirect angle increases the chances that the vehicle will intrude into travel lanes. This would put other vehicles in danger as well as risk the impacting vehicle. The site characteristics related to large redirect angle are as follows.

A) Design Speed

Design speed is linearly related to the importance of preventing a vehicle from having a large redirect angle after impact. The graph that represents this is shown in Figure 4.29.

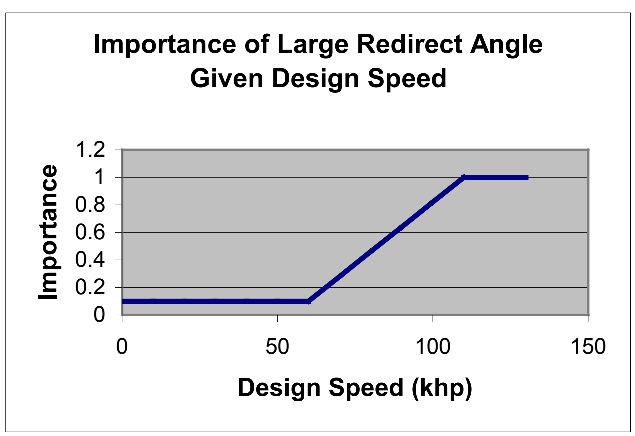


Figure 4.29: Importance of Large Redirect Angle Given Design Speed

As the design speed of the roadway increases, the importance of preventing large redirect angles increases because the negative consequences of a high-speed impact are greater. This was based on common sense.

B) Traffic Count

Traffic counts are linearly related to the importance of preventing a vehicle from having a large redirect angle after impact. When there are more vehicles on the travel road, the consequences of having a large redirect angle increases since there are more vehicles that can impact a vehicle redirected into the travel lanes. The graph shown in Figure 4.30 was based on cutoffs for average daily traffic counts found in Figure 3.1 of the Roadside Design Guide [3].

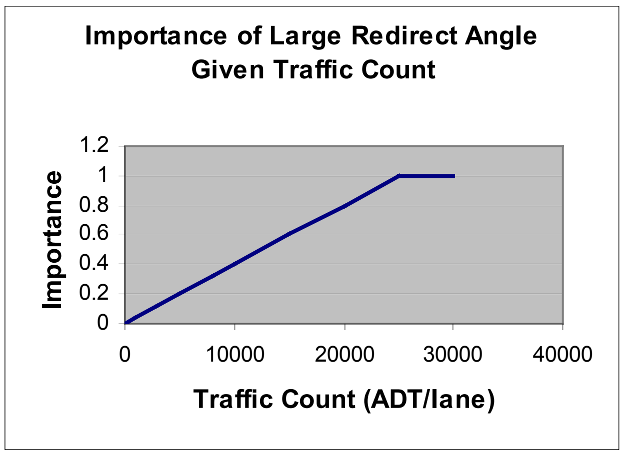


Figure 4.30: Importance of Large Redirect Angle Given Traffic Count

C) Lateral clearance to Traffic

The lateral clearance to traffic is linearly related to the importance of preventing a vehicle from having a large redirect angle after impact. As the distance of lateral clearance increases, the importance of having a large redirect angle decreases. The graph shown in Figure 4.31 was based on the width of a typical vehicle (lower limit) and the Energy Absorption Systems SNAP program (upper limit) [4]. With a small clearance, vehicles with large redirect angles have increased chances of intrusion into travel lanes.

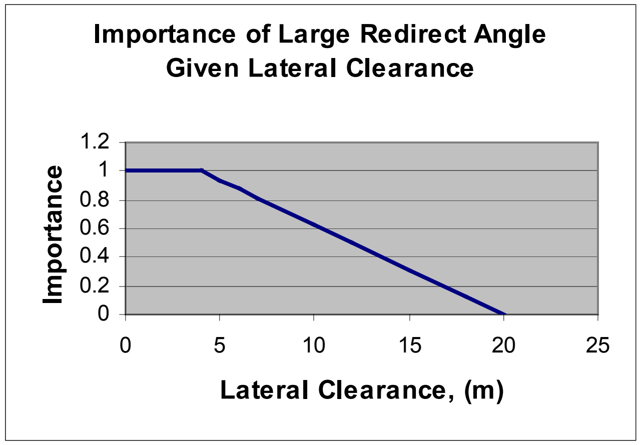


Figure 4.31: Importance of Large Redirect Angle Given Lateral Clearance

D) Pedestrian Use
Pedestrian use is linearly related to the importance of preventing a vehicle from having a large redirect angle after impact. If a vehicle impacts an attenuator and has a large redirect angle, it puts pedestrians at a greater risk rather than if the vehicle is contained after impact. Therefore, as the pedestrian use factor increases, the importance of preventing large redirect angles increases. The graph shown in Figure 4.32 is based on this theory.

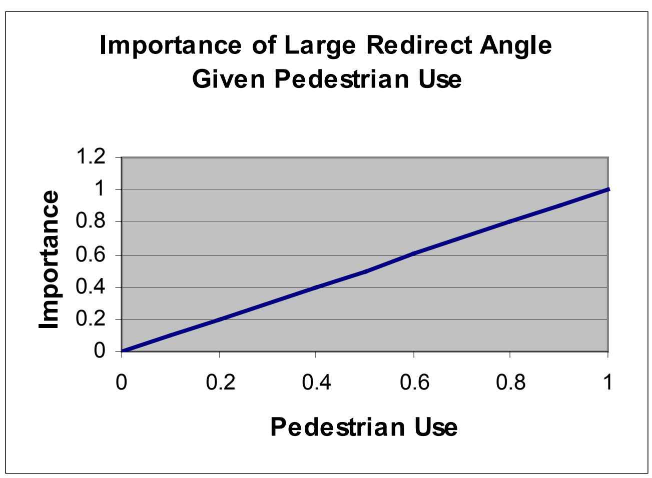


Figure 4.32: Importance of Large Redirect Angle Given Pedestrian Use

Criteria 1.3.1.3 (Tendency to Gate)

Gating occurs when a vehicle impacts an attenuator and the attenuator does not redirect the vehicle, but instead allows the vehicle to continue in the same direction (as if it passed through a gate). The site characteristics relating to gating are as follows.

A) Design Speed

The design speed is linearly related to the importance of preventing a vehicle from gating. As the design speed of the roadway increases, the importance of not allowing a vehicle to gate increases. The graph shown in Figure 4.33 was loosely based on information from Table 5.7 of the Roadside Design Guide [3].

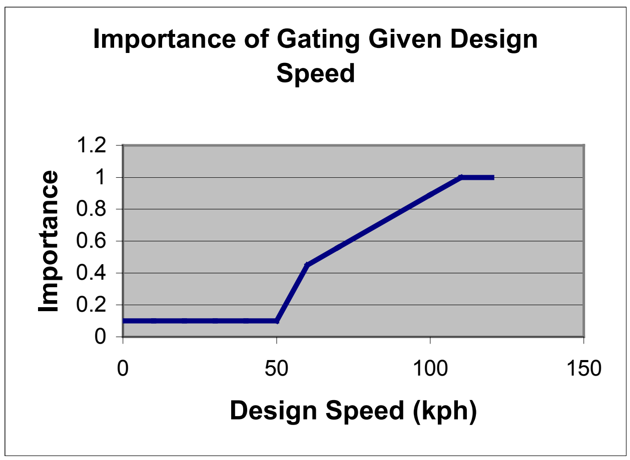


Figure 4.33: Importance of Gating Given Design Speed

B) Traffic Count

Traffic counts are linearly related to the importance of preventing a vehicle from gating. When there are more vehicles on the travel road, the possibility of a secondary impact upon gating increases; therefore, the importance of not allowing vehicles to gate increases. The graph shown in Figure 4.34 was based on cutoffs for average daily traffic counts found in Figure 3.1 of the Roadside Design Guide [3].

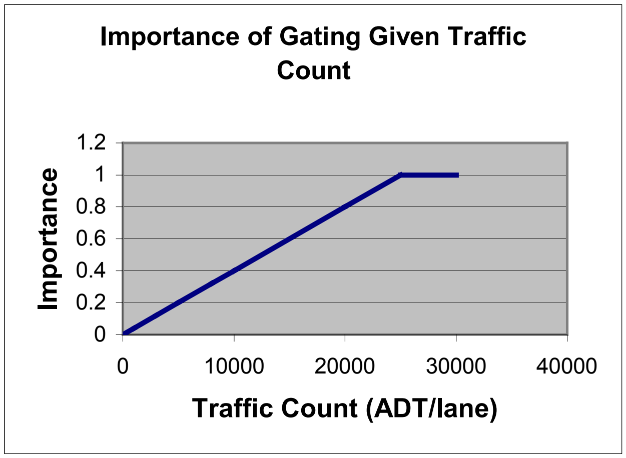


Figure 4.34: Importance of Gating Given Traffic Count

C) Width of Clear Zone

The width of the clear zone is linearly related to the importance of preventing a vehicle from gating. As the width of the clear zone increases, the importance of a vehicle gating decreases. If an impact occurs and there is enough clear zone width that the vehicle poses no risk to other vehicles, then preventing gating is not as important as it would be if the clear zone width were reduced. The graph in Figure 4.35 was determined from the Energy Absorption Systems SNAP program [4].

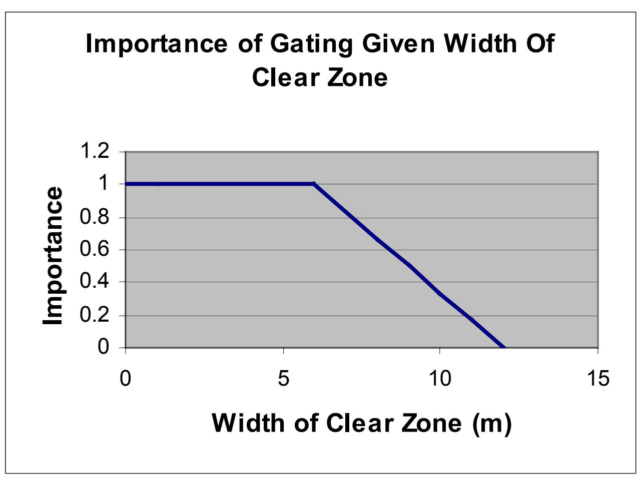


Figure 4.35: Importance of Gating Given Width of Clear Zone

Gating is more important when the clear zone width is small because of the possibility of traffic or other obstacles on the other side. When the width becomes 20 m or more, the consequences of gating are less important because the vehicle has run-out space; 12 m was selected to be conservative. The lower limit was based on the size of a typical vehicle.

D) Length of Clear Zone

The length of the clear zone is linearly related to the importance of preventing a vehicle from gating. As the length of the clear zone increases, the importance of a vehicle gating decreases. If an impact with an attenuator occurs and there is sufficient clear zone length that the vehicle poses no risk to other vehicles, then preventing gating is not as important as it would be if the clear zone length were reduced. The graph shown in Figure 4.36 was loosely based on information extracted from the Synthesis of Highway Practice Report 205 [13]. Similar information was found in the Energy Absorption Systems SNAP program [4].

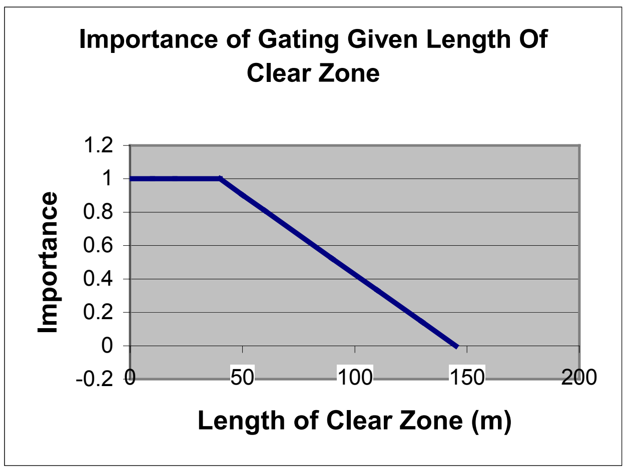


Figure 4.36: Importance of Gating Given Length of Clear Zone

E) Pedestrian Use

Pedestrian use is linearly related to the importance of preventing a vehicle from gating. If a vehicle impacts an attenuator and gates, it puts pedestrians at a greater risk. The graph in Figure 4.37 was determined using common sense. When pedestrian use is high, gating is very important. In places where pedestrians usually aren't present, it is not as important if gating occurs. However, protecting pedestrians is always important to some degree, so the importance function never reaches zero.

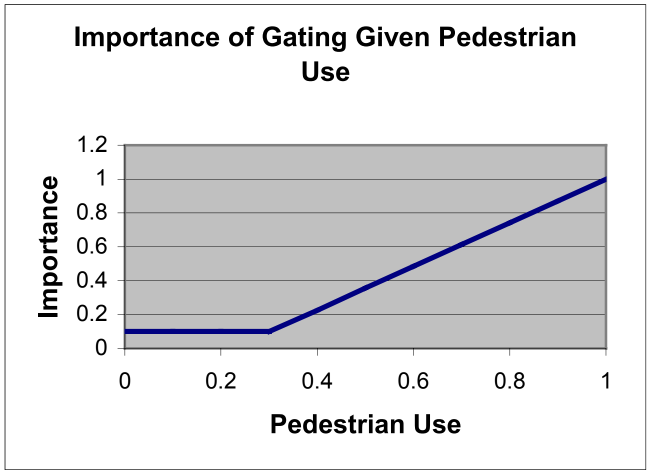


Figure 4.37: Importance of Gating Given Pedestrian Use

Criteria 1.3.1.4 (Tendency to Scatter Debris)

The tendency to scatter debris is important because it can cause major problems to other motorists. Debris can penetrate the occupant's compartment, cause other cars to get into accidents, or do harm to surrounding people along the roadway. Debris that is left on the roadway after an impact can cause passing vehicles to get into other accidents. There are many characteristics involved with debris including the following.

A) Design Speed

The design speed is linearly related to the importance of whether a vehicle scatters debris. The graph in Figure 4.38 was determined by common sense.

