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16. Abstract

    The goal of this research is to develop a methodology for computation of expected in-service life cycle costs for highway crash attenuators placed alongside of highways. Since crash attenuators are designed to be hit, logically their in-service costs should be taken into consideration in addition to their initial cost in their selection. A methodology that would allow calculation of the life cycle cost of crash attenuators at the time of their selection can lead to significant long term cost savings for Caltrans Maintenance. The research question addressed in this research is can a formula or methodology be developed to allow the computation of the life cycle cost of crash attenuators at the time of their initial selection? Attenuator in-service maintenance costs are comprised of a series of difficult to quantify factors with dependent and complex inter-associations. These fundamental relationships need to be identified and characterized with a formal and rigorous analysis. The scope of this study is limited to Caltrans approved and deployed attenuators and their associated in service maintenance costs on California highways. The in-service costs are solely derived from Caltrans sources and processed in respect to Caltrans procedures and operations. The resulting methodology and formula developed in this study was circulated to appropriate State, Federal and industry representatives in an effort to acquire reviews and suggestions. The comments received were incorporated into this report and reflected in the final form of the methodology.

    This research has determined that two of the most important site attributes influencing life cycle costs of crash attenuators are the expected impact frequency and the access factor. For highway sites with elevated values of either of these factors, in-service maintenance costs becomes the compelling consideration and products designed for cost effective reset/repair are preferred. This study identifies and describes a class of severe duty attenuators developed expressly to enable simple reset/repair after impacts and based on the methodology, quantifies the expected site specific cost savings. The final objective of this research is to provide Caltrans traffic designers a means to identify and justify the selection of the most appropriate attenuator product designs for a given site based on its unique attributes.

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i

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CRASH ATTENUATOR USAGE ALONG TRAVELWAYS AND IN WORK ZONES

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

BACKGROUND

Current Attenuator Standards

Crash attenuators are installed along travel ways to help protect the motoring public. They are designed to safely decelerate or redirect a vehicle with minimal risk to the impacting vehicle's occupants and third party vehicles. In order for an attenuator to be approved by the Federal Highway Administration (FHWA), there is a series of crash tests which are performed. These standards are outlined in the NCHRP report 350 [3] which were released in 1992 and have been considered the standard for some time. The NCHRP standards are being updated through the implementation of the MASH 08 [4] standards. The tests outlined by these reports typically specify the vehicle weight, speed, trajectory, and the point of impact on the vehicle. The collected results focus on the vehicle ride-down characteristics and occupant safety metrics, with little regard to the state of the attenuator after the impact. Chapter seven of the NCHRP 350 report mentions the need for in-service evaluations, but the industry in general has been slow to respond. One reason for this may be that repair costs fluctuate significantly depending on the type of impact. The required level of restoration can also be very subjective. Therefore, it would be impractical to presume that a representative repair cost figure could be determined from a small number of in-field case studies or the standard regiment of crash tests. Regardless, dramatic differences in service repair costs are implicitly linked to attenuator design characteristics. A new class of severe duty attenuators is emerging. These products are designed to be easier to reset on the highway. However, these systems typically have higher initial costs. The cost effectiveness of this class of attenuator is overlooked with the current initial cost centric method. Applying these low maintenance cost products to all locations is not cost effective as certain locations may not experience enough impacts to justify the higher initial cost.

Caltrans Attenuator Procurement

For crash attenuators to be used on California highways, they must first meet federal guidelines and pass specific crash tests. Then Caltrans conducts an engineering review of the product to ensure that the attenuator is appropriate for Caltrans use. The result is that the attenuator is added to the Caltrans qualified products list (QPL) and thus can be selected for use on state highway projects. Designers determine which attenuators from the list are most appropriate for their projects while taking into account location's specific requirements. An attenuator's maintenance characteristic is often one of the major requirements Caltrans considers in the selection process. For projects seeking Federal funding, designers must specify three acceptable attenuators for a project to qualify, even when three equally suitable approved products don't exist. In practice logically the installation contractor will favor the product with the lowest initial cost which will characteristically have the higher in-service cost. For active locations, a high in-service cost will quickly overcome a lower installation cost and become a drain on Caltrans resources. The most appropriate and cost effective attenuator can be simply identified by comparing the life cycle cost which represents a combination of installation cost and in-service costs. When Caltrans designers are tasked to mitigate a problematic highway site with extraordinary conditions, where three equally suitable products on the QPL may not exist, they can take two paths of action. First they often elect to just use State funds, or they can elect to submit a form Request for Approval of Cost Effectiveness/Public Interest Finding (PIF) and

seek an exception to the Federal Funding three bid requirement. The basis for such a justification is typically associated with a high in-service maintenance cost, but a standardized method to analyze the potential specific product cost saving has not been universally adopted.

Caltrans Attenuator Classifications

At present, Caltrans classifies attenuators as either repairable or sacrificial. These classifications draw the line between an attenuator which is destroyed when hit verses an attenuator which can be repaired. Caltrans has been contending with high maintenance costs where attenuators with high repair costs are situated at locations experiencing high impact frequencies. As a first step in mitigating this situation, an effort is in progress to establish a new resettable category for the purpose of acknowledging attenuator designs which are easily restored in-place and consequently have lower in-service costs. The key attributes of a resettable attenuator are that the time, tooling, and parts necessary for a typical restoration are minimal and predictable. Often, repairable attenuators require multiple trips to restore, including an inspection trip to the attenuator to assess the extent of damage and determine what parts are needed. Subsequent trips are scheduled with traffic control to complete the work, thus increasing the individual impact repair costs.

Severe Duty Classification

Several States have created a special designation for a class of attenuators specifically designed to be easily restored after impacts. The Indiana DOT has created a critical duty or "CR" category for attenuators that can be quickly and easily repaired in the field, Iowa DOT has a "Severe Use" category, and Oregon DOT has a "Low Maintenance" rating. Caltrans engineers use the term "Severe Duty" when referring to this type of easily resettable low in-service cost attenuator. Caltrans is likewise interested in officially creating a special "Severe Duty" class of attenuators to reduce in-service maintenance costs when specifying attenuators. For justification, Caltrans established this study to develop a methodology, which accurately quantifies the expected in-service costs uniformly for all of the currently qualified attenuators. At least two states have made a similar effort to justify a "Severe Duty" class of attenuators based on studies. Arizona DOT in connection with FHWA released a "Finding in the Public Interest" study in 2006 and Kansas DOT released a basic justification report in 2008. These reports in general recognized the importance of quantifying repair costs and using it to influence the attenuator selection process. However, neither report presented a sufficiently detailed methodology that could be adopted universally for making such an evaluation.

The Kansas DOT report presented a method of specifying an attenuator based on a linear relationship between ADT/Lane and life cycle cost [1]. By examination, the correlation relationship presented has a 0.037 co-efficient of determination which is an accuracy rating when evaluating the prediction of future outcomes. The co-efficient of determination is one for a perfect correlation and zero for no relationship at all. The ADT/Lane relationship conclusion is therefore too close to zero to be considered a reliable predictor. The Kansas DOT report also seemed to be focused on comparing the in-service costs of just two specific products. Their conclusions were drawn from a data comparison between Quadguard™ costs and Smart Cushion™ costs. The report did not include data for all other comparable common products; such data would make the comparisons more realistic.

The Arizona DOT - FHWA public interest study [5] compares in-service cost data of various attenuators and justifies the use of the Smart Cushion™ attenuators for active Arizona highway locations. The in-service cost data used is based partially on actual repair costs and partially on engineering estimates. This is a very useful data set and can be improved as more actual repair cost data would become available.

These States clearly recognize the importance of recognizing a severe duty class of attenuators characterized by simple repair/reset operations which results in lower in-service costs. However a more systematic and objective method of evaluating which attenuators qualify as severe duty must be developed for the term to achieve widespread meaning. Upon first examination, it may appear logical to develop a list of mechanical features which would establish severe duty attenuator status. Since the principles of operation and beneficial features are design specific and comparisons involve complex trade-offs, it would be imprecise to directly rank attenuators based on mechanical features. In general lists of beneficial mechanical features are essentially assertions based on interpretations. A more scientific approach would be to attempt to indirectly rank an attenuator as severe duty based on their in-service cost histories. The cost history will have to be filtered to eliminate the occasional impact which is greater than TL-3. For the purpose of this report, nuisance hits are defined as impacts which have no associated cost record. In fact, many times these impacts go completely un-noticed. After filtering the cost history, an average repair cost can be ascertained. Based on this information, the in-service costs can be estimated. The attenuator products with the lowest expected in-service repair costs would be classified as severe duty.

In summary, the current attenuator classification process separates products in two distinct categories: sacrificial or repairable. This division is very straightforward amongst products and is fairly difficult to contest. However, based on testimony from industry professionals there is a clear distinction within the repairable category that should be more explicitly defined which is the "Severe Duty" category. There are currently only two Caltrans approved products which many industry professionals feel fit into this category which are the REACT350™ and the Smart Cushion™. This category breakdown is illustrated in Figure 1 below.
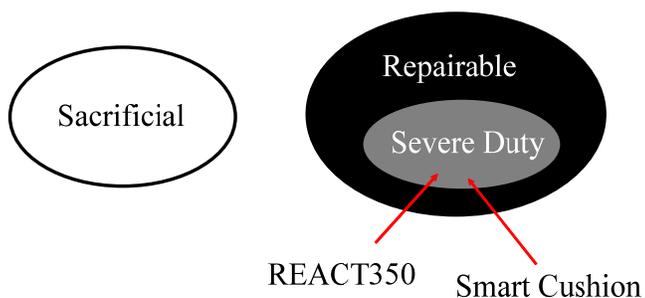
**Figure 1: Category Breakdown**

Through this adoption of the severe duty attenuator category, designers will be able to apply this specification to the deployment of products at appropriate locations in order to help make a tremendous amount of cost savings. The biggest hurdle to establishing this category is that the division between a repairable product and a severe duty product is not clearly defined.

3

LIFE CYCLE COST MODEL

Life-Cycle Cost Analysis

In order to make a realistic value comparison of attenuator products when considering severe duty products, a life cycle model needed to be developed which includes a term for the expected in-service costs together with the conventional initial cost basis. The three key contributing factors to in-service maintenance costs are the bare repair cost, access cost, and the number of impacts. Two of these, the bare repair cost and access cost, can be considered to be the per event cost. The third key element is the expected number of impacts which acts basically as a multiplier to both the repair and access costs. Obviously, for a site with a high frequency of impacts, the cheapest attenuator to repair/reset will have the lowest life cycle cost, even with a significantly higher initial cost. The opposite is also true that if a location never gets hit, then the repair/reset cost isn't a factor and the life cycle cost is essentially just the initial cost.