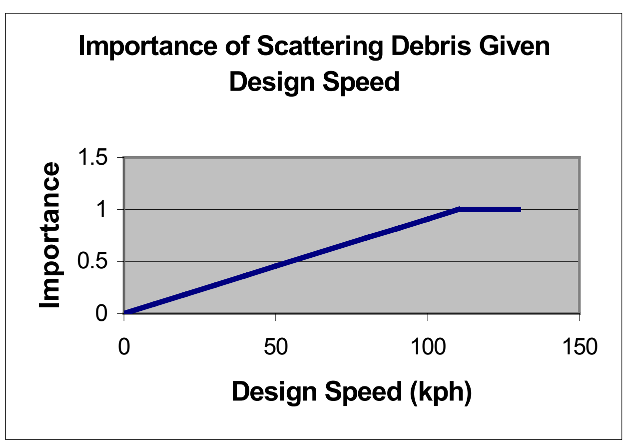


Figure 4.38: Importance of Scattering Debris Given Design Speed

As the design speed of the roadway increases, the importance of the vehicle not to scatter debris increases. At any speed an impact will create some sort of debris. There will be much more debris at higher speed impacts. There will be very few accidents where there will be no debris present.

B) Traffic Count

Traffic counts are linearly related to the importance of whether a vehicle scatters debris. When there are more vehicles on the travel road, if a vehicle scatters debris, it increases the risk of an accident. Figure 4.39 was based on cutoffs for average daily traffic taken from Figure 3.1 of the Roadside Design Guide [3].

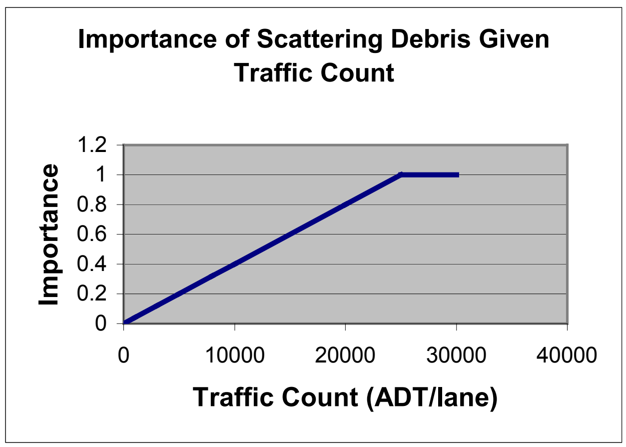


Figure 4.39: Importance of Scattering Debris Given Traffic Count

C) Lateral Clearance to Traffic

The lateral clearance to traffic is linearly related to the importance of whether a vehicle scatters debris. As the amount of lateral clearance increases, the importance of whether the vehicle scatters debris decreases. The graph shown in Figure 4.40 was based on common sense. When there is minimal clearance, a tendency to scatter debris is very important; when there is a lot of lateral clearance, the importance of debris scattering is virtually zero.

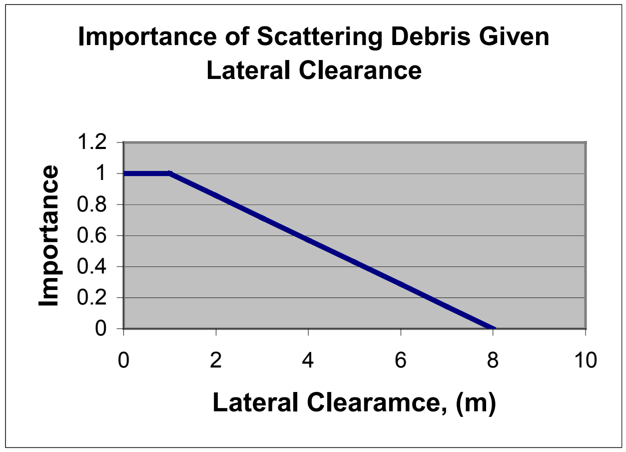


Figure 4.40: Importance of Scattering Debris Given Lateral Clearance

D) Width of Clear Zone
The width of the clear zone is linearly related to the importance of whether a vehicle scatters debris. As the width of the clear zone increases, the importance of whether a vehicle possibly scatters debris decreases. If an impact occurs and there is enough clear zone width that the debris poses no risk to other vehicles or pedestrians located beyond the clear zone, then a tendency to scatter debris is less important than would be if the clear zone width were reduced. A tendency to scatter debris is very important in minimal clear zone width areas because debris may not be able to be contained in the given width. The graph shown in Figure 4.41 was based on common sense.

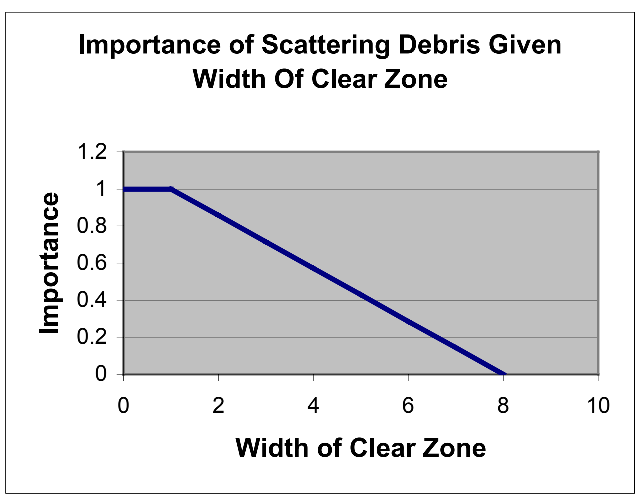


Figure 4.41: Importance of Scattering Debris Given Width of Clear Zone

E) Length of Clear Zone

The length of the clear zone is linearly related to the importance of whether a vehicle scatters debris. As the length of the clear zone increases, the importance of a vehicle to possibly scatter debris decreases. If an impact occurs and there is enough clear zone length that the debris poses no risk to other vehicles, then a tendency to scatter debris is less important than it would be if the clear zone length were reduced. The graph is shown in Figure 4.42 and was determined from the Synthesis of Highway Practice Report 205 [13]. If an impact occurs and there is enough clear zone length that the debris poses no risk to other vehicles or pedestrians located beyond the clear zone, then a tendency to scatter debris is less important than would be if the clear zone width were reduced. A tendency to scatter debris is very important in minimal clear zone length areas because debris may not be able to be contained in the given length.

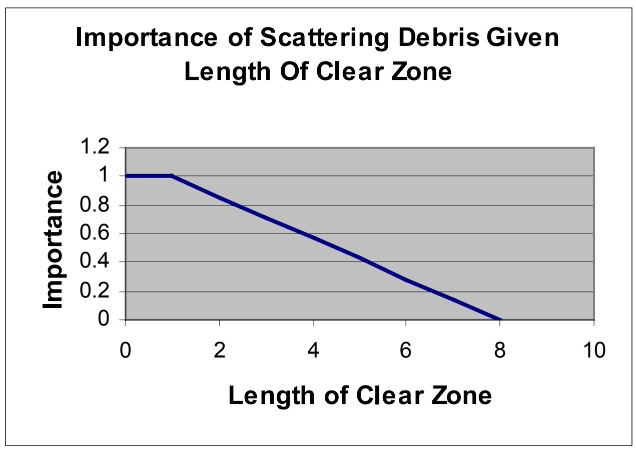


Figure 4.42: Importance of Scattering Debris Given Length of Clear Zone

F) Work Zone Use

The work zone use graph states that the tendency of a vehicle to scatter debris in a work zone is important no matter what. Common sense tells us that scattering debris will be more important in a work zone because of the presence of work zone equipment and workers. The graph is shown in Figure 4.43.

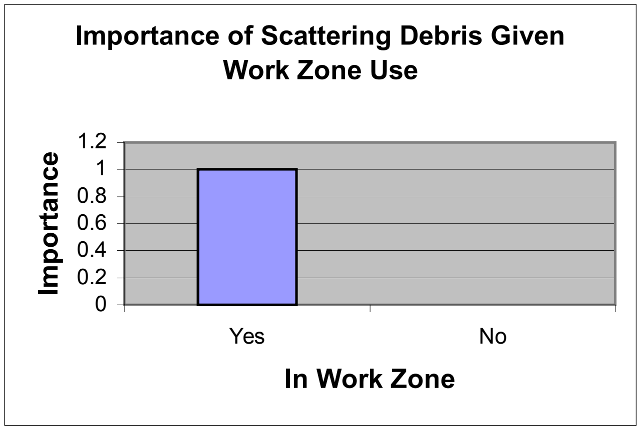


Figure 4.43: Importance of Scattering Debris Given Work Zone Use

G) Pedestrian Use

Pedestrian use is linearly related to the importance of whether a vehicle scatters debris. Common sense tells us that the more likely pedestrians are present, the more important scattering debris becomes. We never want scattered debris, but it is not as important where there are few to no pedestrians. The graph is shown in Figure 4.44.

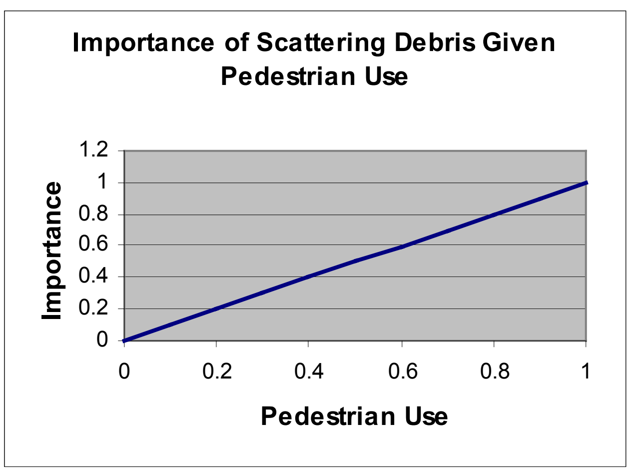


Figure 4.44: Importance of Scattering Debris Given Pedestrian Use

Criteria 1.3.2.1 (Response Time)

Response time, that is, the time between an impact and the subsequent repair, is important because an un-repaired attenuator might not perform adequately upon a second impact. The following are the site characteristics related to response time.

A) Work Zone Use

The work zone use graph states that the response time to an attenuator after impact in a work zone is important no matter what. Common sense tells us that response time will be more important in a work zone because of increased traffic, work zone equipment, and workers. Response time when there is no work zone is still important, but this value is only half that of when there is a work zone. This graph was developed using common sense. The graph is shown in Figure 4.45.

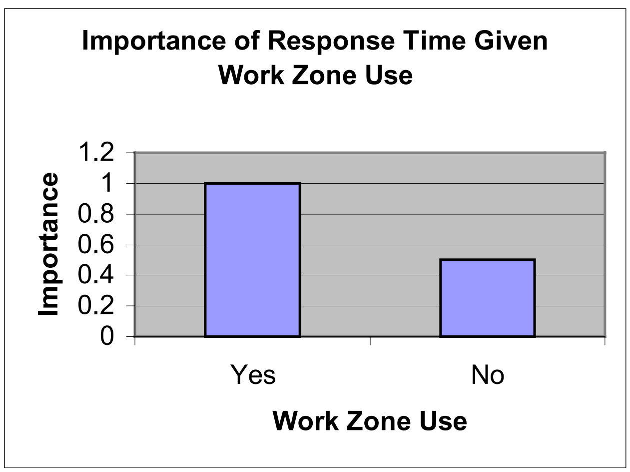


Figure 4.45: Importance of Response Time Given Work Zone Use

B) Rigid Hazard

Although no specific reference materials were used to develop this function, common sense indicates that response time is always important to some degree, but it is very important if a rigid hazard is present because the consequences of impacting a rigid object are the most severe. This graph is shown in Figure 4.46.

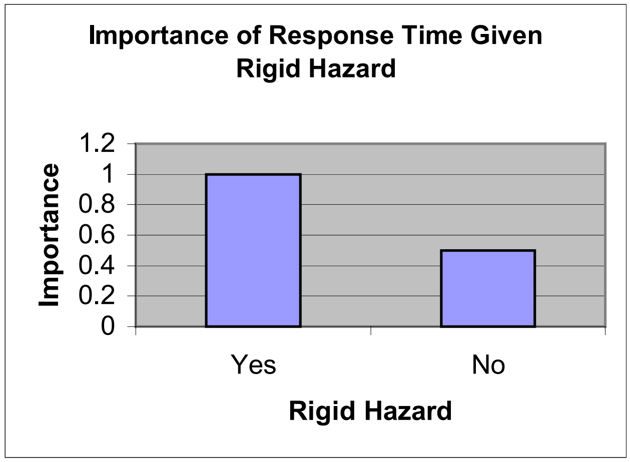


Figure 4.46: Importance of Response Time Given Rigid Hazard

C) Impact Frequency

Impact Frequency is linearly related to the importance of the response time. As the attenuator is impacted more often, the importance of a quick response time increases. The graph is shown in Figure 4.47 and was determined using common sense.

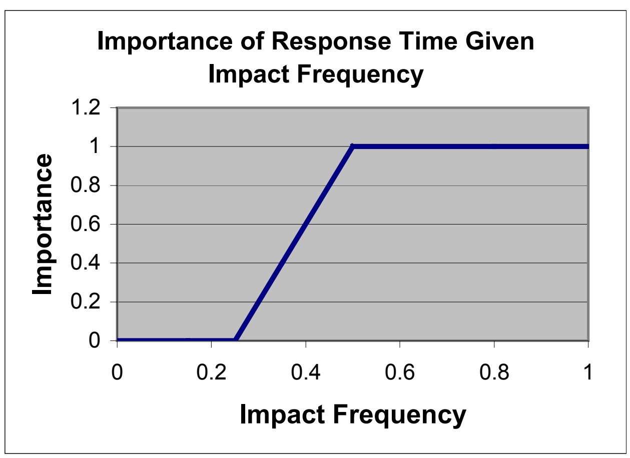


Figure 4.47: Importance of Response Time Given Impact Frequency

Criteria 1.3.2.2 (Repair Time)

After a cushion has been impacted and the workers have seen what is needed to repair the damage, the next important critera is how quick the damage is repaired. The main concern during repairs is the workers that perform the repair. They need to be quick and precise because they are putting themselves at risk since they are out on open roadways with vehicles moving at high speeds. The site characteristics related to repair time are the following.

A) Design Speed

The design speed is linearly related to the importance of the repair time of an attenuator. As the design speed of the roadway increases, the importance of the repair time increases. The graph is shown in Figure 4.48. The maximum and minimum design speeds of Florida interstates are 60 – 110 km/hr respectively. Repair time will always have some importance, but as speed increases, there is much more threat to workers, so the importance is greater. This graph was developed using common sense.

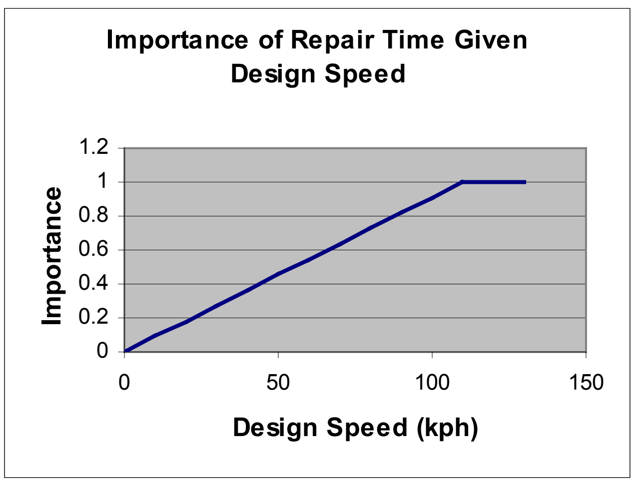


Figure 4.48: Importance of Repair Time Given Design Speed

B) Traffic Count

Traffic counts are linearly related to the importance of the repair time of an attenuator. When there are more vehicles on the travel road, the possibility of a vehicle to impact an attenuator increases, which puts the repair crew at a greater risk of being involved in an impact. The limits on the graph shown in Figure 4.49 were determined from average daily traffic cutoffs taken from Figure 3.1 of the Roadside Design Guide [3]. The importance of repair time will gradually increase as the number of cars (ADT) increases.

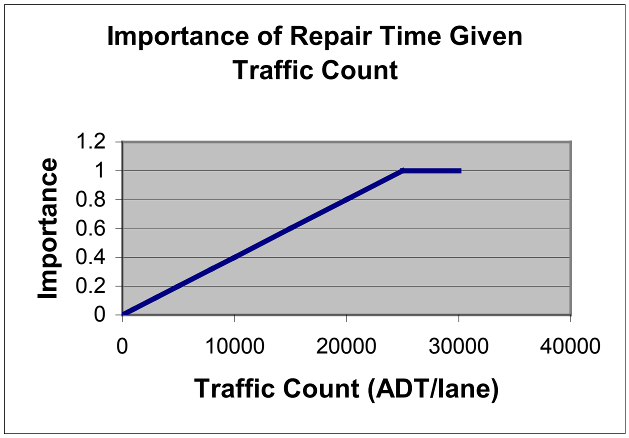


Figure 4.49: Importance of Repair Time Given Traffic Count

C) Longitudinal Clearance

The longitudinal clearance to traffic is linearly related to the importance of the repair time of an attenuator. As the amount of longitudinal clearance increases, the importance of the repair time of an attenuator decreases. The graph is shown in Figure 4.50. Repair time is very important when space is considered. Common sense states that the more room you have to complete the job the safer and smoother it goes. When there isn't enough room it makes it dangerous to do the work. The cutoff is based on providing sufficient room for a repair vehicle.

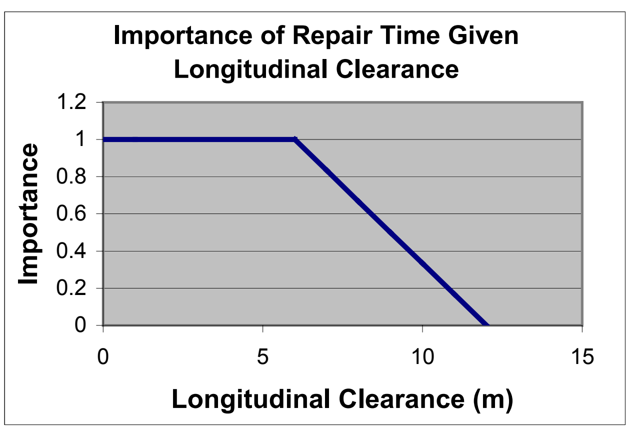


Figure 4.50: Importance of Repair Time Given Longitudinal Clearance

D) Lateral Clearance to Traffic

The lateral clearance to traffic is linearly related to the importance of the repair time of an attenuator. As the amount of lateral clearance increases, the importance that the attenuator is repaired promptly decreases. The graph shown in Figure 4.51 was based on the Energy Absorption Systems SNAP program (upper limit) and the size of a typical repair vehicle (lower limit) [4]. A small lateral clearance means that a quick repair is more important for the safety of the workers.

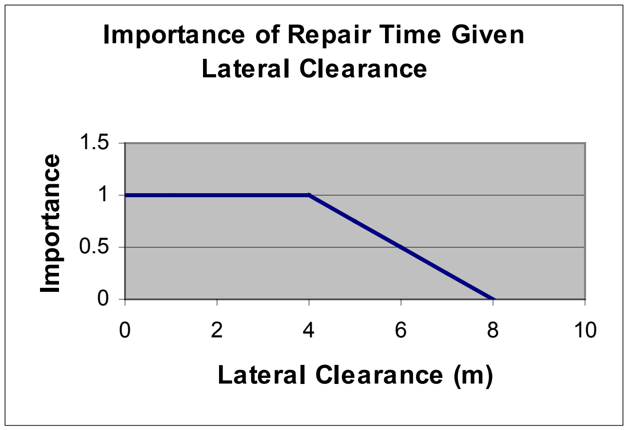


Figure 4.51: Importance of Repair Time Given Lateral Clearance

E) Impact Frequency

Impact Frequency is linearly related to the importance of the repair time of an attenuator.

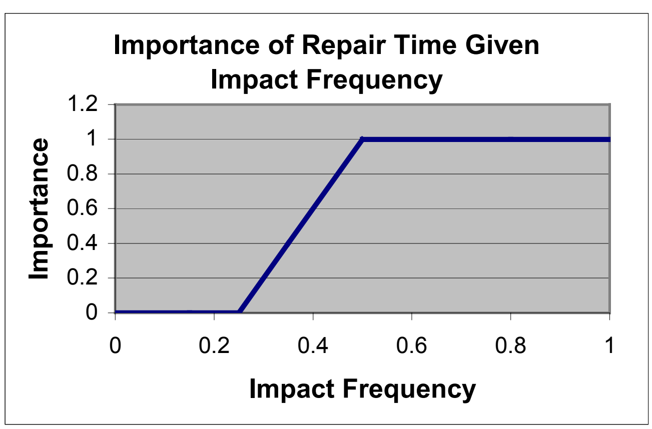


Figure 4.52: Importance of Repair Time Given Impact Frequency

If the attenuator is impacted more often, the importance of repairing the attenuator promptly increases. The graph is shown in Figure 4.52. This was determined using common sense.

Criteria 1.4.1 (Susceptibility to Vandalism)

The characteristics of vandalism are the following.

A) Longitudinal Clearance

The longitudinal clearance to traffic is linearly related to the susceptibility of the attenuator to vandalism. As the distance of longitudinal clearance increases, the importance of the susceptibility of vandalism to the attenuator increases. Crash cushions are susceptible to vandalism when there is a lot of space between it and the roadway, because there is space between the attenuator and the roadway for vandals to stand. The graph is shown in Figure 4.53; it was based on the amount of space a person would need to stand in.

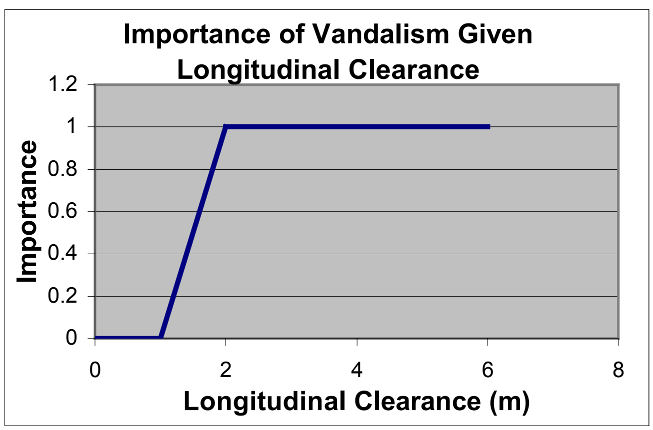


Figure 4.53: Importance of Vandalism Given Longitudinal Clearance

B) Lateral Clearance to Traffic

The lateral clearance to traffic is linearly related to the importance of the susceptibility of an attenuator to vandalism. As the amount of lateral clearance increases, the importance of the susceptibility to vandalism of an attenuator increases. When there is more clearance, it will be more susceptible to vandalism because there is space between the attenuator and the roadway for vandals to stand. The graph shown in Figure 4.54 was based on the amount of space a person would need to stand in [4].

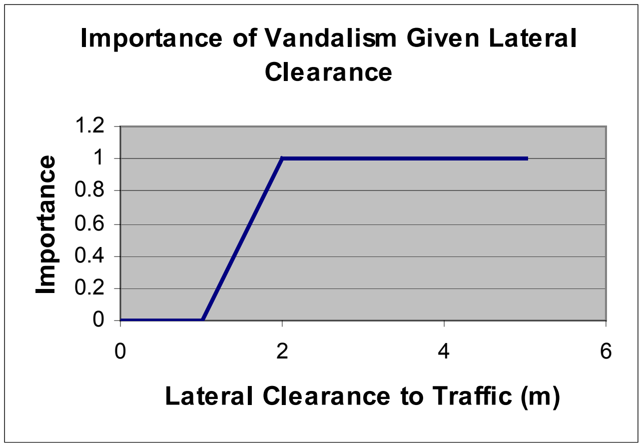


Figure 4.54: Importance of Vandalism Given Lateral Clearance

C) Urban Location
Although no specific reference materials were used to develop this function, common sense indicates that susceptibility to vandalism is always important to some degree, but it is very important if the attenuator is in an urban location because damage may occur more often to the attenuator. Susceptibility to vandalism will always be important, but not as important when the attenuator is in an urban location. This graph is shown in Figure 4.55.

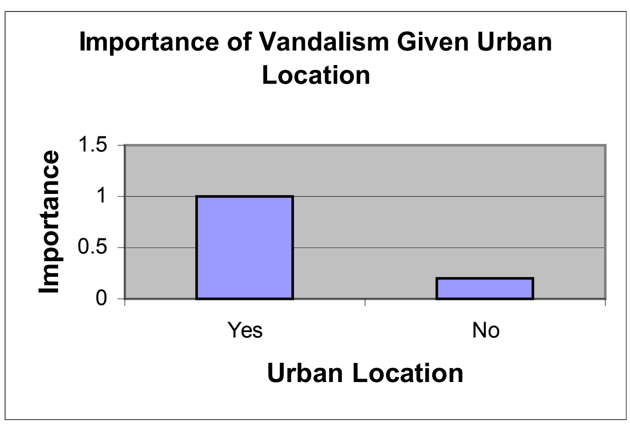


Figure 4.55: Importance of Vandalism Given Urban Location

Criteria 1.4.2 (Susceptibility to Environment)

The environment can have many affects on the attenuator. The sun can cause the diaphragms to dry out and crack, as well as the water filled containers may lose water to evaporation. These problems can affect the performance of the attenuator. The following site characteristic is related to susceptibility to environment.

A) Climate

There was no data found for this function, so heuristically, we determined that susceptibility to the environment was of minimal importance in a normal climate, but very important in an extreme climate. Everyday conditions and temperatures are considered normal, but heat, fog, smoke, very cold weather, or anything out of the ordinary, is considered an extreme condition. This graph is shown in Figure 4.56.

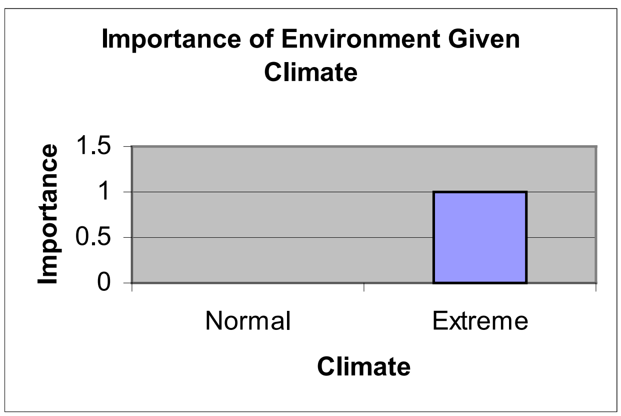


Figure 4.56: Importance of Environment Given Climate

Criteria 2.1.1 (Installation Time)

Installation time is very important because you have workers at the site while there is traffic flow. Optimal room is required for the workers to get the job done and to be safe. It also puts the drivers at risk because they want to see what is going on. This will cause traffic jams and accidents. So, the less time it takes to install a cushion, the better. The following site characteristics are related to installation time.

A) Design Speed

The design speed is linearly related to the importance of installation time for an attenuator. As the design speed of the roadway increases, the importance of the installation time increases. The graph is shown in Figure 4.57. The maximum and minimum design speeds of Florida interstates are 60 – 110 km/hr respectively; so 110 km/hr was used as the cutoff for maximum importance. Installation time will always have some importance, but as speed increases, there is much more threat to workers, so the importance is greater.

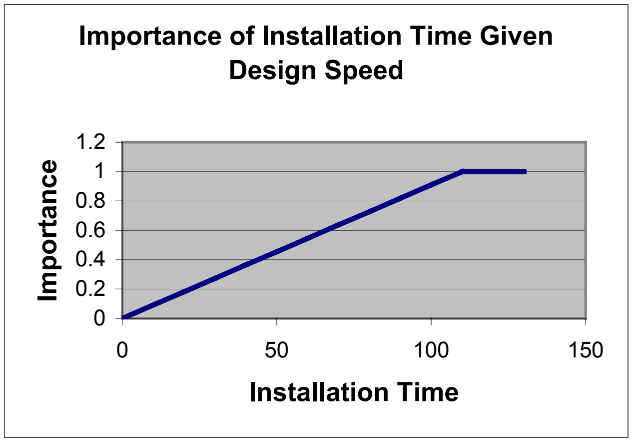


Figure 4.57: Importance of Installation Time Given Design Speed

B) Traffic Count
Traffic counts are linearly related to the importance of the installation time for an attenuator.

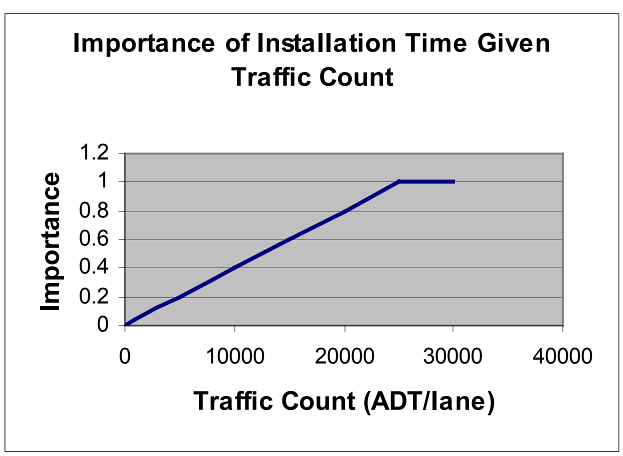


Figure 4.58: Importance of Installation Time Given Traffic Count

When there are more vehicles on the travel road, the possibility of a vehicle impacting an attenuator increases, which puts the installation crew at a greater risk of being involved in an impact. The graph shown in Figure 4.58 was based on cutoffs for average daily traffic taken from Figure 3.1 of the Roadside Design Guide [3]. Traffic count is always of some importance because of the workers' safety. But, it will gradually increase as the number of cars (ADT) increases.