The bare repair cost of an attenuator is defined as the cost to repair the attenuator under normal conditions, independent of site based impediments which may contribute to increased repair costs. In other words, this is the cost of repairing the attenuator in a theoretical situation where no traffic control is required. Hence, the bare repair cost for specific attenuators is not location sensitive, therefore, a common average values can be established and used for the purpose of life-cycle cost estimation. The other major factor, the access cost, is predominantly location dependent. The access cost is defined as the cost of establishing and removing the traffic safety measures needed to provide maintenance crews with a suitable space to perform on the highway repairs. The estimated in-service costs and consequently the life cycle costs must consider both location and product specific values. One of the key assumptions of breaking down the analysis of the problem in this way is that the space required to repair the various products is similar enough to allow the access cost to be estimated independently of the product. This assumption also allows all repairs (independent of location) to be considered when computing the average repair cost.

How access issues can significantly drive life cycle costs is less obvious and is often overlooked. Most critical attenuator locations are congested with minimal off-road workspace and are often located at traffic redirecting points on the highway. These locations represent the greatest direct traffic hazard to exposed maintenance personnel. Access to this type of location requires the most significant traffic control measures to ensure safety for both maintenance workers and motorists. Several exits and key interchanges are closed at the same time in some cases. In other cases, special evening closures, usually involving overtime pay requiring additional workers and vehicles with law enforcement support may be required. The cost of such a closure several times a year, even if the repair/reset is minimal, represents a major in-service cost. In addition, should the struck attenuator be deemed to be a traffic hazard, an emergency highway closure will be required, risking a traffic jam. That same attenuator located a good distance off the shoulder on straight highway could be repaired/reset with a small number of workers and vehicles with no appreciable traffic impact. Certainly access is a major factor that contributes to in-service costs and likewise the life cycle costs. The access cost is location specific and in general, is not attenuator specific. The cost may increase if extra repair time is required, or if multiple trips are required to complete the attenuator reset task.

Life-Cycle Cost Formula

A basic mathematical model will be utilized to illustrate how the major influential factors (access cost, repair cost, and number of impacts) and lesser more site specific factors are accounted for when evaluating the life cycle costs. Although many of the factors involved in the conceptual formulation are primarily qualitative, the abstract mathematics can help to understand some of the key aspects. Some factors included in the model are product specific, while other factors are location specific.

Life cycle costs are made up of initial installation costs and the in-service cost. This formulation can be seen in equation 1 below.

$$\$_{LC} = \$_{Inst} + \$_{in-service} \qquad\qquad \textbf{1}$$

where

$\$_{LC}$ = The life-cycle cost
$\$_{Inst.}$ = The installation cost
$\$_{in\text{-}service}$ = The in service cost

While the installation cost is straightforward, the in-service is much more complex. The in-service cost represents the maintenance costs, and the sum total of repair costs. This can be mathematically expressed in equation 2 below.

$$\$_{in-service} = \sum_{i=1}^{n}\$_{I(i)} + \$_{Main} \qquad\qquad \textbf{2}$$

where

$\$_{I(i)}$ = The impact specific repair cost
$\$_{Main.}$ = The maintenance cost
n = The number of impacts

Equation 1 can be substituted into equation 2, yielding equation 3 below.

$$\$_{LC} = \$_{Inst} + \sum_{i=1}^{n}\$_{I(i)} + \$_{Main} \qquad\qquad \textbf{3}$$

Equation 3 shows three types of cost that are all contributors to life-cycle cost which are the initial installation cost, the sum total of all incurred repair costs, and the manufacturer required maintenance costs.

The installation cost ($\$_{Inst.}$) can be easily quantified as an average based on bid history and then modified for any special installation requirements. If one were to plot life-cycle costs vs. impacts this would be the "y" intercept value as shown in Figure 2.
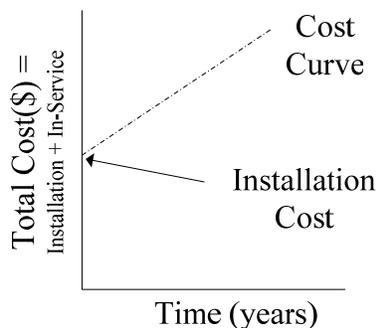
Figure 2 Installation cost relative to life-cycle cost

The number of impacts (n) is a location specific estimation based on site impact history for attenuator replacement, or a prediction for new construction. The estimate should be ideally based on the experience that local traffic designers and maintenance personnel have with the specific site. The variable "n" typically represents an expected number of impacts over a fixed time frame (X_{years}). Another way to capture "n" is to define the mean time between hits (MTBH) which can be expressed by equation 4 below.

$$MTBH = \frac{n}{X_{years}} \qquad\qquad 4$$

where

    n = The number of impacts
    MTBH = Time between hits at a location (units = years)
    X_{years} = The design life of the analysis

It is important to recognize that the product could potentially affect the MTBH, due to the driver's perception of the device, however this effect is very difficult to quantify.

The most difficult part of the equation to look at is the cost of an attenuator repair for a single impact. In truth the impact repair cost has two main components as expressed in equation 5.

$$\$_{I(i)} = \$_{AC(i)} + \$_{R(i)} \qquad\qquad 5$$

where

    $\$_{AC(i)}$ = The cost to accessing the site
    $\$_{R(i)}$ = The cost of performing the specific repair

The site access cost ($\$_{AC(i)}$) refers to the costs associated with maintenance crews accessing the location for a given impact and includes labor and equipment costs. $\$_{R(i)}$ is the sum total of the cost of labor, equipment, and materials for a given repair once the traffic control plan is in place.

The site access cost has four major parts and can be expressed by equation 6.

6

$$\$_{AC(i)} = \$_{ACS(i)} + \$_{ACM(i)}(t_i) + \$_{ACR(i)} + \$_{AC\_pi(i)}(t_i) \qquad\qquad \textbf{6}$$

where

> $\$_{ACS(i)}$ = The cost to setup of the traffic control to access the site
> $\$_{ACM(i)}$ = The hourly expense associated with maintaining the access
> $\$_{ACR(i)}$ = The cost associated with removing the traffic control
> $t_{(i)}$ = The time it takes to perform the repair
> $\$_{AC\_pi(i)}$ = The cost to the public (loss of productive time)

One thing which should be noted here is that most attenuators require the same amount of workspace by design. This means that $\$_{ACS(i)}$ and $\$_{ACR(i)}$ terms of the equation are independent of the attenuator. Therefore these terms will be consolidated into a single term that represents the fixed access cost ($\$_{ACF(i)}$), which is expressed in equation 7.

$$\$_{ACF(i)} = \$_{ACS(i)} + \$_{ACR(i)} \qquad\qquad \textbf{7}$$

Since the middle term ($\$_{ACM(i)}(t_i)$) is dependent on repair time duration it has both a product specific element as well as a location specific component. In many cases, this term only consists of a small hourly rate for the vehicles which are strategically placed to aid in traffic management. The personnel who drove the vehicles to the site typically aid in the actual repair and are accounted for in the repair cost. The public impact cost is the most difficult term to quantify. In most areas, the cost impact is minimal. However in congested metro areas, public impact costs alone might be the most significant factor. In summary, the access costs can be expressed as shown in equation 8 by substituting equation 7 into equation 6.

$$\$_{AC(i)} = \$_{ACF(i)} + \$_{ACM(i)}(t_i) + \$_{AC\_pi(i)}(t_i) \qquad\qquad \textbf{8}$$

It should also be noted that since the cost to setup and remove the traffic control from a given site is independent of the impact, the subscript 'i' can be omitted. Assigning any numerical value to the time dependant public impact term would have to be done on a case by case basis. Estimating the cost to maintain the traffic control ($\$_{ACM(i)}$) could easily be done by understanding the site's traffic control plan and the duration of the repair. This term is intended to encompass the cost associated with the people and equipment required for traffic control but do not directly involved with the physical repair of the product.

Although the fixed access cost has been treated in equation 8 as essentially independent of the attenuator, there are some aspects of specific attenuators which could influence this portion as well. If a product is impacted and has no remaining energy absorbing capability, an emergency closure could be required. This could have significant impact on the fixed access cost in comparison to a product that still has some energy absorbing capacity after an impact. This may allow maintenance to perform the repair at a time when the access cost will be reduced as well as allowing them to make the repair at a time which places the worker at significantly less risk.

7

The next issue to realize is that while the fixed access cost essentially remains constant regardless of the level of impact (as well as the specific product), the parts, labor, equipment, and time required for a repair are a reflection of the level of impact. This is outlined in equation 9 below.

$$\$_{R(i)} = \$_{RL(i)} + \$_{RP(i)} + \$_{RE(i)} \qquad \qquad \textbf{9}$$

where

$\$_{RL(i)}$ = Cost of labor for the specific repair
$\$_{RP(i)}$ = Cost of parts for the specific repair
$\$_{RE(i)}$ = Cost of equipment for the specific repair

By substituting equations 7, 8, and 9 into equation 2 yields equation 10 below.

$$\$_{LC} = \$_{Inst} + \$_{Main} + \sum_{i=1}^{n}\left(\$_{ACF} + \$_{AC\_pi(i)}(t_i) + \$_{ACM(i)}(t_i) + \$_{RL(i)} + \$_{RP(i)} + \$_{RE(i)}\right) \qquad \textbf{10}$$

NOTE the elimination on the subscript "i" to the fixed access cost ($\$_{ACF}$)

Equation 10 can be rewritten as equation 11 as shown.

$$\$_{LC} = \$_{Inst} + \$_{Main} + n * \$_{ACF} + \sum_{i=1}^{n}\frac{\$_{AC\_pi(i)}(t_i)}{+}\sum_{i}^{n}\$_{ACM(i)}(t_i)$$
$$+ \sum_{i=1}^{n}\left(\$_{RL(i)} + \$_{RP(i)} + \$_{RE(i)}\right) \qquad \textbf{11}$$

There are two major issues with this formulation of life-cycle cost. The first is that in order to calculate the life-cycle cost a continuous curve of cost vs. impact energy would need to be determined as well as a similar curve for repair times vs. impact energy. Theoretically this could be accomplished; however, it would be tedious and expensive endeavor. The other problem is that the likelihood that a designer will be able to predict the number of impacts and the magnitude of each one in representative fashion is unreasonable. There are no current means to predict or measure attenuator impact magnitudes at any useful level of detail. Both of these issues actually combine to form a reasonable solution to a problem.