C) Longitudinal Clearance to Traffic

The longitudinal clearance to traffic is linearly related to the importance of the installation time of an attenuator. As the amount of longitudinal clearance increases, the importance of installation time decreases, because there is more room for the installation process to occur. The graph is shown in Figure 4.59. It is based on the space required for a typical construction vehicle.

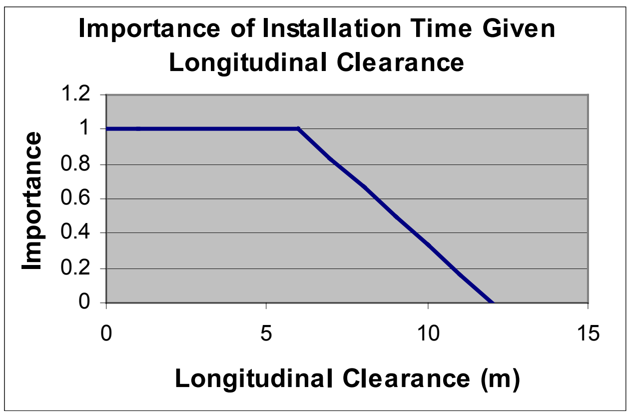


Figure 4.59: Importance of Installation Time Given Longitudinal Clearance

D) Lateral Clearance to Traffic

The lateral clearance to traffic is linearly related to the installation time of an attenuator. As the distance of lateral clearance increases, the importance of the installation time decreases. However, when the lateral clearance is small, workers are at more danger, which makes the installation time more important. The upper limit in the graph shown in Figure 4.60 was based on the Energy Absorption Systems SNAP program [4], and the lower limit was based on the space required for a typical construction vehicle.

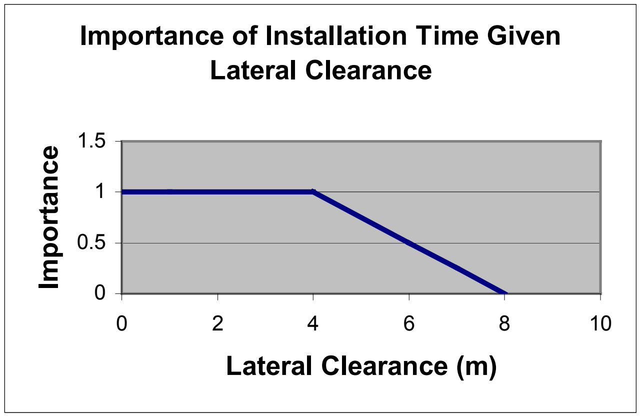


Figure 4.60: Importance of Installation Time Given Lateral Clearance

Criteria 2.1.2 (Installation Equipment)

Installation equipment is that which is required to put in and set up the attenuator. Most of the equipment required to install an attenuator is hand held. However, a truck is sometimes required to bring the unit to the site or assist in positioning it. The characteristics that are important to the amount of installation equipment are as follows.

A) Longitudinal Clearance to Traffic

The longitudinal clearance to traffic is linearly related to the importance of the installation equipment required for an attenuator. As the amount of longitudinal clearance increases, the importance of the installation equipment decreases. There needs to be enough room for the truck and crew to do the required installation. The graph shown in Figure 4.61 was based on the space required for a typical construction vehicle.

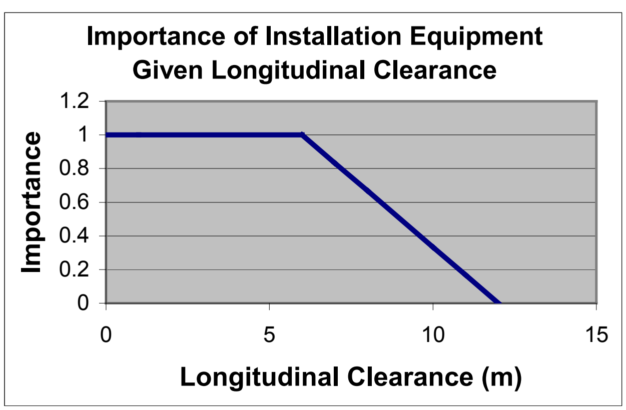


Figure 4.61: Importance of Installation Equipment Given Longitudinal Clearance

B) Lateral Clearance to Traffic

The lateral clearance to traffic is linearly related to the importance of the amount of installation equipment required for an attenuator. As the amount of lateral clearance increases, the importance of the installation equipment decreases. The graph shown in Figure 4.62 was based on the space required for a typical construction vehicle (lower limit) and the Energy Absorption Systems SNAP program (upper limit) [4]. When the clearance is small, the equipment used may get damaged and one is either limited to the type of equipment used or required to close lanes to install the attenuator.

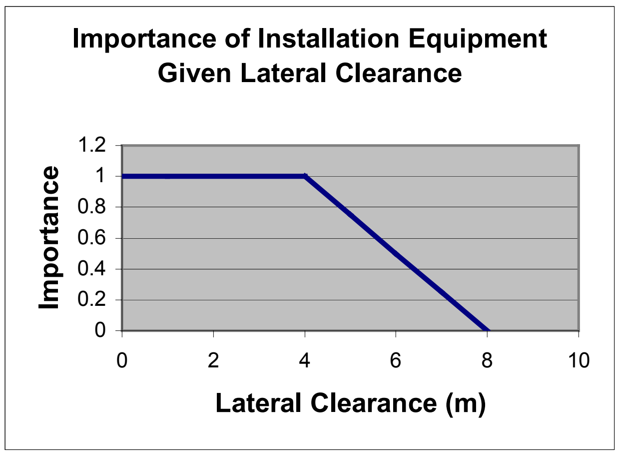


Figure 4.62: Importance of Installation Equipment Given Lateral Clearance

C) Width of Clear Zone

The width of the clear zone is linearly related to the importance of the amount of installation equipment required for an attenuator. As the width of the clear zone increases, the importance of the amount of installation equipment decreases. The graph shown in Figure 4.63 is again based on the space required for a typical construction vehicle (lower limit) and the Energy Absorption Systems SNAP program (upper limit) [4]. The smaller the width, the more important that requiring less installation equipment is. The equipment is more susceptible to damage and special equipment may be required. The larger the area, the more options the workers have for equipment.

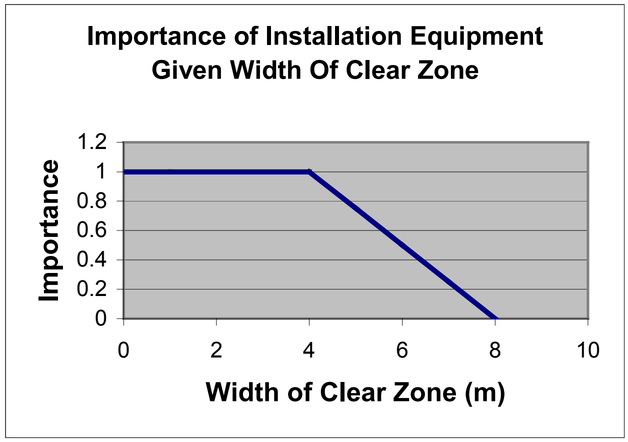


Figure 4.63: Importance of Installation Equipment Given Width of Clear Zone

D) Length of Clear Zone

The length of the clear zone is linearly related to the importance of the amount of installation equipment required for an attenuator. As the length of the clear zone increases, the importance of the amount of installation equipment decreases. The graph shown in Figure 4.64 is again based on the space required for a typical construction vehicle (lower limit) and the Energy Absorption Systems SNAP program (upper limit) [4]. The smaller the length, the more important that requiring less installation equipment is. The equipment is more susceptible to damage and special equipment may be required. The larger the area, the more options the workers have for equipment.

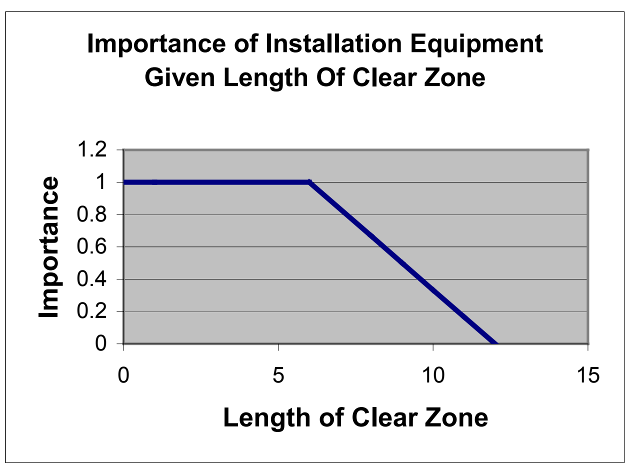


Figure 4.64: Importance of Installation Equipment Given Length of Clear Zone

Criteria 2.2.1 (Repair Time)

Repair time is very similar to installation time, except that the cushion is already there. New parts are still required, but the required number of workers may decrease. Like installation time, repair time can cause traffic jams and accidents. After a cushion has been impacted and the workers have seen what is needed to repair the damage, the next important criteria is how quickly the damage can be repaired. The main concern during repairs is the safety of the workers that perform the repair. The following are the characteristics of repair time.

A) Design Speed

The design speed is linearly related to the importance of the repair time required for an attenuator. As the design speed of the roadway increases, the importance of the repair time increases. The graph is shown in Figure 4.65. The maximum and minimum design speeds of Florida interstates are 60 – 110 km/hr respectively. Repair time will always have some importance, but as speed increases, there is much more threat to workers, so the importance is greater. One may also need to close lanes to get the repair done which means slower traffic and jams.

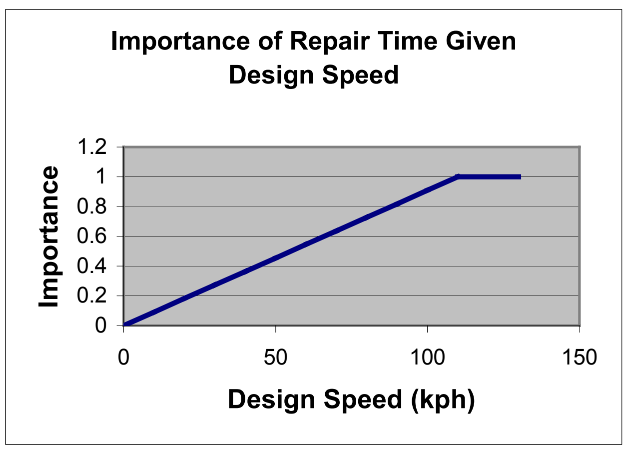


Figure 4.65: Importance of Repair Time Given Design Speed

B) Traffic Count

Traffic counts are linearly related to the importance of the repair time of an attenuator. When there are more vehicles on the travel road, the possibility that a vehicle will impact an attenuator increases, which puts the repair crew at a greater risk of being involved in an impact. The graph in Figure 4.66 was determined using cutoffs established in Figure 3.1 of the Roadside Design Guide for average daily traffic [3]. The repair time is always of some importance because of the safety of the workers. But, it will gradually increase as the number of cars (ADT) increases.

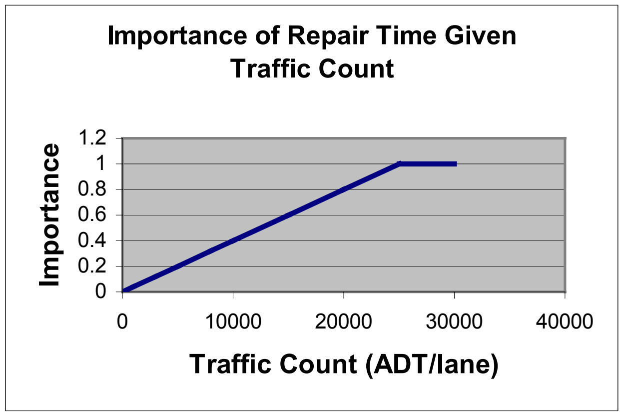


Figure 4.66: Importance of Repair Time Given Traffic Count

C) Longitudinal Clearance to Traffic

The longitudinal clearance to traffic is linearly related to the importance of the repair time of an attenuator. As the amount of longitudinal clearance increases, the importance of the repair time decreases. The graph is shown in Figure 4.67. It is based on the amount of space required for a typical construction vehicle. When there is more room to perform repairs, there is less risk for the workers and equipment.

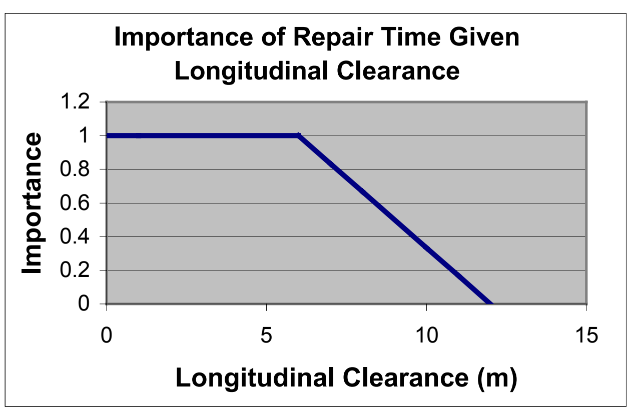


Figure 4.67: Importance of Repair Time Given Longitudinal Clearance

D) Lateral Clearance to Traffic
The lateral clearance to traffic is linearly related to the importance of the repair time of an attenuator. As the amount of lateral clearance increases, the importance of the repair time of an attenuator decreases. The graph shown in Figure 4.68 was based on the space required for a typical construction vehicle (lower limit) and the Energy Absorption Systems SNAP program (upper limit) [4]. Repair time is critical and more important when space is limited.