If we look at real world cost data and subtract the access costs, an estimate for the sum total of repair cost for a single impact can be obtained. If enough repair cost data is collected for a specific attenuator a reasonable number for the average cost of repair can be determined by applying equation 12 below.

8

$$\$_{\overline{RCost}} = \frac{\sum_{i=1}^{m}\left(\$_{RL(i)} + \$_{RP(i)} + \$_{RE(i)}\right)}{m} \qquad \textbf{12}$$

where

$\$_{\overline{RCost}}$ = The typical impact bare repair cost
m = The number of impacts included in the calculation.

As the number of data points collected (m) increases, the value of the average repair cost will converge to a value which represents the cost of a typical impact repair. In an effort to have a reasonable estimate for the average repair cost ($\$_{\overline{RCost}}$), it is important to filter out any impacts which are clearly outside the intended design range and therefore, are considered outliers. This filtering process will be somewhat qualitative since the exact details of an impact which could be used to determine if a specific impact is within the design range will be unavailable. The intent of this filtering process is to remove extreme impacts which are clearly in excess of a TL-3 rating based on the damaged state of the attenuator and would unfairly skew the average repair cost value. This is not to say that the costs associated with outliers should be thrown out entirely, they should simply be omitted from the calculation of $\$_{\overline{RCost}}$ from equation 12. Having access to the outlier cost may be useful to designers during the selection process in cases where there is a higher probability of an outlier impact.

Similarly, the same could be done in order to calculate typical repair times ($\overline{t}$) as shown in equation 13 below.

$$\overline{t} = \frac{\sum_{i=1}^{m} t_i}{m} \qquad \textbf{13}$$

The average time of repair ($\overline{t}$) is somewhat problematical to quantify. The difficulty is that the more appropriate unit of measure for the time of repair is to look at man hours. The trade-off is that other key time reference aspects such as public impact and the cost of maintaining the work zone, are functions of absolute time. It stands to reason that the absolute value of time will decrease as more people help on the repair. In terms of number of people involved in the repair, there are two key points. One point is the minimum number of workers. This represents the fact that there are a minimum number of people required for the repair. The other key point is the optimal point. Obviously as the number of people involved in the repair increases, the time it takes to repair the system will presumably decrease. However, there is a limit to this effect as there are only so many things that can be done at one time. The optimal point is the point where adding another worker will yield a negligible reduction in the absolute repair time. The assumption that is made in the formulation above is that the repair is performed at this optimal point. The man-hours portion associated with labor is the $\$_{RL}$ portion of the $\$_{\overline{RCost}}$ term discussed above, which is related to the integral under the curve in the Figure 3 below. The only place where $\overline{t}$ is relevant is when the public impact and the cost of maintaining the site access is included in the life-cycle cost.

9
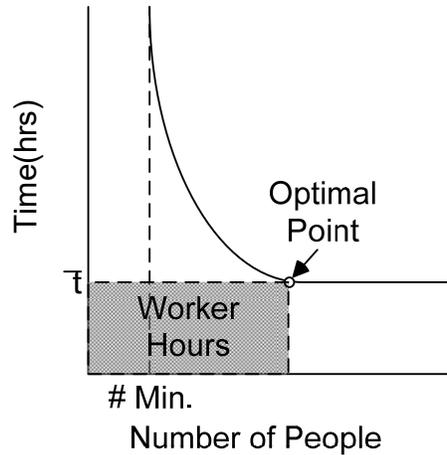
Figure 3: Optimal number of people for repair efficiency

The point is that the value of $\bar{t}$ that is computed based on product repairs will correspond to the optimal repair time. This can then be a reasonable approximation for the estimation public impact and the traffic control maintenance portion on the repair cost.

The logic presented above would suggest that there should be a fixed number of people for a repair which can be rigidly defined and become a standard based on the product which is being repair. However, due to the fact that each site has enough subtle differences, the optimal number of people will vary slightly. By creating a specification for the exact number of people to repair a particular product, it may force people to do things that are inefficient for a particular site. Since the time and repair cost are based on averages, this subtle variation in the optimum point will even out once sufficient data is collected.

Now that $\bar{t}$ is defined, it is important to look back at the cost of maintaining the work zone. Specifically the $ACM(i)t(i) portion of equation 11. The cost of maintaining access to the work zone ($ACM(i)) can also be simplified. This term is a location specific fixed hourly rate based on the traffic control plan that is independent of the level of impact. Mathematically, this can be represented by equation 14.

$$\$_{ACM(i)} = \$_{ACM} \qquad\qquad \textbf{14}$$

This term consists of the additional resources that are being utilized to maintain a safe working environment for the people performing the repair. The time associated with each repair ($t_{(i)}$) is product dependant and can be quantified by using the product specific value "$\bar{t}$" from equation 13 This then turns the term in equation 11 into equation 15 below.

$$\sum_{1}^{n} \$_{ACM(i)} t_{(i)} = n\$_{ACM}\bar{t} \qquad\qquad \textbf{15}$$

Incorporating the equations 12, 13, and 15 into equation 11, the life-cycle cost can be expressed by equation 16.

10

$$\$_{LC} = \$_{Inst} + \$_{Main} + n\left(\$_{ACF} + \$_{ACM}\left(\bar{t}\right) + \$_{AC\_pi}\left(\bar{t}\right) + \$_{\overline{RCost}}\right) \qquad \textbf{16}$$

In this formulation, 'n' represents the number of typical impacts. By averaging the repair cost and the repair time across a multitude of impacts with varying magnitude, the value "n" can be correlated to a typical impact. It should also be noted that the public impact term (which is extremely qualitative), can also be treated as a location specific value that is influenced by the average time of repair.

Now the maintenance cost term can be explored and expanded. In order to perform any maintenance on a product the location must be accessed. Therefore the fixed access cost must be factored into this part of the equation. The vendor of the product will have information regarding a maintenance schedule. This means the maintenance costs can be expressed as shown in equation 17.

$$\$_{Main} = f_{Main} * X_{years}\left(\$_{ACF} + \$_{MR} + \$_{ACM}\left(t_R\right)\right) \qquad \textbf{17}$$

where

> $f_{Main.}$ = the maintenance frequency
> $\$_{MR}$ = costs associated with the vendor's suggested maintenance routine
> t_r = time it takes to perform the required maintenance

There is an argument to eliminate the maintenance term to the equation. The argument is that most maintenance districts do not have the resources to perform routine maintenance. However, it seems reasonable to assume that there are products which should be checked (however briefly) to make sure there is no debris in the moving components of the system. In order to allow for a situation when this does become relevant, the equation includes maintenance. In cases where routine maintenance costs are irrelevant the "$f_{Main.}$" term could easily be set to zero, and thus excluding it from the life-cycle cost computation.

Equation 17 can be substituted into equation 16 above, yielding equation 18 below.

$$\$_{LC} = \$_{Inst} + f_{Main} X_{years}\left(\$_{ACF} + \$_{MR} + \$_{ACM}\left(t_r\right)\right)$$
$$+ n\left(\$_{ACF} + \$_{ACM}\left(\bar{t}\right) + \$_{AC\_pi}\left(\bar{t}\right) + \$_{\overline{RCost}}\right) \qquad \textbf{18}$$

One of the last key properties to recognize is that some products will require additional access trips in order to evaluate the extent of the damage and to ensure that when the actual repair is scheduled, all of the required parts are on hand. The actual time to be physically inspecting the system in order to evaluate the extent of the damage is relatively small, but the access cost could be appreciable. An additional cost term needs to be attributed to attenuator products which routinely require these extra trips for damage assessment. The cost is associated to site access, but is exclusively product specific. The way this will be incorporated into the formulation is to introduce an access cost modifier (m_{ac}) to quantify this aspect of product repair. The access cost modifier can be explicitly expressed by equation 20 below.

11

$$m_{ac} = \frac{\#_{visits}}{\#_{impacts}} \qquad\qquad \textbf{19}$$

It should also be noted that for a specific site, it may make sense to have a fractional value to the number of access visits. For example, maybe the repair requires full traffic control but in order to assess the damage the cost of traffic control was cut in half. This would mean the m_{ac} is 1.5. The m_{ac} term can be incorporated into equation 18 as shown in the equation 20.

$$\$_{LC} = \$_{Inst} + f_{Main} * X_{years}\left(\$_{ACF} + \$_{MR} + \$_{ACM}(t_r)\right) +$$
$$n\left(m_{ac} * \$_{ACF} + \$_{ACM}\left(\bar{t}\right) + \$_{AC\_pi}\left(\bar{t}\right) + \$_{\overline{RCost}}\right) \qquad\qquad \textbf{20}$$

Attenuator products considered to be resettable would have a m_{ac} value close to one and repairable products would have a m_{ac} factor closer to two since an extensive inspection would be required for most every repair. Product specific m_{ac} terms will be calculated from Caltrans repair data. The access cost modifier term also accounts for less conventional repair costs. For instance there could be a case where the system is resettable (which requires no prior system inspection), and upon performing the system reset, additional parts are required and another visit is warranted. This situation would cause product m_{ac} to rise above one accordingly. It should also be noted that in the case of a sacrificial attenuator, the m_{ac} would also be close to one as it is understood that once hit, a complete system replacement is required. This means that this metric alone cannot be used to justify inclusion into the severe duty category.

Equation 20 represents a generic form of attenuator life cycle cost. The practical application of life cycle costs ordinarily includes a time basis such as a time of reference, or expected service life. The time aspect is introduced inherently through the form of the number of impacts, which is a value provided by the user. Consequently, the formula can express life cycle costs in almost any user defined time frame to make product comparisons and evaluations. In order to utilize equation 20, numbers for any combination of two of the variables from equation 4 must be defined.

Estimating the installation cost is straightforward. The fixed portion of the access cost as well as the access maintenance rate ($\$_{ACM}$) can be easily quantified by designers familiar with the area and are the most qualified to do so. Based on their experience, they know what the location specific work zone requirements are, traffic mitigation issues, and required maintenance resources. They also are best prepared to estimate number of expected impacts based on site history and tools are available to assist them with this task. The number of impacts the system is subjected to over the useful life can be estimated by understanding the specific location. The site specific public impact cost is a difficult term to quantify since it is a very qualitative term. However in some instances, the public impact could be significant enough that it will have a major influence in the selection process. $\bar{t}$, m_{ac}, and $\$_{\overline{RCost}}$ are all terms that can be determined by looking at cost reports and speaking with maintenance personnel. The other terms in the equation ($f_{main.}$ and $\$_{MR}$) are easily quantified by communication with the vendor.