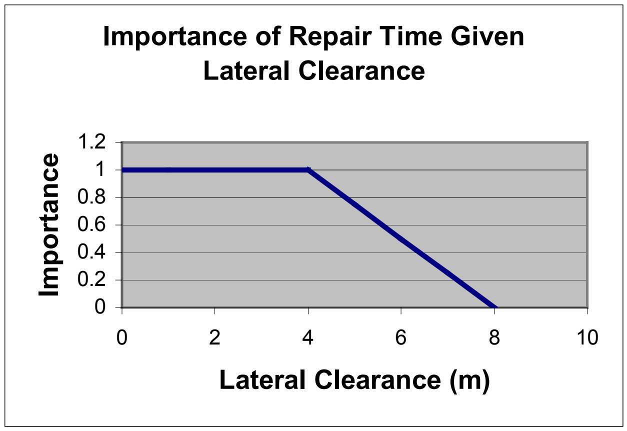


Figure 4.68: Importance of Repair Time Given Lateral Clearance

E) Impact Frequency
Impact Frequency is linearly related to the importance of the repair time of an attenuator.

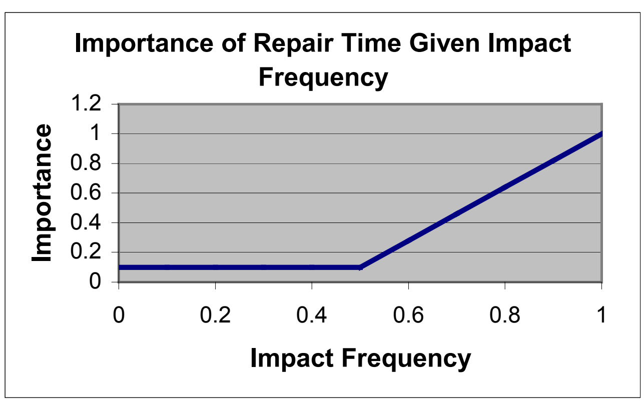


Figure 4.69: Importance of Repair Time Given Impact Frequency

If the attenuator is impacted more often, the importance of repairing the attenuator promptly increases. The graph shown in Figure 4.69 was determined from common sense.

Criteria 2.2.2 (Repair Equipment)

Repair equipment is that which is required to repair an attenuator after an impact. Most of the equipment required to repair an attenuator is hand held. However, a truck is sometimes required to bring the components to the site or assist in positioning them. The following characteristics are related to repair equipment.

A) Longitudinal Clearance to Traffic

The longitudinal clearance to traffic is linearly related to the importance of the amount of repair equipment required for an attenuator. As the amount of longitudinal clearance increases, the importance of the repair equipment requirements decreases. This criteria is the same as installation equipment. Providing sufficient distances around the attenuator is very important for the workers do get their job done and to be safe. The graph is shown in Figure 4.70. It is based on the amount of space required for a typical construction vehicle. When there is more room to perform repairs, there is less risk for the workers and equipment.

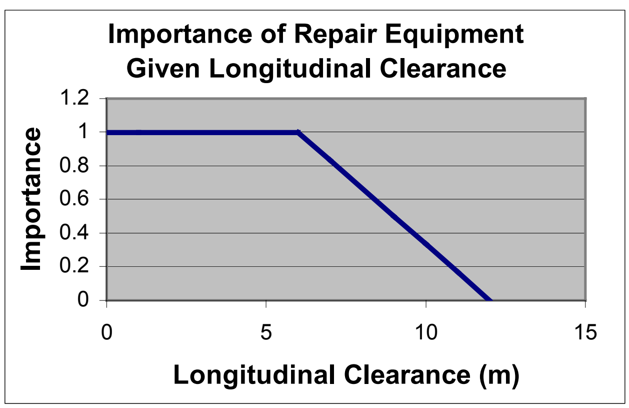


Figure 4.70: Importance of Repair Equipment Given Longitudinal Clearance

B) Lateral Clearance to Traffic

The lateral clearance to traffic is linearly related to the importance of the repair equipment of an attenuator. As the amount of lateral clearance increases, the importance of requiring minimal repair equipment decreases. The graph shown in Figure 4.71 was again based on the space required for a typical construction vehicle (lower limit) and the

Energy Absorption Systems SNAP program (upper limit) [4]. When the clearance is small, the equipment used may get damaged and one is either limited in the type of equipment used, or closing lanes during the repair is required.

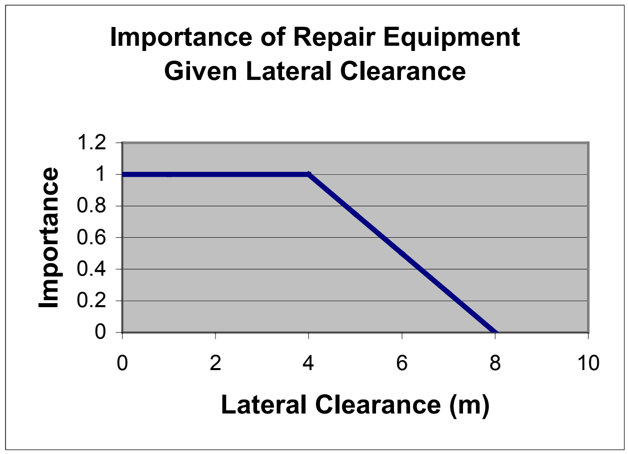


Figure 4.71: Importance of Repair Equipment Given Lateral Clearance

C) Width of Clear Zone

The width of the clear zone is linearly related to the importance of the repair equipment requirements of an attenuator. As the width of the clear zone increases, the importance of the amount of repair equipment required decreases. If there is enough clear zone width for the required repair equipment, then having large equipment requirements is not as important as it would be if the clear zone width were reduced. The graph shown in Figure 4.72 was again based on the space required for a typical construction vehicle (lower limit) and the Energy Absorption Systems SNAP program (upper limit) [4]. The smaller the width of the clear zone, the more important the repair equipment requirements are. The equipment is more susceptible to damage and special equipment or lane closures may be required. The larger the area, the more options the workers have for equipment.

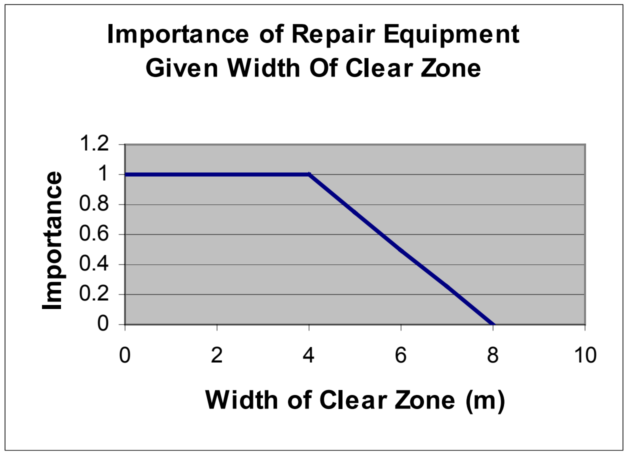


Figure 4.72: Importance of Repair Equipment Given Width of Clear Zone

D) Length of Clear Zone

The length of the clear zone is linearly related to the importance of the repair equipment requirements of an attenuator. As the length of the clear zone increases, the importance of the amount of repair equipment required decreases. If there is enough clear zone length for the equipment, then it is not as important as it would be if the clear zone length were reduced. The graph shown in Figure 4.73 was again based on the space required for a typical construction vehicle (lower limit) and the Energy Absorption Systems SNAP program (upper limit) [4]. Having large equipment requirements is more important when space is limited due to the type of equipment required.

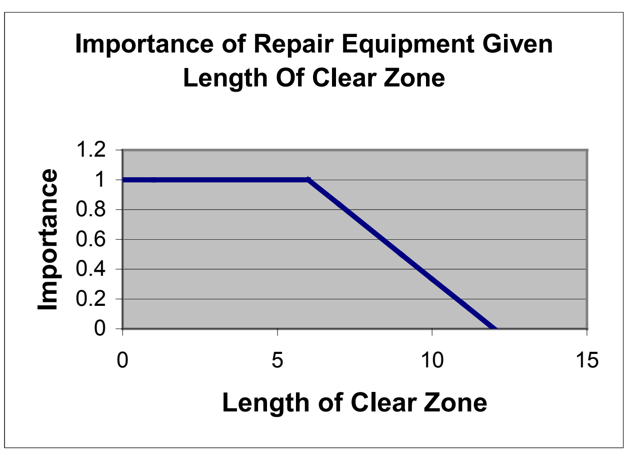


Figure 4.73: Importance of Repair Equipment Given Length of Clear Zone

E) Impact Frequency

Impact Frequency is linearly related to the importance of the amount of repair equipment required for an attenuator. If the attenuator is impacted more often, the importance of repairing the attenuator promptly increases. Having large equipment requirements might lengthen the repair time; it might also increase the possibility of an impact with the repair equipment. The graph shown in Figure 4.74 was determined using common sense.

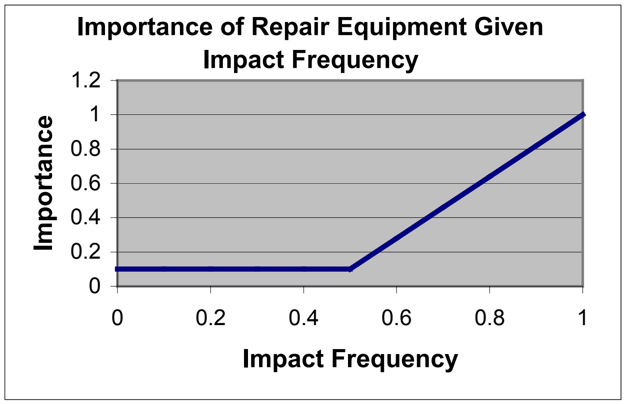


Figure 4.74: Importance of Repair Equipment Given Impact Frequency

Criteria 2.2.3 (Inventory Requirements)

The inventory requirements include any parts required to do the repair work. There is not enough room to store all the different parts for all the different attenuators. This means that an attenuator, which has fewer parts and therefore requires less of an inventory, is more desirable. The following site characteristic is related to inventory requirements.

A) Impact Frequency

The importance of inventory requirements is linearly related to impact frequency. The importance of having decreased inventory requirements increases as the impact frequency increases, because more parts must be maintained to account for the increased possibility of impacts. The graph shown in Figure 4.75 was determined using common sense.

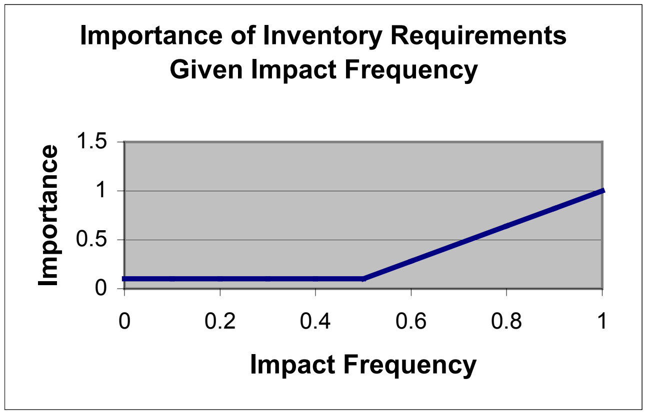


Figure 4.75: Importance of Inventory Requirements Given Impact Frequency

Criteria 2.3 (Portability)

Portability refers to the ease of transportation of an attenuator. The attenuators that are portable usually have no assembly required. A truck brings them in already assembled and places the attenuator in the required spot. Portable attenuators are primarily used in work zones, but are sometimes left there after work is completed if they are needed. The site characteristics related to portability are as follows.

A) Work Zone Use

The work zone use graph states that the portability of an attenuator in a work zone is important no matter what. If an attenuator is used in a work zone, it needs to be portable, so in this case it is always important. Figure 4.76 represents this and was based on common sense.

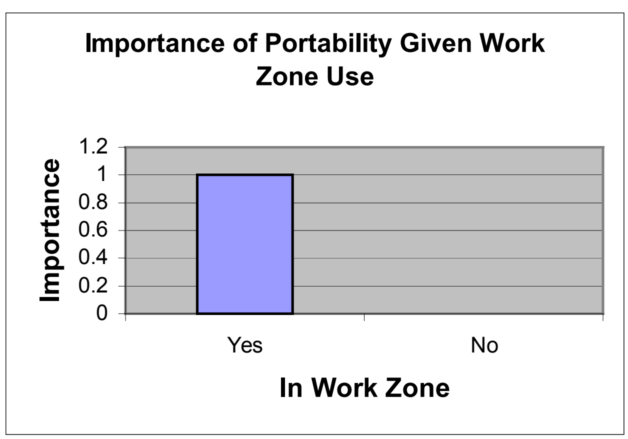


Figure 4.76: Importance of Portability Given Work Zone Use

B) Impact Frequency
Impact Frequency is linearly related to the importance of portability of an attenuator. If the attenuator is impacted more often, the importance of portability increases because the more often an attenuator is impacted, the faster a new one needs to be in place. Figure 4.77 represents this and was based on common sense.

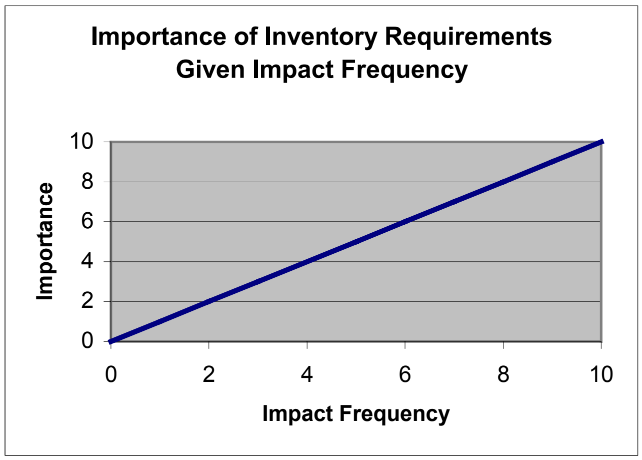


Figure 4.77: Importance of Portability Given Frequency

Criteria 3.2 (Maintenance Cost)

Maintenance cost refers to anything that needs to be done to the attenuator to maintain its in proper working order. Some of this includes adding water, changing diaphragms, adding sand, labor fees, and tightening bolts. This does not include actual repairs caused by impacts. The site characteristics related to maintenance are the following.

A) Longitudinal Clearance to Traffic
The longitudinal clearance to traffic is linearly related to the maintenance cost of an attenuator. As the distance of longitudinal clearance increases, the importance of the maintenance cost to the attenuator decreases. Maintenance cost is more important at smaller distances because of the potential need for more repair time, special equipment, etc. There is also the increased possibility that lane closures will be required if the clearance to traffic is very small. The graph is shown in Figure 4.78.

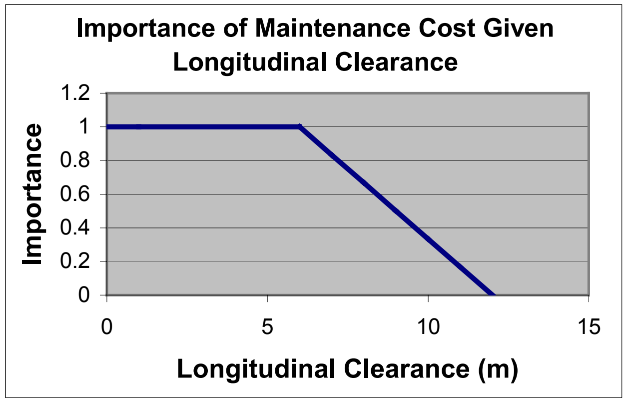


Figure 4.78: Importance of Maintenance Cost Given Longitudinal Clearance

B) Lateral Clearance to Traffic
The lateral clearance to traffic is linearly related to the importance of the maintenance cost of an attenuator. As the distance of lateral clearance increases, the importance of the maintenance cost to an attenuator decreases. The graph shown in Figure 4.79 is again based on the space required for a typical construction vehicle (lower limit) and the Energy Absorption Systems SNAP program (upper limit) [4]. Maintenance cost is more important at smaller distances because of the potential need for more repair time, special equipment, etc. There is also the increased possibility that lane closures will be required if the clearance to traffic is very small.

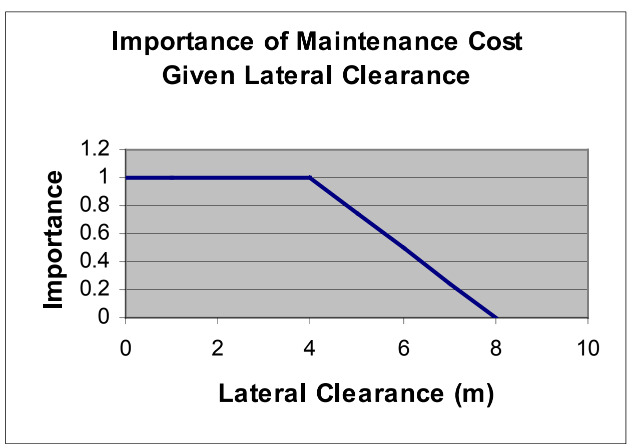


Figure 4.79: Importance of Maintenance Cost Given Lateral Clearance

C) Width of Clear Zone

The width of the clear zone is linearly related to the importance of the maintenance cost of an attenuator. As the width of the clear zone increases, the importance of maintenance cost decreases. The graph shown in Figure 4.80 was again based on the space required for a typical construction vehicle (lower limit) and the Energy Absorption Systems SNAP program (upper limit) [4]. Special equipment may be needed, and more time may be required for maintenance with smaller clear zones. All of this makes the job cost more.

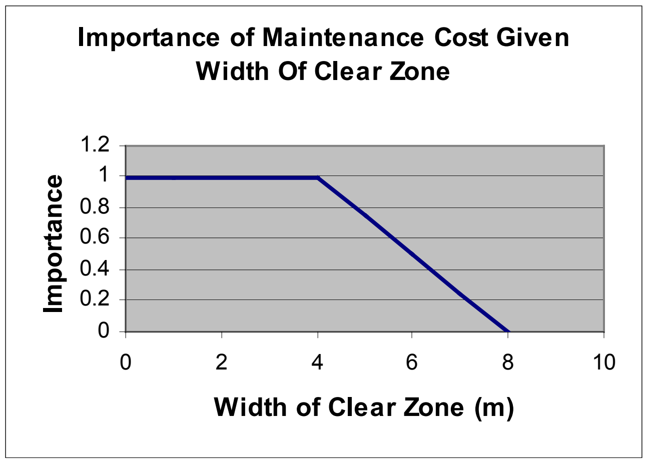


Figure 4.80: Importance of Maintenance Cost Given Width of Clear Zone

D) Length of Clear Zone

The length of the clear zone is linearly related to the importance of the maintenance cost of an attenuator. As the length of the clear zone increases, the importance of maintenance cost decreases. The graph shown in Figure 4.81 was based on information found in the Synthesis of Highway Practice Report 205 [13]. The graph is also supported by information found in the Energy Absorption Systems SNAP program [4]. Typically 5 to 10 meters is needed for stopping, but up to 20 meters should be provided to be safe. Repair/Replacement cost is more important when the clear zone length is limited. This is because of the equipment required, number of workers, traffic, and time needed for the maintenance operation.

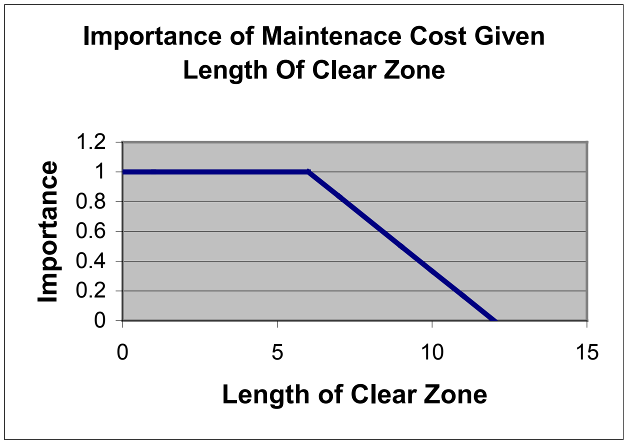


Figure 4.81: Importance of Maintenance Cost Given Length of Clear Zone

E) Climate

The environment can have many affects on the attenuator. The sun can cause wood diaphragms, plastic cylinders, or foam cells to dry out and crack, and water filled containers may lose water to evaporation. Constant maintenance is required for these types of attenuators. These problems can affect the performance of the attenuator. Extreme conditions cause maintenance to be more important. This is because more routine checks are required on the attenuator. This will also mean more repair work. There was no data found for this, so heuristically, we determined that everyday conditions and temperatures can be considered normal, but heat, fog, smoke, very cold weather, or anything out of the ordinary, is considered an extreme condition. The graph is shown in Figure 4.82.

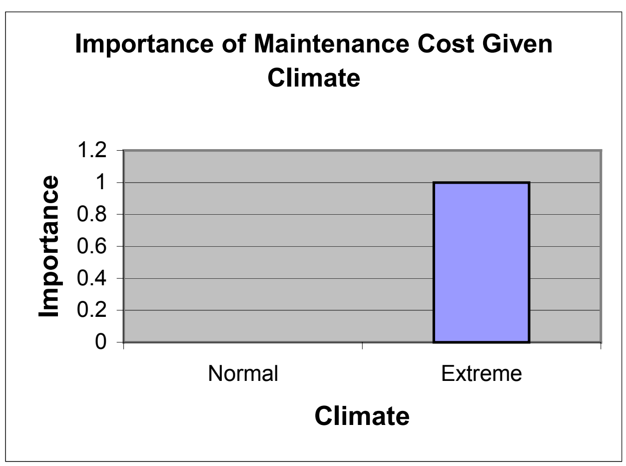


Figure 4.82: Importance of Maintenance Cost Given Climate

Criteria 3.3 (Repair/Replacement Cost)

Repair or replacement cost deals with anything that needs to be done to the attenuator to restore it to normal operating conditions after an impact occurs, as well as the labor to complete the repair. Everything that costs money to fix the attenuator is included in this cost. The site characteristics related to repair/replacement cost are the following.

A) Longitudinal Clearance to Traffic

The longitudinal clearance to traffic is linearly related to the importance of the repair/replacement cost of an attenuator. As the amount of longitudinal clearance increases, the importance of the repair/replacement cost of the attenuator decreases. Smaller clearances mean more time and special equipment are needed to do the job. Maintenance workers need to be more careful, and there is also the increased possibility that lane closures will be required. The graph is shown in Figure 4.83.

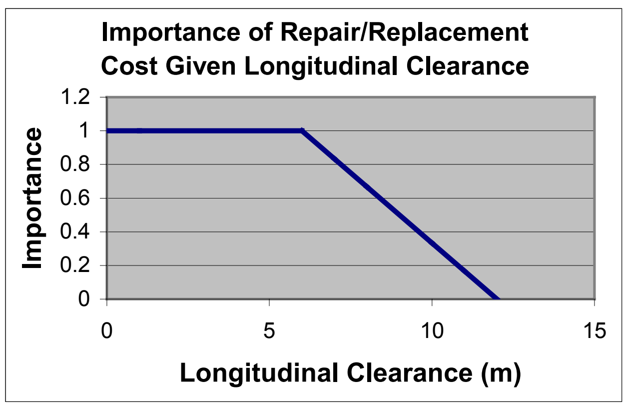


Figure 4.83: Importance of Repair/Replacement Cost Given Longitudinal Clearance

B) Lateral Clearance to Traffic

The lateral clearance to traffic is linearly related to the importance of the repair/replacement cost of an attenuator. As the distance of lateral clearance increases, the importance of the repair/replacement of an attenuator decreases. The graph shown in Figure 4.84 was again based on the space required for a typical construction vehicle (lower limit) and the Energy Absorption Systems SNAP program (upper limit) [4]. As with lateral clearance, smaller longitudinal clearances mean more time and special equipment are needed to do the job. Maintenance workers need to be more careful, and there is also the increased possibility that lane closures will be required.

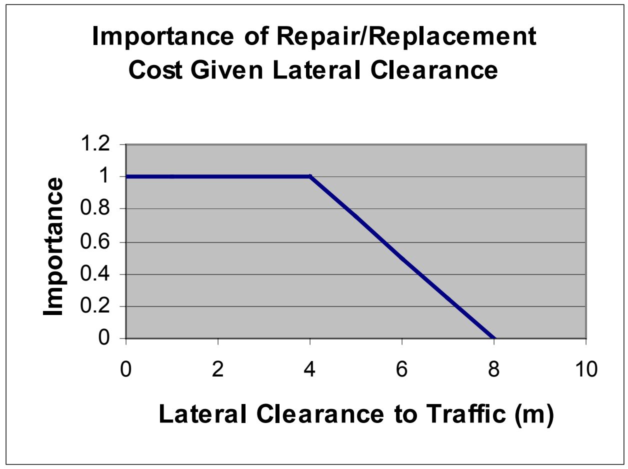


Figure 4.84: Importance of Repair/Replacement Cost Given Lateral Clearance

C) Width of Clear Zone

The width of the clear zone is linearly related to the importance of the repair/replacement cost of an attenuator. As the width of the clear zone increases, the importance of repair/replacement cost decreases. The graph shown in Figure 4.85 was again based on the space required for a typical construction vehicle (lower limit) and the Energy Absorption Systems SNAP program (upper limit) [4]. Safety, equipment, and time all become a factor when repair/replacement of attenuators is done in small clear zones widths, which makes it more important.

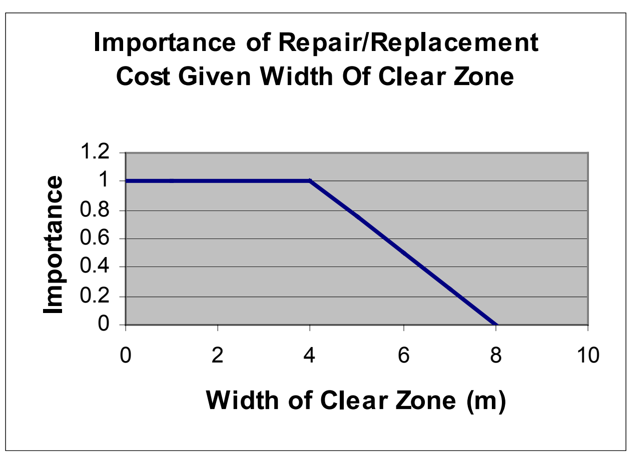


Figure 4.85: Importance of Repair/Replacement Cost Given Width of Clear Zone

D) Length of Clear Zone

The length of the clear zone is linearly related to the importance of the repair/replacement cost of an attenuator. As the length of the clear zone increases, the importance of repair/replacement cost decreases. The graph shown in Figure 4.86 was based on information found in the Synthesis of Highway Practice Report 205 [13]. The graph is also supported by information found in the Energy Absorption Systems SNAP program [4]. Typically 5 to 10 meters is needed for stopping, but up to 20 meters should be provided to be safe. Repair/Replacement cost is more important when the clear zone length is limited. This is because of the equipment required, number of workers, traffic, and time needed for the maintenance operation.

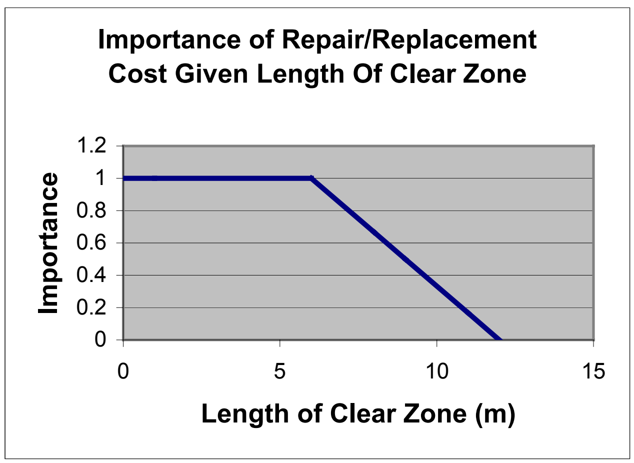


Figure 4.86: Importance of Repair/Replacement Cost Given Length of Clear Zone

E) Impact Frequency

Impact Frequency is linearly related to the importance of the repair/replacement cost of an attenuator. If the attenuator is impacted more often, the importance of the repair/replacement cost of the attenuator increases. The graph is shown in Figure 4.87 and was determined using common sense.

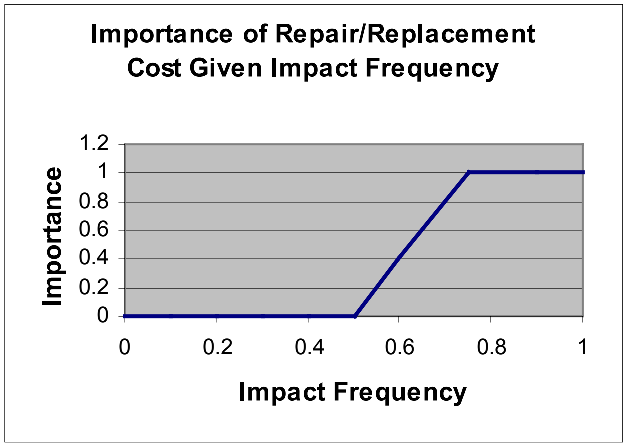


Figure 4.87: Importance of Repair/Replacement Cost

CHAPTER 5
RESULTS

To test the Decision Support System, a number of cases were ran analyzing different sites, different standards and different objective weights. These results are included in this chapter, along with one example run showing the moderate output. Based on the results, there doesn't appear to be much of a change in the attenuator recommendation. Possible reasons for this, as well as changes that can be made to affect this, will be discussed later in the chapter. The results contained in this study are intended only to evaluate the operation and performance of the decision support system. The results do not in any way reflect the performance of any attenuator. There is not enough data within the database at present to make a performance related decision.