In summary, equation 20 above is a reasonable way to approximate the life-cycle cost of an attenuator. Table 1 summarizes the key variables and sites potential sources of information. This

formulation presented here systematically breaks down attenuator life-cycle cost in a manner which isolates the location specific attributes from the product specific attributes. This is done to facilitate an objective comparison between different products/categories.

Table 1: List of variables used in the life-cycle cost formula 20

Parameter	Definition (units)	Source	Key aspect
f_{Main}	Frequency of required maintenance visits (#/year)	Vendor specification	Product/category Specific
$\$_{Inst}$	Cost of installation ($)	Contract history Vendor estimates	Product/category Specific
$\$_{MR}$	Cost incurred by performing the required maintenance ($/#)	Vendor estimates	Product/category specific
t_r	Time is takes to perform required maintenance (time)	Vendor estimates Direct/indirect data	Product/category specific
$\bar{t}$	The average time of repair once the traffic control is in place (time)	Vendor estimates Direct/indirect data	Product/category specific
$\$_{\overline{RCost}}$	The average cost of repair after traffic control is set up. ($/#)	Vendor estimates Direct/indirect data	Product/category specific
$\$_{ACF}$	The site access cost which would include setup and removal of the traffic control plan($/#)	Direct/indirect data can be used to guide the designer's estimates	Location specific
$\$_{AC\_pi}(\bar{t})$	The time dependant public interest cost ($/(# time))	Designer estimates	Location specific
X_{years}	The number of years which is considered the design life of the location. (time)	Standard	Standard
n	Number of estimated impacts (#)	Direct/indirect data based on site history. can guide the designer's estimate	Location specific
$\$_{ACM}(\bar{t})$	The cost of maintaining access to the location. ($/#)	Direct/indirect data can serve as a guide the designer's estimates.	Location specific
m_{ac}	Access cost modifier	Direct/indirect data	Product specific

The Un-quantifiable Parameters

The above analysis is based on parameters which are well understood and quantifiable entities. Many more parameters could be indentified which have a less significant influence on attenuator life cycle costs, or have an indirect relationship. In either case, these additional parameters would be very difficult to quantify. The above formulation can also be considered an initial framework for understanding what data to collect. As more information is collected, the framework can be refined to better fit the data and hence be more realistic.

One parameter not specifically identified in the formula is a numerical value associated with safety. The access cost value is essentially defined as the cost to safely access the attenuator site on the highway and therefore does not warrant a separate or unique parameter. The access cost is comprised of all traffic control countermeasures, worker protection equipment, additional manpower, and off schedule work hours required to safely access the site. In summary, there in no explicit parameter which is dubbed "the worker safety cost", however, this is somewhat indirectly captured in the access cost parameter.

Another un-quantifiable parameter is the notion of product uniformity. The possible benefit is that as maintenance crews become more familiar with the uniform product, repair efficiency will naturally increase as represented by a reduction of $\bar{t}$ from above. Another benefit of product uniformity which is not quantifiable is the notion that the spare parts inventory can be better optimized and/or maintained. Having an extensive parts inventory for a few products vs. a minimal parts inventory for a wide range of products will allow for a greater likelihood that replacement parts will be readily available and that the time between impact and repair will be reduced. This time represents a qualitative risk to the public. It should also be noted that in the case of severe duty products, this public risk factor would also be reduced. However, this is a very subjective concern.

The form of the equation that is being implemented by the simulation tool will not include maintenance initially. The reason for that is because there is no real sense on weather or not this is part of the life-cycle cost in reality. During the next phase of the project, this issue will be looked at in order to better understand the effect on the life-cycle cost. This notion reduces equation 20 to equation 21 given below.

$$\$_{LC} = \$_{Inst} + n\left(m_{ac} * \$_{ACF} + \$_{ACM}\left(\bar{t}\right) + \$_{AC\_pi}\left(\bar{t}\right) + \$_{\overline{RCost}}\right) \qquad \textbf{21}$$

The public interest cost is also an unquantifiable cost. One of the key difficulties of this is that it is purely qualitative. The term was included in the formulation above as it is important to explicitly keep in mind. This term encompasses the loss in productive time by the general public for their daily endeavors.

LIFE CYCLE COST DATA

Life Cycle Data Generation

As with any formula, the correctness of its calculations is entirely dependent upon the accuracy of the data it is based upon. The evaluation of attenuator Life Cycle Costs using this equation is likewise based, in large part, on different aspects of the in-service costs. To generate data sufficiently detailed to accurately predict in-service costs, the source of the data has to be based entirely on actual documented costs, not engineering estimates. Caltrans construction bids and in-service maintenance IMMS records will provide the raw data, but the breakdown between different aspects of the costs is not always clear. For example, IMMS labor costs are typically provided in total and not divided between tasks, i.e. traffic control, attenuator repair, etcetera. Therefore, an analysis has to be conducted on much of data to obtain legitimate values. In addition some aspects of cost can be product specific such as the installation cost, while others such as repair cost are far too complex to be reported on a product specific basis. Therefore, each of these data sets may have unique, collection, filtering and statistical approaches to retain the integrity of the overall calculated result.

Product Specific Data

The installation cost is a product specific data value which can which can be easily evaluated. A simple source would be to look at the bids for several new installations and understand the

costs associated with the installation of the attenuator. This will require studying the bid information to isolate the attenuator installation cost as often times this is a small part of a larger project. Since this is how products are already selected, this portion of the life-cycle cost is the easiest to quantify.

Evaluations of attenuator specific repair costs are an altogether different matter. All the relevant attenuator impact and repair data which is available, or which will be collected is attenuator specific and unique. Furthermore, each highway site has unique characteristics which alter an attenuators performance data. Therefore if data accuracy was the primary objective of this study, each attenuator would be evaluated individually and based on some type of site characteristic rubric. Logically then from this information, a ranking could be determined, which identified the best product specific cost value. To accomplish this level of detail to a high degree of confidence would require an enormous long term research effort and a tremendous amount of cost. Additionally, it would be expected that the complex calculation itself would be continually disputed by product manufactures whose data results were consistently unfavorable. Given the modest size of this study and the expected purpose of developing a tool Caltrans designers could use near term, clearly individual product level detail would not be practical.

Attenuator Categories Data

The logic of grouping attenuator product designs by function was explained in detail in the methodology section of this report. Determining attenuator in-service cost data by categories is far more consistent with the Caltrans policy which favors identification of multiple acceptable products over the practice of determining the best single product. Evaluation of data on a product group basis is obviously less precise, but when filtered through pragmatic analysis can produce results which are more accurate overall. Collected data is still generally product related, but identifying data types which are analogous to other products within a mutual category and contrast to other categories, vastly reduces the scale of the required data collection effort. Modes of operation, repair/reset characteristics and replacement parts inventories are examples of various potential distinctive category specific data domains.

ATTENUATOR CATEGORIES

A process for how to include products in the appropriate categories and have their data integrate with the system is important. First, adding repair information to the crash testing requirements would serve as a mechanism to initially categorize a product and incorporate some preliminary numbers for that particular product into the CAL-Cost system. The preliminary category placement would be on a provisional basis and would need to be monitored for product placement validation. For products which are already approved, the IMMS data could be utilized for the same purpose in order to crudely understand a product's repair cost and hence establish a preliminary categorization which would then require additional impact monitoring for validation. Meanwhile, direct data based on in-service costs could be collected and understood to allow the tool to utilize more robust data. However, in order to fully understand how to categorize products a basic understanding of how they perform is vital. In an effort to shed light on this the "modes of operation" concept was developed.

Mode of Operation

The mode of operation refers to the resulting state of the attenuator after an impact in respect to recovery. This attribute is directly coupled to the repair cost which is one of three primary factors dictating life cycle costs. The concept of mode of operation is a way to logically portray how bare repair cost data is to be presented. Attenuator specific characteristics and the impact vector determine which one of the four modes of operation results. The common operational modes are defined as, Self-Restoring, Resettable, Repairable, and Sacrificial.
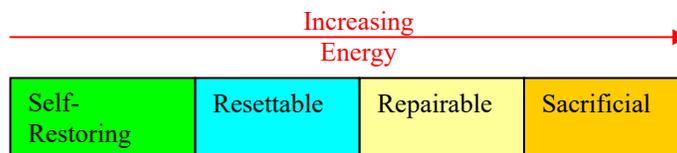
Figure 4: General graph of the modes of operation

Figure 4 shows a general plot of how an attenuator's resulting mode of operation varies as impact energy increases. Although Figure 4 shows the regions being somewhat equal, the distribution is entirely attenuator dependant. In addition, some operational modes do not apply to certain types of attenuators in a practical application. For instance, if a sand barrel is hit by someone on a bicycle, the sand barrel will in all likelihood operate as self-restoring. This example illustrates a case with very low impact energy that is outside the range of impacts typically seen on the highway. It is helpful to band the mode of operation graph with a practical working range as shown in Figure 5. The lower limit of this range is not well defined. However the upper limit of this can be typically designated by the TL-3 NCHRP test level, which is the common standard.
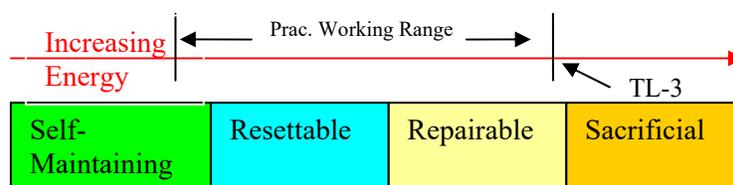
Figure 5: Banded mode of operations profile

Considering the example of a sand barrel again, the practical working range is almost entirely encompassed in the sacrificial mode of operation and the other modes do not occur. Figure 6 illustrates how the practical working range of common attenuators would appear. According to the currently accepted Caltrans categories, Attenuators A, B, and C would all be considered repairable and the sand barrel would be sacrificial. The practical working range of a typical repairable attenuator would look something like Attenuator A. Current products considered to be severe duty would have a practical working ranges similar to Attenuators B and C. The practical working range of an ideal severe duty attenuator would operate almost entirely in the Self-Restoring range. At present none of the attenuators on the Caltrans accepted products list can be officially considered Self-Restoring.

16
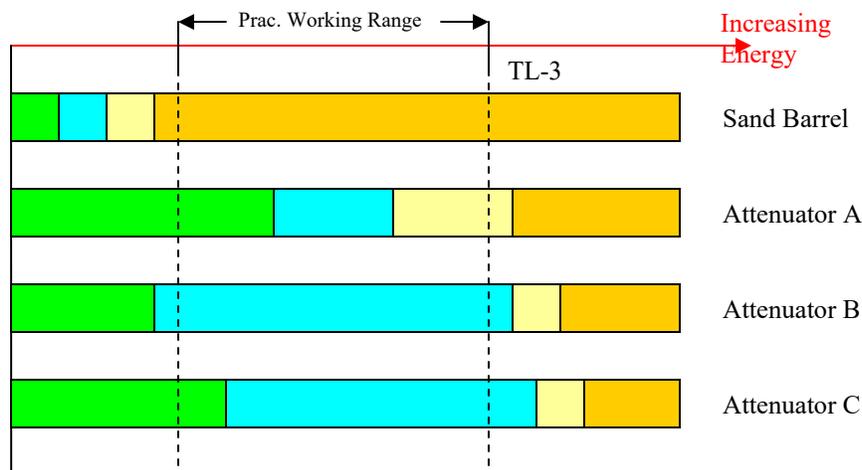
Figure 6: Representation of the mode of operation profile for various products (use Figure 5 as legend)

Mode of Operations Definitions

Considering modes of operation states and practical working ranges is a useful technique in characterizing the differences between attenuator function, but data isn't currently available to make exact evaluations. Additionally, collecting accurate data to quantify these graphs in detail would be a very time consuming task. Understanding the basic operational profile of a specific attenuator is useful in classifying that product. In order to fully understand this operational profile, it is important to define in more detail what each of the four regions represents.

The first mode of operation is "Self-Restoring". This is when an attenuator is hit and retains full energy dissipation capability without any resetting or repairs. Few if any attenuator manufacturers certify their products to operate in this manner to near TL-3 level impacts. Illinois DOT specifies three attenuators as Self-Restoring, but a detailed explanation, or justification for this designation is not apparent. From a practical standpoint, Self-Restoring would encompass impacts which occur in the field that go unnoticed. Interviews with maintenance personnel have revealed that it is common to perform attenuator maintenance and see evidence of multiple unreported hits. In general impacts which happen in the range are often referred to as nuisance impacts which will be the convention used in this project.

The second mode of operation is the "Resettable" mode. This mode of operation encompasses attenuator impacts that occur where maintenance personal must visit the location and work on the system without the need for vendor specific replacement parts. This aspect would constitute a low $\$_{\overline{RCost}}$. These repairs typically include straightening the system. However, allowances will be made for systems which require a low cost non-proprietary part (Ex. shear pins). There are two other key aspects to this kind of attenuator impact repair that should also be noted. First, a typical repair only requires a single site visit as the repair is very common and well characterized. This would come out in the data through the determination of m_{ac}. For a resettable product, this will be a number close to 1. Second, the repairs are short in duration (in other words a low $\bar{t}$ value). The repairs made in this mode of operation are relatively prompt, as there is no waiting period to obtain repair parts from the vendor.

The third mode of operation is "Repairable". This mode of operation encompasses attenuator impacts that require extensive repair of the attenuator. Often times these repairs are a two step process. Step one is to determine what needs to be replaced and evaluate the extent of the damage. The second step is to actually perform the repair once the replacement parts are obtained. In some cases, an inventory of parts is maintained to minimize the downtime for attenuators whose practical working characteristics are primarily in this mode operation. Additionally, it is common practice to remove the damaged system and repair it under safer conditions (i.e. in the yard). Some maintenance yards also have the benefit of being able to maintain a parts inventory or have a spare system around which will reduce the downtime and potentially reduce the number of site visits (i.e. reduce the associated access cost modifier). The yards ability to have this inventory is primarily based on the physical size of the yard and the space required to house any parts inventory. This aspect is also exacerbated by the fact that there is not product uniformity within a yards maintenance region.

The last mode of operation is "Sacrificial". This mode of operation encompasses attenuator impacts where the most cost effective repair is to completely replace the system. The replacement cost is equivalent to a new installation cost. The costs associated with site preparation for the initial installation can be equated to the site cleanup costs during product replacement.

These modes of operation are important to understand as they correlate to the associated cost of the repair. The difficulty in comparing different systems is that the operating characteristics within the practical working range can be impact specific to the individual attenuator. However, by understanding in general how the attenuators typically operate, their modes of operation can be a convenient tool for comparing and contrasting different products on the market.

Mapping the modes of operation to product categories

Now that the modes of operation are well defined, it is important to clarify how the modes of operation differ from attenuator category placement. The mode of operation concept is a means to understand how a specific product performs and is basically a characterization of a products state after an impact vs. the impact energy. Due to the expense of crash testing, it would be impractical to measure the state of an attenuator for multiple levels of impact. Hence, generating a quantifiable curve is not an option. Currently attenuators are classified based on how they perform for the typical impacts they experience. For the current process, it is easy to define a product category. A product is either completely destroyed (Sacrificed) or can be repaired (Repairable). In order to distinguish the severe duty products from repairable products, a criteria needs to be defined which helps to distinguish a repairable attenuator from a severe duty product based on some mode of operation performance criteria. Product categories and the attenuator modes of operation are not necessarily synchronized. Figure 7 below graphically depicts how product categories relate to the modes of operation. The fundamental difference is that the mode of operation is a map of how a specific product operates as a function of impact energy. The category is a means of grouping products based on how they perform for a majority of the impacts the product is subjected to.

	Modes of Operation for typical impacts			
	Sacrificial	Repairable	Resettable	Self-Maintaining
Current Cat.				
Sacrificial				
Repairable				
Proposed Cat.				
Sacrificial				
Repairable				
Severe Duty				

Project Primary Goal: To explain the need/definition this category division (Future project will focus on the quantization of this)

Figure 7: Chart of categories vs. mode of operation

Figure 7 mentions one of the primary goals of this project. As a better understanding of actual repairs becomes more evident, the definition will become better defined. However, for inclusion into this category the following qualitative conditions must be met. One is that the repair must be predictable and hence only one visit to repair the system is required. The repair must take a relatively short amount of time to perform. Lastly, the majority of repairs do not require vendor specific proprietary parts. Future efforts will include a means by which to make these requirements more quantitative which will be accomplished through data collection. By developing a quantitative standard based on metrics which can be agreed upon, there will be significantly less room for dispute.

Identifying Severe Duty Classified Products

The decision to identify attenuator products as "Severe Duty" is ultimately the responsibility of State and Federal DOT engineers. The modes of operation of some products though, function unmistakably as severe duty attenuators. These products include the Energy Absorption Systems Inc. REACT350™ impact attenuator and the SCI Products Inc. Smart Cushion™ crash attenuator. These products require minimal parts for typical repairs and have a proven record of low in-service costs. Several other current and emerging products have modes of operation that may qualify them as severe duty. The focus of this report is the study of severe duty attenuators. For highway locations experiencing a greater number of hits, low in-service costs add up to significant cost reductions and can quickly justify a higher initial cost. Extending the in-service cost data list to all common attenuator products would be informative in the long term. However, proper deployment of severe duty products will yield significant short term cost savings. As discussed above, there is a clear need to establish a mechanism to distinguish between severe

19

duty products and repairable products. This report is intended to quantitatively demonstrate those needs. As data is further understood a quantitative means for the distinction between repairable and severe duty products may become apparent. Some key metrics that will be initially looked at to develop the category boundaries are m_{ac}, $\$_{\overline{RCost}}$, and $\overline{t}$ which are indicative of the level of effort to return the site to the specified NCHRP level.

Correlation Between Modes of Operation and Attenuator Categories

The concept of the modes of operation is intended to provide guidance to product categorization. As discussed in the above section the tool will focus on category averages and not product specifics. This section will explain how these averages will be computed. There are two key things that need to be done. First, products need to be categorized as shown in Figure 1. For the derivation, Table 2 will show how the categories will be denoted.

Table 2: List of category subscripts

SAC	Sacrificial
SD	Severe Duty
R	Repairable

The starting point will be equation 21. In the equation, the terms m_{ac}, $\$_{\overline{RCost}}$ and $\overline{t}$ are all location independent properties. In order to calculate the category average equations 22, 23, and 24 will be used.

$$\overline{t}_* = \sum_{i=1}^{k_*} \overline{t}_i \qquad\qquad \textbf{22}$$

$$m_{ac_*} = \sum_{i=1}^{k_*} m_{ac_i} \qquad\qquad \textbf{23}$$

$$\$_{\overline{RCost}_*} = \sum_{i=1}^{k_*} \$_{\overline{RCost}_i} \qquad\qquad \textbf{24}$$

where

        * = The subscripts denoted in Table 2
        k = The number of products within the specified category

In terms of life-cycle cost analysis this means that for a given location, there are at most 3 life-cycle cost curves to understand and that the tool which will be developed will ultimately recommend and optimum category to use. The idea is to not have the tool so structured that it favors a particular product so much so that it takes the designer's field experience out of the decision process. The idea is to let methodology serve as a logical thought process for the designer's to go though in order to both identify the best products for the specific installation without creating any additional hurdles to the implementation of those products.

LOCATION-DEPENDENT DATA

As mentioned above, there are many aspects of a specific location which play a role in the life cycle cost. This section is intended to break down many factors that should be looked at in order to reasonably assess the life-cycle cost. The section below explains many of the bigger factors to consider when looking at the site specific life-cycle costs. It should also be noted that many of this issues will affect the traffic control required for a repair and are therefore are currently considered by people who work in this area. It is also important to understand that a majority of this cost is independent of the specific product that is installed. The main goal of this section is to point out some of the bigger issues that need to be looked at in order to assess the life-cycle cost of a particular area.

Impact Frequency

The impact frequency is defined as the number of impacts which require repairs over a time frame (Ex. 12 hits/year). Initially, nuisance hits will not be addressed because documentation of these events is not currently available and their effect on life cycle cost is not well understood. Another equivalent way to represent impact frequency is the mean time between hits (MTBH) which doesn't require a qualifier time frame. The terms will be used interchangeably in this study as appropriate. The impact frequency is entirely location dependant and essentially unrelated to the type of attenuator product deployed. Every location has a unique set of properties that influence the MTBH. Developing a formulaic approach to estimate the MTBH is impractical as each site will have a very unique set of issues. It may be possible to look at the history of the specific site in order to get an estimate of the impact history. Two identified sources of this would be documented historical information, such as IMMS records, or input from the local maintenance supervisor. A more exact approach is to source data on an expected range based on a detailed understanding of site history. Averaging the expected data range then results in the most accurate site prediction data values available.