5.1 Example Run

This section contains an example run of the Decision Support System. In this example, attenuators are ranked for their suitability for a moderate site, that is, one with neither extremely harsh nor extremely benign site conditions. The first step of the procedure involves entering the site characteristics and other search parameters for the Decision Support System. Figure 5.1 shows an example of the data input for the moderate site.

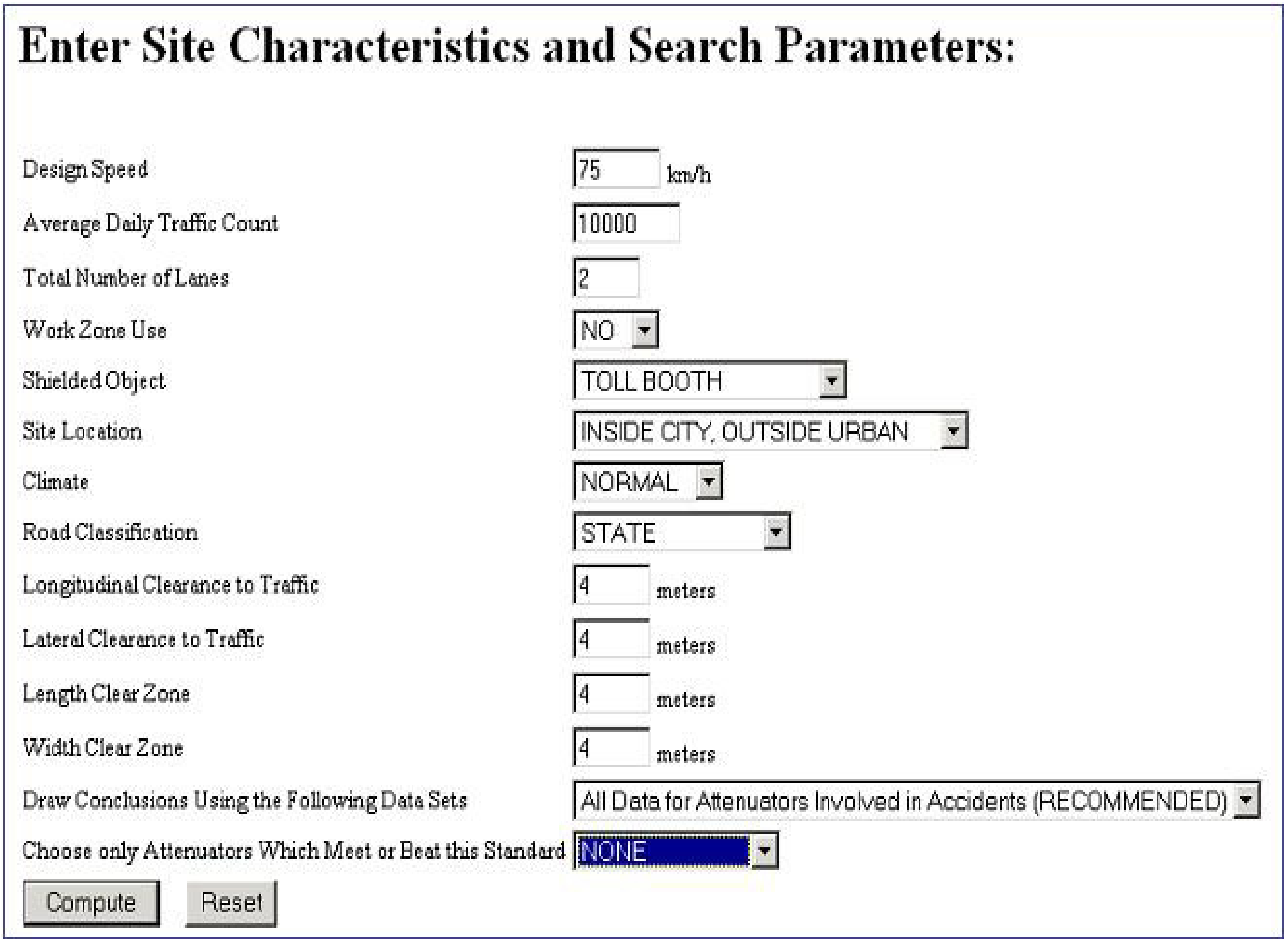
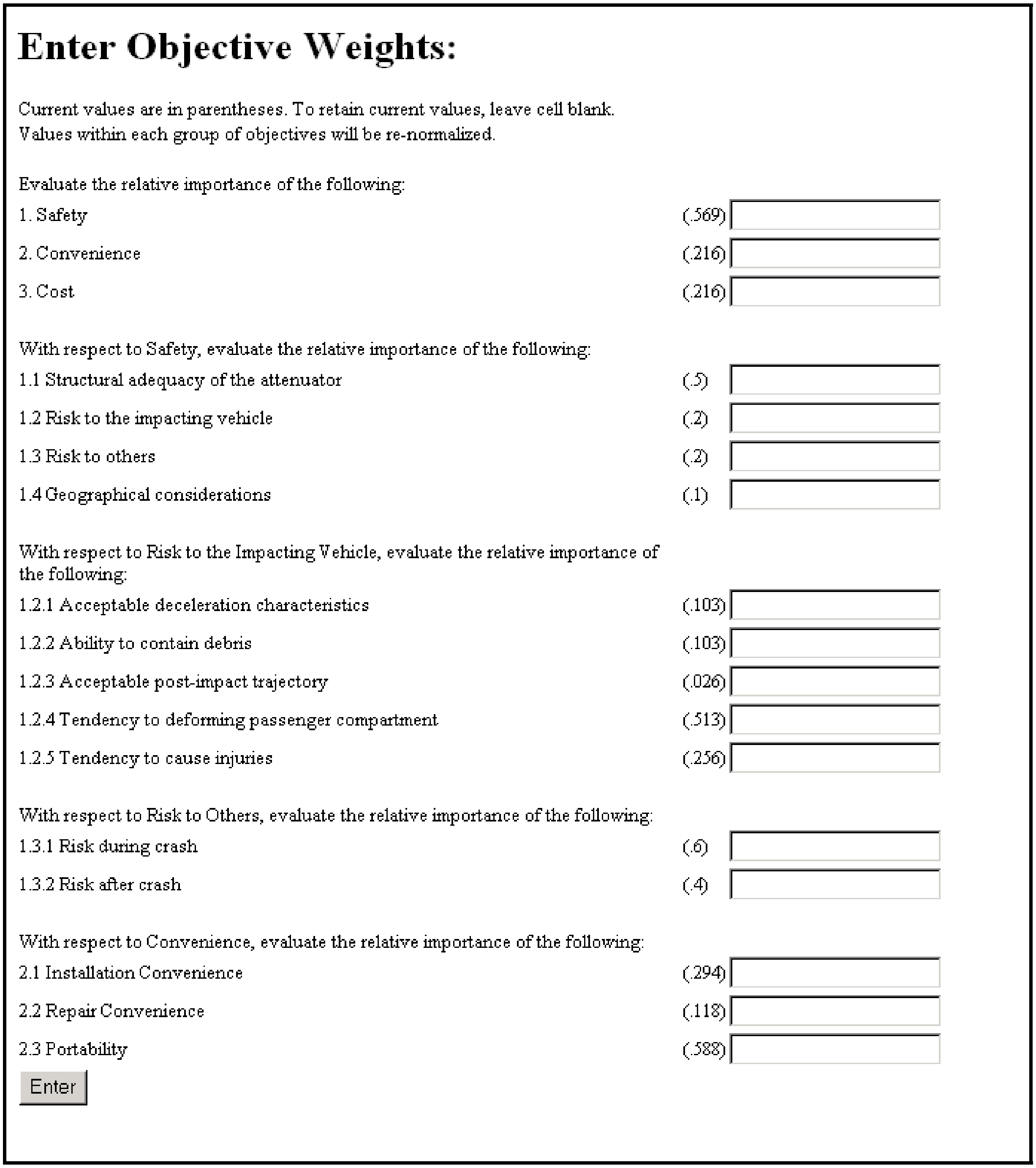


Figure 5.1: Input Screen for Site Characteristics and Search Parameters

The next step in the process is to define objective weights. The objective weights are values given to the three primary objectives: safety, convenience and cost. These objective weights can be changed within the Decision Support System by selecting the "Change objective weights" option at the main menu and editing the value of the weights. Figure 5.2 shows the input screen for objective weights, prior to any data entry. Note that the current values for the objective weights are shown next to the text boxes for comparison purposes.



Enter Objective Weights:

Current values are in parentheses. To retain current values, leave cell blank.
Values within each group of objectives will be re-normalized.

Evaluate the relative importance of the following:

1. Safety	(.569)
2. Convenience	(.216)
3. Cost	(.216)

With respect to Safety, evaluate the relative importance of the following:

1.1 Structural adequacy of the attenuator	(.5)
1.2 Risk to the impacting vehicle	(.2)
1.3 Risk to others	(.2)
1.4 Geographical considerations	(.1)

With respect to Risk to the Impacting Vehicle, evaluate the relative importance of the following:

1.2.1 Acceptable deceleration characteristics	(.103)
1.2.2 Ability to contain debris	(.103)
1.2.3 Acceptable post-impact trajectory	(.026)
1.2.4 Tendency to deforming passenger compartment	(.513)
1.2.5 Tendency to cause injuries	(.256)

With respect to Risk to Others, evaluate the relative importance of the following:

1.3.1 Risk during crash	(.6)
1.3.2 Risk after crash	(.4)

With respect to Convenience, evaluate the relative importance of the following:

2.1 Installation Convenience	(.294)
2.2 Repair Convenience	(.118)
2.3 Portability	(.588)

Enter

Figure 5.2: Input Screen for Objective Weights

All three objective weights for the primary objectives should add up to a value of 1.0. In an example for a moderate site, the following values shown in Table 5.1 were used, indicating that safety is more important than either convenience or cost, both of which are weighted equally.

Table 5.1: Primary Objectives and Objective Weights

Objective		Objective Weight
1	Safety	0.50
2	Convenience	0.25
3	Cost	0.25

Each of the primary objectives are divided into sub-objectives as described in Chapter 4. Table 5.2 shows the weights computed by the D.S.S. for each of the 29 criteria, based on the objective weights and the importance of each criteria within the objective. The criteria weights for safety (criteria numbers 1-20) will add up to 0.50 to equal the objective weight assigned in Table 5.1. The same process is followed for convenience (criteria numbers 21-26) and cost (criteria numbers 27-29). The following table lists the criteria number, criteria name and assigned criteria weight based on the moderate site example. The objective and criteria weights are used to calculate the overall rank of each attenuator based on the example procedure outlined in Chapter 4, Section 4.2.1: Example Decision Tree.

Table 5.2: Criteria Weights for Moderate Site

Criteria Number	Criteria Name	Weight
1	Frontal Capacity	0.135
2	Ability to Redirect	0.115
3	Tendency to Snag	0.005
4	Tendency to Pocket	0.017
5	Tendency to Spear	0.007
6	Tendency to Scatter Debris	0.004
7	Tendency to Rollover	0.019
8	Tendency to Over-ride Attenuator	0.011
9	Tendency to Under-ride Attenuator	0.005

Table 5.2 continued

Criteria Number	Criteria Name	Weight
10	Tendency to deform passenger compartment	0.023
11	Rate of Occupant Injury	0.003
12	Severity of Occupant Injury	0.031
13	Tendency to Rebound Backwards	0.021
14	Tendency towards large redirect angle	0.010
15	Tendency to Gate	0.024
16	Tendency to Scatter Debris	0.005
17	Response Time	0.027
18	Repair Time	0.013
19	Susceptibility to Vandalism	0.025
20	Susceptibility to Environment	0.000
21	Installation Time	0.042
22	Installation Equipment	0.058
23	Repair Time	0.038
24	Repair Equipment	0.051
25	Inventory Requirements	0.011
26	Portability	0.050
27	Initial/Installation Cost	0.095
28	Maintenance Cost	0.076
29	Repair/replacement Cost	0.079
	Total Weight	1.000

Criteria 1 (Frontal Capacity) has a weight of 0.135 and is almost always the highest because that is the most important function of an attenuator. As stated in Chapter 4 for Criteria 1.1.1, as the design speed of the roadway increases, the importance of providing sufficient frontal capacity increases. The scores for Criteria 20, (Susceptibility to Environment) and Criteria 25,

(Inventory Requirements) are 0.000 and 0.011 respectively, which are on the lower end of the scale for this site. These criteria are given less weight because our site does not require that strong of a performance in those areas.

Table 5.3 shows the scores that each attenuator configuration received for each criteria, based on the criteria numbers. The configuration names are shorthand references to the attenuator type and model. For instance, E90 represents an Energite Sand Barrel array rated for 90 km/hr; F75 represents a Fitch Sand Barrel array rated for 75 km/hr.

Table 5.3: Criteria Scores Per Configuration

Criteria #	**Configuration Name**					
	E90	**F***	**F75**	**F85**	**F90**	**Etc.**
1	20	20	20	20	20	
2	0	0	20	20	0	
3	20	20	13.9082	20	20	
4	0	0	4	20	0	
5	20	20	20	20	20	
6	0	1.4923	2.4137	1.4925	1.4925	
Etc.						

The criteria number corresponds to each criteria name in Table 5.2. The criteria scores are based on the test data in the database. The attenuator scores will be higher for attenuators that performed very well with respect to a particular criteria, and lower for poorer performing attenuators. However, the high scores will vary based on the amount of data in the database and the various formulas that were used to generate the scores. These scores are manipulated as described in Chapter 4 to come up with the overall attenuator ranking.