Access Data

In-service costs have been described as primarily a combination of repair cost and access cost. The access cost is defined as the resources required to merely position a repair crew safely at the attenuator. Often, the attenuator sites are extremely hazardous places where traffic diverges. The access cost is the sum total of all the expenses associated with traffic control. There are many things which impact the access cost such as: barrier vehicles, traffic advisory equipment, lane closures, ramp closures, traffic detours, nighttime and weekend operations (typically with overtime pay and associated off-duty time minimums), etcetera. These represent Caltrans direct access costs. On occasion, an attenuator is hit and presents an immediate hazard to traffic. In this case an emergency closure is required. This closure could result in traffic jams which creates additional indirect costs to the motoring public due to loss of productive time. The presence of traffic control and traffic diversions also increases the risk of traffic accidents.

The site access cost is one of the key factors that drive the life cycle cost value and also one of the easiest to quantify. Generally, the average access cost to an individual site is fixed and well understood by the local maintenance supervisor. The Caltrans maintenance manual provides

safe traffic control guidelines. The local crews can draw upon these guidelines and their extensive understanding of the location to develop the best strategy to access the site. Therefore, the most accurate access cost value will be one provided by the local maintenance supervisor. A formulaic approach could be developed for calculating access costs. This could be potentially useful tool for new construction, or if contact with the local maintenance supervisor isn't possible. The roadway geometry, standard traffic control measures, and locally available resources could all be entered in a worksheet format and evaluated to produce a theoretical cost value. For standard sites, the calculated value may be sufficient, but for sites with special circumstances, the value may be completely erroneous. For example, an attenuator located at a metro highway break point in District 11 is on a curve in the roadway such that drivers can't see traffic control in advance. To establish a standard safe work zone, the interchange would have to be closed at night and a detour provided. This would suggest an expensive access cost, but in practice the actual access cost is negligible. The local maintenance supervisor makes use of the chronic morning traffic crawl to access the attenuator with no additional traffic control required. Intangible factors like this example highlight the conclusion that the most accurate access value is typically provided by someone with intimate knowledge of the site. Imposing a strict formulaic approach to this process would hamper the ability to incorporate first hand field experience into the evaluation of the access cost.

In many conversations, the notion of having a term to quantify worker risk was mentioned. Although this is a real concern, quantifying this risk is too qualitative and would lend itself to extensive debates. However, the access cost by definition is the costs imposed by placing working in a "safe" work zone. Hence, places with higher worker risk will inherently have a higher access cost and will therefore will include some compensation for worker safety.

SPECIFIC SITE CONSIDERATIONS

The principal consideration of attenuator selection is the specific circumstances of the site. It is of common belief that a formulaic approach to attenuator selection could be generated based on geometric considerations and documented traffic patterns. Considering the large number of dependant factors needing to be integrated, to generate a strictly formulaic approach seems implausible and implicitly inaccurate. A more exact approach is to source data on an expected range based on a detailed understanding of site history. Two main factors that are driven by the specific site are the access cost ($\$_{ACF}$) and the mean time between hits (MTBH). These two factors are coupled, but have very different effects on the life cycle cost formula. To better characterize the differences, a more comprehensive understanding of them is needed.

Travelway Geometric Considerations

Geometric considerations are defined as site attributes that characterize the travelway. The key location considerations can be categorized into three main sub-types: Non-geometric, global and local geometric considerations. Non-geometric considerations encompass those properties of a location which can not easily be pointed out on a map. The driving culture, average speed and average daily traffic (ADT) are all non-geometric considerations. In many areas, there is an underlying driving culture that will influence on the number of impacts. If people tend to drive aggressively, the probability of them adjusting their driving within a work zone are reduced, giving rise to the need of greater traffic control. The typical speeds on the road will also affect

proper attenuator selection and access costs. The speeds will determine the minimum TL certification of what is installed. Additionally, the speeds affect the access cost by influencing the level of traffic control. Generally speaking, areas with a high ADT will have a higher probability of impacts. This can be seen when comparing the extreme cases of a rural location to an urban one. However, in urban areas the global and local geometric considerations will have a more significant influence on the MTBH when comparing between locations in the same urban area. From a maintenance standpoint, the ADT may place restrictions on when the work can occur. If the location is part of a high volume daily commute cycle, restrictions could be imposed as to when the repair can take place. One thing that complicates the issue is that in some areas, maintenance can take advantage of the congestion and actually reduce the level of required traffic control due to the slower congested speeds. Another key non-geometric consideration is the public impact cost. The public impact ($\$_{AC\_pi}$), as discussed above, could be significant enough to drive the selection process. However, only engineers with an understanding of the local area will be able to reasonably assess these factors. The point about the above example is that this scenario is an instance where there are a unique set of circumstances that allow for a very different approach to that site which would not be evident unless extensive knowledge of the specific location were known. This is not intended to suggest that the standard practice should be rewritten in order to make this standard practice for all locations. The situation is meant to illustrate that people who are familiar with the area may be able to find creative solutions in order to make a safer more cost effective repair.

The global geometric considerations look at the big picture of the traffic flow. There are many factors that need to be considered when looking at the global geometry. The key aspect here is to look at the traffic flow dynamics. Onramps prior to the specific location puts the general flow of traffic in a state of flux. If traffic is diverging in the vicinity of an attenuator, the likelihood of impacts increases. An extremely dynamic situation often occurs at locations where an on-ramp and off-ramp are in close proximity. At these specific locations, vehicles are trying to merge right and decelerate to get off the highway while other vehicles are trying to merge left and accelerate to the general flow of traffic. This state of flux will contribute to increasing the number of impacts. This will also greatly affect the access cost as questions will arise as to whether or not the on-ramp needs to be closed. Another key location consideration is the radius of curvature prior to the location (see Figure 8). This curvature will affect the driver's line of sight. If the driver has a good line of sight to what is going on, they will have more time to adequately respond hence lowering the number of impacts. From an access cost standpoint this will increase the need for advance notification.

Figure 8 : An attenuator located at a point where the radius of curvature reduces the visibility at the gore point. This global geometric factor would both increase the fixed access cost as well as negatively affect the MTBH.

The local geometric considerations are also important to factor in. They include the condition and width of shoulders and the amount of space between the virtual gore point and the attenuator (See Figure 9). These affect the impact distribution by being an indicator of how confined the location is. Wide shoulders and a large area between the virtual gore point and the attenuator will indicate a more open area. This would lower the number of impacts. From a maintenance standpoint, this would indicate what kind of lane closures would be needed in order to safely perform the work. Some locations may also have an issue with reverse hits. This reverse hit concern is driven by the location. Whether or not an attenuator can handle a reverse hit is part of the manufacturer's specifications, and therefore, it is either accepted or unaccepted.

Figure 9: Shows the attenuator's location and the associated virtual gore point. The virtual gore point is the point where the lane lines diverge to direct traffic. The term "virtual" is used since there is no physical barrier.

For a majority of repairs, the access cost can be considered independent of the specific product as all products have very similar workspace requirements. However, as mentioned above, there is a time component associated with the access cost portion of the equation. For

24

many situations, this term is somewhat negligible as it relates to equipment parked at strategic locations leading up to the work zone. In some special cases, this part of the access cost relates to a significant impact to the public. One example of this is an attenuator installed in district 3 that the 80 East to 99 South split shown in Figure 10.

Figure 10**: The local geometry would require significant closures. Since this location is part of a major interchange, the public impact cost of a long duration repair would be significant**

The image clearly shows that the local-geometry would require significant closures on a major freeway interchange. A long duration repair would have a huge public impact cost. This would make the time dependant portion of the access cost very significant. Due to the unquantifiable public impact cost, a severe duty attenuator may be more appropriate at this location.

Severe Duty Locations

Severe duty locations are defined as travelway sites with higher than normal in-service costs; typically as a result of high impact frequency, extreme access cost, or a combination of both factors. Several States have developed official parameters of when to classify a travelway site as severe duty. The classification is necessary to justify the deployment of severe duty attenuators, which typically have a higher initial cost, but if deployed correctly provide far better life cycle value. The Indiana DOT specification refers to sites where lateral clearance is limited. The Utah DOT requirement calls for sites where more than one impact per year is anticipated, or when repair history indicates two or more impacts over a three year period. Connecticut DOT recommends severe duty attenuators for location where a high number of incidents have occurred on high speed and high volume roadways. Illinois DOT application is where expected crashes are more than 1 in 3 years. Arizona DOT definition is for 3 vehicle impacts in any three year period on high speed roadways. Maintenance cost savings would be the most dramatic where appropriate severe duty attenuators could be matched with severe duty locations. The application of an accurate life cycle cost evaluation methodology reduces the need and dependence on arbitrary requirements to justify severe duty sites. For any given site, the evaluation and comparison of expected life cycle costs alone will show if a severe duty attenuator is appropriate.

APPLICATION OF LIFE CYCLE COSTS

Severe Duty Assessment

In practice an attenuator site gains the attention of Caltrans engineers when maintenance issues arise due to impact damage, high maintenance costs, and/or travelway changes. If the site is deemed at risk due to short MTBH, high access costs, or a combination of these factors, the site my be considered severe duty. Then to select and compare attenuators, the life cycle values for attenuators are calculated based on site specific factors. If the site doesn't necessitate a severe duty attenuator, the cost data will indicate a standard attenuator is more cost effective. A more active site will result in life cycle cost comparisons that favor higher priced severe duty attenuators. The life cycle formula will implicitly assess if a site requires a severe duty attenuator. The formula will not require the adoption of an arbitrary standard without looking at the specific location of interest.

Life Cycle Cost Calculation

Life cycle costs can be defined and represented in many different ways; the most appropriate form is determined by its intended use. The form in which the user enters the number of impacts into the formula dictates what the evaluated life cycle cost value specifically represents. Therefore, the user needs to identify initially what is the most appropriate form of life cycle cost to achieve their intended evaluation or comparison objectives. The most common form of life cycle costs includes a time basis, such as cost over a time period. The time period typically is either an arbitrary time reference value, or an expected service life. Application of this conventional approach in most cases will provide sufficient information to make an educated decision.

Upon closer examination, the practice of evaluating product life cycles based on an arbitrarily user defined time frame can effectively skew the results of life cycle product comparisons. In regards to attenuators, any time frame is fundamentally arbitrary and should be well understood when making rational attenuator comparisons and decisions. Basing life cycle costs on product expected service life is the most logical approach, but unfortunately doesn't correspond in general to the nature of attenuators. This is the case because attenuator service life is not dependent directly on time alone, but is primarily affected by impacts. Hence, in theory, a rudimentary attenuator life span model could be defined as the number of impacts it can survive before replacement. In reality a combination of the impact magnitude and the number of impacts would be a much more accurate measure of attenuator life. This could be expressed mathematically by looking at the attenuators viability (V) or ability to absorb impact energy. Every new attenuator can be thought of as having a viability potential (V_p) which is a measure of the system's functionality. The remaining viability potential (V_R) of an attenuator decreases by the relationship shown in equation 25.

$$V_R = V_P - \sum_{i=1}^{n} f\left(IE_i\right) \qquad \textbf{25}$$

where

26

V_R = The remaining viability potential
V_P = The initial viability potential
$f(IE_i)$ = The viability potential loss function

Once the remaining viability potential reaches a threshold level (0 for simplicity), attenuator replacement would be warranted. The most difficult part of the above relationship is that the viability potential loss function ($f(IE_i)$) term is extremely non-linear due to properties of the product and specific details of the impact. The following argument can be made to better illustrate the nonlinear nature the viability function. A single immense impact can wipeout any attenuator and the same attenuator could survive repeated minimal impacts indefinitely. Furthermore, since impact magnitude information is not practically attainable, defining the details of the loss function relationship would be unrealistic. Additionally, having a user predict the magnitude of impacts would also be unreasonable. Therefore, life cycle cost based on attenuator viability would be inherently inaccurate due to a combination of uncertainties in the loss equation and inaccuracies in impact magnitude prediction.

Consequently, introducing a purely arbitrary life cycle time reference for an ad hoc study period skews the comparison results. Each attenuator product design has an initial cost and unique cost performance characteristics (as described above). The estimated life cycle cost of an attenuator product uniquely changes along with the time frame. Since product comparison is the primary use of life cycle analysis, applying an arbitrary short time frame will benefit certain products while longer time frames will favor others. For example, a longer time frame reference will favor high initial cost attenuators with low in-service costs and vice versa. If there was a justification for a definite time frame this approach may be useful, but in general application, the attenuators are expected to last as long as possible, not for a foreshortened period.

A more precise, albeit less conventional method of comparison is to graph attenuator cost performance over time at a given location as shown in Figure 11. Based on these curves the designer can visualize the optimum products based on the location information provided to the selection tool.
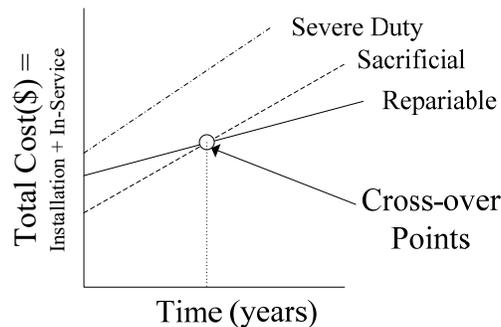

Figure 11: Example plot of life-cycle cost.

When several category cost performance curves are graphed together, attenuator performance trends and cost comparisons become more apparent. Crossover points indicate at what time interval in years of service the attenuator life-cycle cost performances are equivalent. The user can then more easily determine which side of the crossover point meets their design goals. This form makes for a more precise product comparison, but because it is less conventional it may

27

prove to be less popular with Caltrans. Ultimately, it is the responsibility of the user to understand what form of life cycle cost is most useful for their purposes and enter the site specifics accordantly.

Figure 11 shows the life cycle cost in terms of cost over time. This is the conventional way that people think of life-cycle cost. However, in this situation the most significant parameter is the number of impacts, therefore it is more relevant to look at life-cycle cost in terms on number of impacts.

Figure 12 consists of two distinct graphs plotted against the number of impacts. The upper plot on Figure 12 shows the life-cycle cost performance of each of the three categories utilizing equation 21. In addition, the lower line plot indicates the optimal category vs. the number of impacts the determination of this optimum category is explained in Appendix B. This plot is location specific as both the public interest and the access costs are included. However, the lower line graph can easily serve as a guideline for category selection. Say for instance the number of impacts is clearly above 4 at this location, a severe duty attenuator would be the clear choice. However, say the estimate is somewhere between 1-3 impacts, then the tool does not give a huge amount of guidance for the selection as there is no clear optimum product.
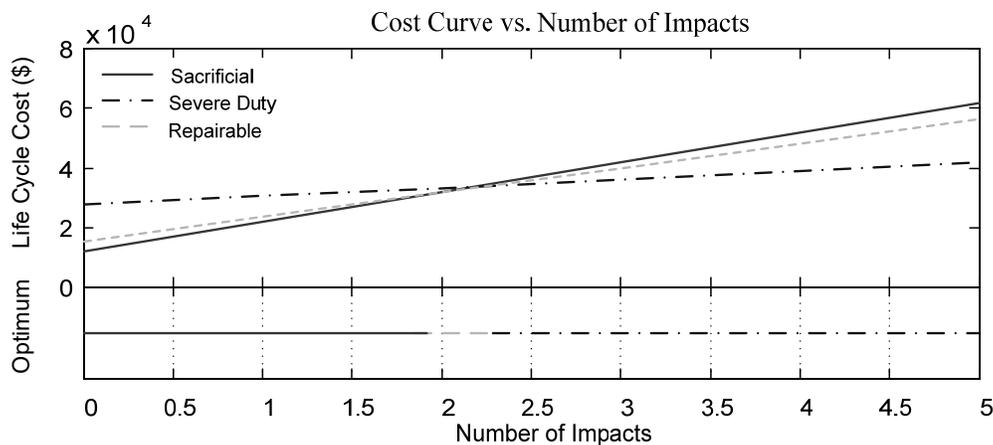

Figure 12: Plot of life-cycle cost performance vs. number of impacts

In summary, the plot shown in Figure 12 represents the life-cycle cost of an attenuator at a specific location. This life-cycle cost takes into account any additional costs due to the location. Although the temptation exists to say that any location that has over 3 impacts for the design life should in fact require a severe duty product, this generalization would not accurately represent the specific location and hence may misrepresent the access costs.

Cost Distribution

From a business perspective, another way to look at the results is to look at the cost distribution of the product's life. The cost can be broken down into 4 major categories: installation, public impact, access, and repair. Referring back to equation 21 the costs can be categorized as shown in Table 3 below.

Table 3: Life-Cycle cost distribution breakdown

$\$_{LC} = \$_{Inst} + n\left(m_{ac} * \$_{ACF} + \$_{ACM}\left(\bar{t}\right) + \$_{AC\_pi}\left(\bar{t}\right) + \$_{\overline{RCost}}\right)$	
$\$_{Inst}$	Total Installation Cost
$n\left(m_{ac} * \$_{ACF} + \$_{ACM}\left(\bar{t}\right)\right)$	Total Impact Cost
$n\left(\$_{AC\_pi}\left(\bar{t}\right)\right)$	Total Public Impact Cost
$n\left(\$_{\overline{RCost}}\right)$	Total Repair Cost

One benefit of looking at the cost in this manner is that is allows for problem optimization. By looking at cost for each category one can see that the net life-cycle cost of each category is fairly equal in the plot presented below in Figure 13. However, by looking at where the primary source of cost is, it could influence the category selection and help to identify areas of focus for cost reduction.

For instance in the scenario below in Figure 13, one can see that the fundamental difference in cost is primarily an issue of installations costs vs. the repair costs. In a situation where the current budget is limited it may be more relevant to put more emphasis on the repairable or sacrificial categories as the upfront cost will be lower and the total life cycle cost will be more of a distributed cost over time which may be preferred due to short term budget limitations.

Sacrificial : $\$_{lc}$ = $35261.41

Severe Duty : $\$_{lc}$ = $35639.31

Repairable : $\$_{lc}$ = $37729.52

Based on 1.85 Impacts over the coure of 5 yrs

The optimum choice is a Sacrificial Attenuator
Savings over a Severe Duty Attenuator = $377.90
Savings over a Repairable Attenuator = $2468.12

Repair
Installation
Public Impact
Access
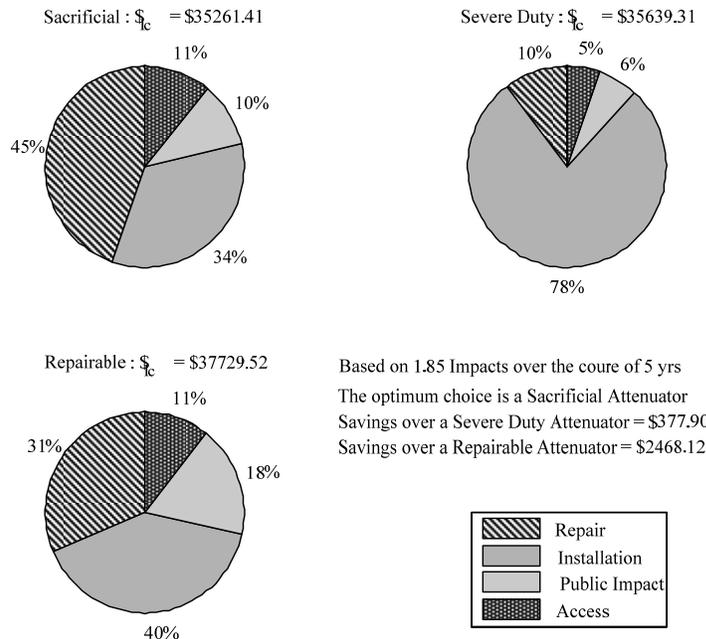
Figure 13: Cost distribution of the 3 categories

Another way that the cost distribution could be utilized is by looking at the chart and understanding the source of the cost and re-evaluating the problem. For instance, if the access

29

cost is a large contributor to the life-cycle cost, efforts could be made to reduce the access cost (such as changing the traffic control plan) in order to reduce life-cycle cost. This could be category dependant as some locations can lend themselves to short duration repairs (please note the time dependence on access cost) will require less traffic control vs. a long repair which may require a significantly more complex TCP plan.

CAL-COST IMPLEMENTATION

Tool Development

The development of attenuator life cycle cost methodology and equation was the essential first step in the creation of a tool Caltrans designers could consult to quantitatively determine the most appropriate attenuator products for a given location. It was determined that a server based interactive computer program would be the most efficient method to deploy the methodology. The software tool is called the Crash Attenuator Life-cycle Cost (CAL-Cost) program. It is not presently known if ultimately the program will be hosted by AHMCT, or Caltrans, but clearly the software is intended to continually evolve and require some level of continued research support. The contracted deliverable of this research project was to write an attenuator life cycle cost evaluation report, but the complexity of the calculations necessitated the exploration of a computer program solution. A demonstration version of a program tool is under development which calculates the CAL-Cost based on the methodology and equation described in this report together with user supplied information. The CAL-Cost evaluation is data dependant and preliminary data will be utilized to initiate the deployment process. Through trial use, the internal data values will be refined and hence, iteratively increase result accuracy. Although the above statement seems pretty simple it is important the note how important this is to data development and refinement.