The following table represents the results of the decision support system for the moderate test case. A configuration and a representative model number identify the attenuators. This was done to group together models where the different model numbers represented only cosmetic differences, such as a different color nose. The raw scores are processed from the criteria scores, and the percent scores are normalized so that they will all add up to equal 100. The highest scores are typically less than 10 because there are so many different attenuators. If we had grouped them by attenuator type (i.e. all G-R-E-A-T's, all Hex Foam's, etc.), it would probably result in higher numbers, because the 100% would be divided fewer ways. Based on the moderate site, the G-R-E-A-T G6 configuration, which is represented by model number 200200S6, scored the highest and the Hex Foam Sandwich attenuator, HF9 configuration represented by model number 209509H9S, scored the lowest. If one were to look at the criteria scores for the G-R-E-A-T G6 configuration, one would find that it scored twenty for the first nine criteria and five of the other criteria. This is why it received such a high overall score. The lowest rated attenuator, the Hex Foam Sandwich HF9 only scored twenty on eight of the criteria all together.

Table 5.4: D.S.S. Results

Attenuator Type	Configuration	Sample Model	Percent Score	Raw Score
G-R-E-A-T	G6	200200S6	7.7	.0572
SAND BARREL-FITCH	F85	00209404722140921	7.2	.0534
SAND BARREL-FITCH	F75	00201405704140021F	7.1	.0525
HEX FOAM SANDWICH	HF5	111307H5S	6.3	.0465
SAND BARREL-FITCH	F90	02201403708140021F	6	.0442
HI-DRO SANDWICH	HS4	G111311S4N	5.9	.0435
G-R-E-A-T	G5	200200S5	5.8	.043
HEX FOAM SANDWICH	HF6	111307H6S	5.6	.0415
G-R-E-A-T	G9	200200SF9	5.1	.0378

Table 5.4 continued

Attenuator Type	Configuration	Sample Model	Percent Score	Raw Score
SAND BARREL-ENERGITE	E90	04200840015700721E	5.1	.0377
SAND BARREL-ENERGITE	F*	UNKNOWN--ENERGITE	5.1	.0377
HI-DRO SANDWICH	HS8	G111311N8S	5	.0374
HI-DRO SANDWICH	HS6	G111307N6D	4.8	.0355
HEX FOAM SANDWICH	HF7	2091009H7N	4.7	.0352
G-R-E-A-T	G4	200200F4	4.6	.0342
HEX FOAM SANDWICH	HF12	111400H12S	4	.0294
SAND BARREL-UNKNOWN	S*	UNKNOWN--SAND BARREL	3.9	.0291
HEX FOAM SANDWICH	HF10	204507H10S	3.6	.0267
HEX FOAM SANDWICH	HF9	209509H9S	2.7	.0199

5.2 Varying Site Characteristics

To test the effect of varying site conditions, three test cases were run. For consistency sake, the objective weights remained the same for all of the example test cases that are discussed in this section. Table 5.5 shows the differences in the site characteristics for three test cases. The test cases are classified as mild, moderate and extreme sites.

Table 5.6 shows the recommended attenuators for the three different test cases. The top five recommended attenuators are shown, along with the percent score they achieved for each of the test cases.

Table 5.5: Site Characteristic Selections

Conditions	**Test Cases**		
	1	2	3
	Mild	Moderate	Extreme
Design Speed (km/hr)	30	75	120
Avg. Daily Traffic Count	100	10,000	40,000
Total # Lanes	2	2	2
Work Zone Use	No	No	Yes
Shielded Object	Fence	Toll Booth	Concrete Barrier
Site Location	Outside City/Outside Urban	Inside City/Inside Urban	Inside City/Inside Urban
Climate	Normal	Normal	Extreme
Road Classification	Local	State	Interstate
Longitudinal Clearance to Traffic	20	4	0.5
Lateral Clearance to Traffic	20	4	0.5
Length of Clear Zone	20	4	0.5
Width of Clear Zone	20	4	0.5
Draw Conclusions Using Following Data Sets	All Data for Atten. Involved in Accidents	All Data for Atten. Involved in Accidents	All Data for Atten. Involved in Accidents
Choose only Atten. which meet/beat this Standard	None	None	None

Table 5.6: Recommended Attenuators

Recommended Attenuators	Test Case 1		Test Case 2		Test Case 3	
	Name	Percent	Name	Percent	Name	Percent
1	F85	8.4	G6	7.7	G6	7.7
2	F75	8.3	F85	7.2	F85	7
3	F90	7	F75	7.1	F75	6.9
4	G6	6.6	HF5	6.3	HF5	6.2
5	E90	6.3	F90	6	F90	6.1
etc.						

As seen from these results, one would need a really benign environment to change the recommendations; therefore the sensitivity level on the importance factors might need to be adjusted. The recommendations show changes from the mild to the moderate condition, however there were no changes in the recommendations from the moderate to the extreme condition. However, this might also reflect the relatively low number of cases in the database. As the database grows the possible variation in results will increase.

5.3 Varying Objective Weights

The following examples show the effect of different objective weights. In the second and fourth examples, more emphasis has been put on safety. In the first and third examples, more emphasis was put on convenience and cost: these weights are the same weights that were used in the previous section. The site characteristics for the mild and moderate sites are similar to the site characteristics in Table 5.5, although they have been changed slightly, resulting in differences in the recommended attenuators.

Table 5.7: Varied Objective Weights

Objectives	Test Cases			
	Mild	Mild w/ Changed Weights	Moderate	Moderate w/ Changed Weights
Safety	0.500	0.566	0.500	0.569
Convenience	0.250	0.217	0.250	0.216
Cost	0.250	0.217	0.250	0.215

Table 5.8: Recommendations of Varied Objective Weights

Recommended Attenuators	Test Cases			
	Mild	Mild w/ Changed Weights	Moderate	Moderate w/ Changed Weights
1	G5	F85	G5	F85
2	G4	E80	G4	E80
3	F85	G4	F85	G4
4	E80	G5	E80	G5
5	G9	F90	G9	HF12
Etc.				

This test shows that changing the objective weights did in fact change the recommended attenuators. Comparing the test cases with the original weights (one and three) with those with changed weights (two and four), one can see that fairly small changes in the objective weights resulted in significant changes in the recommendations. The newer weights give higher scores to attenuators that perform better on the criteria related to safety, but less on the criteria related to cost and convenience. This test shows that the Fitch and Energite arrays would perform better in safety criteria (resisting front impacts, not redirecting vehicles into traffic, etc.), but not as well on cost and convenience (possibly due to cleanup costs after an impact, maintenance, etc.) Note however that the changing site characteristics resulted in very little changes in the recommendations.

5.4 Varying Standards

A number of examples were run that had the same objective weights and site characteristics, but the standards that the attenuators had to meet to be included in the comparison have been changed. This allows us to see how the use of different standards might affect the recommended attenuators. As the standard level increases or gets higher, fewer attenuators are recommended. This is due to the fact that fewer attenuators meet the requirements of the higher standards such as the NCHRP 350 standard.

Table 5.9 shows the results when all attenuators that meet the old NCHRP-230 standard are included in the analysis. Note that many attenuators appear on this list. Table 5.10 shows the much shorter results list when only attenuators that meet NCHRP-350 are included in the study. Obviously, limiting the results to those attenuators that meet the newer standard severely shortens the list. At the time of the study, very few attenuators meeting the NCHRP-350 standard had been installed, and even fewer had been in crashes. As a result, very little data on their performance was available to add to the D.S.S. database. Note that, because the total score is being divided among fewer attenuators, the raw scores and percent scores of each of the eligible attenuators is much higher. This shows that scores should only be compared within a single run, not between runs of the D.S.S..

Table 5.9: Sample Run of Attenuators that meet NCHRP-230

Attenuator Type	Configuration	Sample Model	Percent Score	Raw Score
SAND BARREL-FITCH	F85	00209404722140921	7.7	.0572
SAND BARREL-ENERGITE	E80	01201401703140421	7.2	.0532
G-R-E-A-T	G4	200200F4	7.1	.0524
G-R-E-A-T	G5	200200S5	7	.052
HEX FOAM SANDWICH	HF12	111400H12S	6.2	.0461
G-R-E-A-T	G6	200200S6	6	.0444
G-R-E-A-T	G9	200200SF9	6	.0443
SAND BARREL-FITCH	F90	02201403708140021F	5.9	.0435
SAND BARREL-FITCH	F75	00201405704140021F	5.5	.0406

Table 5.9 continued

Attenuator Type	Configuration	Sample Model	Percent Score	Raw Score
SAND BARREL-ENERGITE	E90	04200840015700721E	5.5	.0405
G-R-E-A-T	G3	200200FS3	5.3	.0392
HEX FOAM SANDWICH	HF6	111307H6S	5.3	.039
HEX FOAM SANDWICH	HF7	2091009H7N	5.2	.0387
HEX FOAM SANDWICH	HF8	111311H85	4.6	.0343
G-R-E-A-T	G8	200200SF8	4.6	.0342
HEX FOAM SANDWICH	HF10	204507H10S	4.1	.0305
HEX FOAM SANDWICH	HF5	111307H5S	3.9	.0289
HEX FOAM SANDWICH	HF9	209509H9S	3.1	.0232

Table 5.10: Sample Run of Attenuators that meet NCHRP-350

Attenuator Type	Configuration	Sample Model	Percent Score	Raw Score
SAND BARREL-FITCH	F85	00209404722140921	25.7	.1903
SAND BARREL-ENERGITE	E80	01201401703140421	23.8	.1766
SAND BARREL-FITCH	F90	02201403708140021F	17.1	.1271
SAND BARREL-FITCH	F75	00201405704140021F	16.9	.125
SAND BARREL-ENERGITE	E90	04200840015700721E	16.5	.1227

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

When the research and development of this project first began, the task at hand was to develop a framework for a decision support system to rank and evaluate attenuators. Aside from controlled crash test environments, there was no real-time data to help aid in the determination of which attenuator would best be suited for a specific site based on the site design and characteristics. The objective was to develop a simple framework or foundation for a program that would allow the user to input their site characteristics and objective weights and have it recommend the attenuator that best meets the users' criteria.

The research described herein meets these objectives by providing the framework of a decision support system that can rank attenuators based on accident data taken from actual accident reports and added to an underlying database. The system provides analysis and recommendations based on user-selected site characteristics using a new concept known as importance functions, which affect the importance placed on each sub-criteria. The framework also allows the user to manually alter objective weights at higher levels of the decision tree.

Based on the test cases included in Chapter 5 and other test cases that were ran, the decision support system does work as expected and recommends different attenuators to satisfy different site characteristics and/or situations. It was determined that the decision support system results are more sensitive to changes in the objective weights and test standards and not as sensitive to changes in the site characteristics. The only time site characteristics significantly changed the recommendations is when the type of site was drastically changed. In the case of a mild site, based on the current setup, an attenuator is always recommended; however, another possible recommendation that should be considered is that an attenuator may not be needed at all.

As stated previously, the results presented in Chapter 5 in no way represent conclusions that one attenuator system performs better than another under any specific site conditions. This decision support system should only be considered as a good framework for future research and development. As stated below, there are several areas that require further research and should be addressed accordingly.

First, as stated previously, the D.S.S. is not very sensitive to changes in site characteristics. This sensitivity could be improved by adjusting the upper and lower bounds on the importance functions. In addition, the relationship between the criteria and site characteristics in the framework D.S.S. was solely based on linear/first order functions. In many cases, relevant research studies could not be found to guide the development of the importance functions, and common sense was used instead. Future development and research should refine the importance functions, seeking higher order functions or other equations that better model the importance of the site characteristic being considered.

Another area for improvement would be to add more data to the database. The recommendations are based on historical performance data. Expanding the database would help improve the comprehensiveness and accuracy of the recommendations. It is important to note that there were only about 100 accident records utilized in the database at the time this study was conducted. These 100 accident records were also from the year 1996 only. Future efforts to enhance this program should focus on collecting more historical data that is more representative of the variety of attenuator crashes that can occur. One area where more historical data is required and would be beneficial is on attenuators that meet the NCHRP-350 standards.

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EDUCATION:

Florida State University - Tallahassee, Fl.

Masters of Science in Civil Engineering	April 2004
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Palm Beach Community College - Palm Beach Gardens, Fl.

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Project Manager/Engineer: Manage and design Major and Minor civil engineering projects ranging from residential site plans, stakeouts, wall checks, and final house location surveys to mid-range scale design. Have also managed numerous boundary survey projects. These projects have given me the opportunity to deal with numerous builders and developers. Perform drafting services utilizing Autocad R14 and Softdesk 8 Overlay. Perform various structural services, such as house inspections, beam design, and certifications. Responsible for filling work order requests and billing reviews associated with these projects. Have been responsible for Project Engineers and CAD Designers as well as provide steady workflow for a professional property line surveyor and field crews. Have been involved with commercial design, traffic studies, and storm water design projects. Performed minor field work with survey crews and forest stand delineation. Provide IT support and maintenance for an office network of 25 +/- computers and troubleshoot the problems associated with day-to-day tasks. Maintain direct customer interaction to resolve problems and clarify requirements. Also provided expert testimony for customers in a legal case.

Nodarse & Associates, Inc. - West Palm Beach, Fl. (1999 - 2000)

Geotechnical Project Engineer: Assisted in the development and maintenance of spreadsheets for engineering calculations. Developed marketing and networking skills by attending engineering meetings with clients and co-workers. Coordinated drilling, field, lab and drafting services. Prepared draft proposals and reports. Responsible for reviewing USDA/SCS maps, boring logs, lab analyses and drafting. Reviewed county regulations for Subdivision and Road/Bridge designs and specifications. Prepared invoices and continually remained within budget for scope of services. Served as a field engineer/geologist during construction. Developed project management by being assigned to components of projects to ensure completion above client's satisfaction.

FSU College of Engineering - Tallahassee, Fl. (1996 – 1999)

Research Engineer: Developed a Decision Support System and Database to evaluate and rank attenuators based on client's requirements and factual data. Researched accident and maintenance records for roadside attenuators, utilizing libraries, internet, and computer programs for pertinent information. Worked with different Departments of Transportation districts in the State of Florida to gather attenuator data and to perform in depth research from the Roadside Design Guide, Energy Absorption Systems, and NCHRP Report 350.

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Sales Associate: College part time work to help cover cost of school and living expenses. Required to have an understanding in electronic product knowledge and utilize it with one on one customer interaction. Provided quality customer service to an average of 30 customers per day. Exceeded sales expectations and merchandising of the sales floor. Achieved sales goals on a consistent basis and was awarded top sales performance for the district in October and November 1995. Responsibilities also included demonstrating knowledge in all aspects of electronics and performing custom installations upon request and training new hires.

ACTIVITIES/PERSONAL ACCOMPLISHMENTS:

- Building and upgrading personal computers.
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