Life Cycle Cost Program

The CAL-Cost program currently under development calculates life cycle costs and compares attenuators on a category basis. The results are exceedingly site specific, calculated from a determinable access cost and an expected site impact frequency. The program will prompt the user to enter site specific factors. Based on this information, the program will generate the CAL-Cost estimate and compare attenuator categories. The program output presents the findings in graphical form utilizing charts as shown in Figure 12 and Figure 13. The program output could in subsequent phases be configured to output the CAL-Cost results in the standard form of a FHWA Public Interest Finding or PIF letters to justify limiting acceptable attenuator products to those that are included in the most relevant product categories.

As repair data is collected and analyzed, this new information will be incorporated into a computer program which could serve as a collection tool and as a means to quickly and accurately distribute the repair cost information to designers. The life cycle program could potentially be developed into a web based toolbox. The web version could serve as a means to consolidate product information into a single place, summarize key aspects of the various products, and provide a gateway to access manufacturer's literature. This method would centralize the data to ensure that the data used by the program is the most current. Additional

features might include providing designers with direct access to in- service comments and repair cost information. The goal is to provide designer's with the maximum amount of information so they can select the system which is the most cost effective and meets the needs of the specific location. The form of the final life cycle cost program and the scope of features will be determined in subsequent research phases according to Caltrans' requirements.

DATA DEVELOPMENT FOR THE CAL-COST TOOL

The CAL-Cost tool will calculate predicted attenuator life cycle costs based on data, both user supplied and internally generated by the program. The program will use a module which statistically calculates the internal data figures based on acquired Caltrans actual attenuator cost data. The most significant of these internal data figures are the generated repair costs because these values are not influenced by either the user, or site considerations, but nevertheless represent the primary distinction between classification's computed attenuator life cycle cost. The determination of attenuator repair costs are not a straight forward endeavor since damage is impact dependent and it is unpractical to characterize vehicle impacts to a normal or average magnitude. Actual highway vehicle impact data is not available and an effort to record such data would be a daunting and long term endeavor.

Indirect vs. Direct Data

The fundamental difference between indirect and direct data has to do with event detection. The current process for this would be to look at the IMMS database and see the cost of a repair done on an attenuator. For indirect data, the data collection process is instigated by a repair. This kind of data is more historical in nature as the impact has happened sometime in the past. Direct data is fundamentally different as the data collection process in initiated by an impact. In order to initially develop data to implement into the tool, indirect will be implemented. However efforts will be made to identify the required instrumentation for collecting direct data.

Indirect data would be the ideal way to gather information as the infrastructure to gather this data is already in place (i.e. Caltrans already has the IMMS system in place). Unfortunately, there are some fundamental issues with the data which significantly limits its' utility. One of the difficulties of using data which has been previously collected is that there are gaps in the data. Fundamentally, the IMMS data concentrates on the overall job cost without distinction between product specific costs and location specific costs which is a primary concern in this problem. Although this issue could be reduced by calling the right maintenance people to clarify the issues, they would not completely eliminate the problem. The people of interest may not remember the exact intricacies of a specific repair, making it difficult to decouple the location costs from the repair costs. Another difficult point is that the IMMS data may or may not correctly reflect the parts that were required for the repair as often time repairs are made by utilizing salvaged components.

Another key limitation to indirect data is that in order to get the process of data collection initiated, an IMMS entry must be identified. Often times, primarily for severe duty products, small repairs often go un-entered into the IMMS database. This means that there is no record of them in the database and hence there is no documented reference to this cost benefit. These small repairs represent a huge reduction in average repair cost that will be lost if only IMMS data is

utilized. This becomes an even bigger issue if you include not only the entries which are not reported, but also the entries which are not even noticed by maintenance.

Direct data is collected by monitoring a site and collecting information on when an attenuator is hit. The best way to do this is to include some kind of impact monitoring system on the attenuator. Once an attenuator is hit, the maintenance supervisor can be contacted to help understand the repair cost and supplement any corresponding IMMS entry. This is more of a real time data collection method. This method of data collection will capture some of the cost benefit of certain products by capturing nuisance hits. It would be impossible to have data collected in a completely closed loop fashion. This is due to the plain and simple fact that cost cannot be directly measured.

One of the biggest benefits of direct data is the inclusion of nuisance hits into the repair cost calculation. On of the best ways to explain this benefit is to go back and re-examine equation 12 (Shown again below).

$$\$_{\overline{RCost}} = \frac{\sum_{i=1}^{m}\left(\$_{RL(i)} + \$_{RP(i)} + \$_{RE(i)}\right)}{m} \qquad \textbf{26}$$

The fundamental change to this equation which would affect the determination of the average repair cost is that there would be impacts for which the cost of repair parts, labor, and equipment would be zero and therefore have zero contribution to the numerator. However, a nuisance impact would increase the denominator, and hence significantly impact the average repair cost value. This same reasoning would also figure into equation 19 for the access cost modifier. In the case of a severe duty product, incorporating nuisance hits would bring to evidence the cost savings by having to set up traffic control for every impact.

Now that the effect of nuisance hits on the life-cycle cost is illustrated, there are two key aspects of impact magnitude detection which must be understood. First, a clear distinction between "noise" and a nuisance hit needs to be made. The fundamental way to accomplish this is by placing a lower threshold on the impact sensor in order to make sure that only impacts (and not system vibrations) are included into the computation of the average repair cost. This inherently means that a lower sensor threshold must be determined which will act as a as a filter for the direct data. Equally important, is to come up with a means to filter out those impacts which are outside the crash rating of the product on the upper end of the spectrum. If this upper threshold is not included, there is a chance that an extreme impact (which would in all likelihood have a relatively large associated cost) would lead to a mis-representation the average cost of repair. Communication with maintenance will aid in determining this upper threshold as well as the lower one. However, the lower threshold will be more difficult to determine as those are the impacts which often go un-noticed by maintenance. In general the impact magnitude is irrelevant for impacts which are both documented and within the crash rating of the product. Since repair costs within this range will be averaged to determine the average cost to repair an attenuator for a typical impact, the magnitude of a specific repair is irrelevant. The last aspect of using a threshold for the impact magnitude is that there may be a dependency on the direction of impact and therefore a combination of the magnitude and direction will have to be factored into the filtering process.

The primary purpose of direct data is to characterize nuisance hits. Severe duty attenuators are the most affected by these impacts. For sacrificial and repairable products, it is generally understood that there is a 1:1 ratio between hits and repairs. This is not the case for severe duty products for which the nuisance threshold is significantly higher. It should be noted that for a Smart Cushion™, the repair is relatively easy to characterize. Therefore in order to fully understand the severe duty category, it will be beneficial to better understand the nuisance threshold of a REACT attenuator as these are the two products that are initially included into this category.

Figure 14 below illustrates the fundamental difference between the two main data collection methods which is the data trigger. Future work on this project will focus on the collection of indirect data and supplement those findings with direct data. It should be clear that the direct data will allow for more accurate estimation of the average cost of repair and hence more representative of the of the over-all life cycle costs.
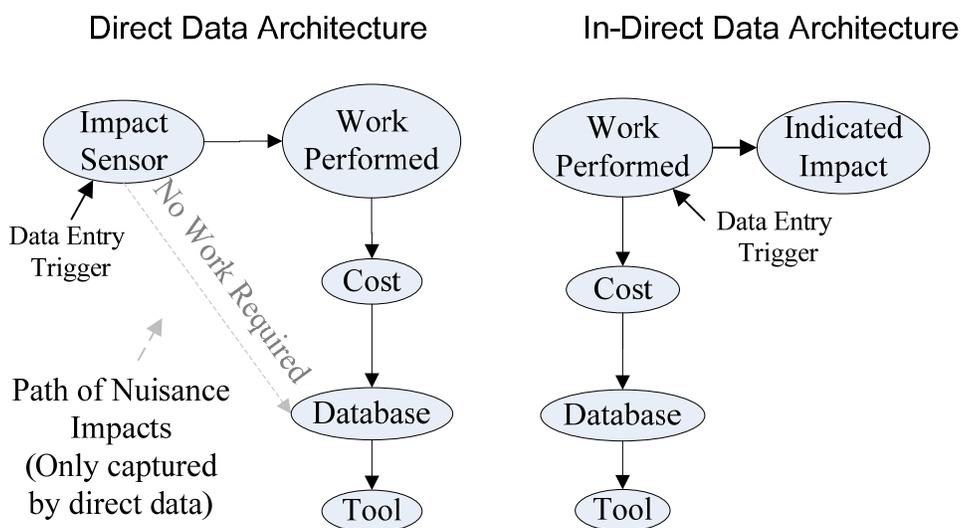
Figure 14: Data flow of direct data vs. indirect data

In order to completely understand the life-cycle cost it will be important to discuss the validity of data with the responsible maintenance party. This will require conversation with repair workers who are familiar with the repair in question. In order to minimize the time spent discussing with maintenance personnel and to have more robust data, it is helpful to develop a questionnaire/datasheet to aid in a more systematic approach to impact data collection. A draft of this questionnaire can be seen in APPENDIX C. It should also be noted that this questionnaire could be handled in two ways. One would be to simply have maintenance people have the form on hand and send it after a repair. However, this would be difficult to enforce and robustness of the data would be under question. A more reliable approach would be to fill out the questionnaire over the phone. This will allow for more reliable data and also to help make any phone conversations much shorter in duration by using the questionnaire as a guide.

In general for data development of the tool the following strategy will be considered the primary means for data development for the tool. The primary source of the data for the tool will be to methodically look at IMMS data supplemented with communication with maintenance. The

direct data will be treated as a secondary source to fill the gaps in the data which are left by indirect methods. Through the process of communicating with maintenance, an additional source, "maintenance experience" can also be brought into the system to help to develop initial values for the tool. Lastly, as the tool is deployed, the user inputs, will also serve as another data source by developing initial documentation of the user's field experience.

Crash Testing Data

There has been some discussion within the industry to establish general product repair costs in connection with the NCHRP 350 qualification testing. Currently, there is very little information reported by crash tests which represents the damage of the attenuator. The reported information is concerned with occupant safety which is of course the primary job of an attenuator. There is additional direct data which could be required in the crash testing reporting process which may aid in data development This approach has not gained in popularity, likely since this test regiment was developed devoid of any attention to repair cost evaluation and manufactures sole motivation is to pass the deceleration tests. In addition, attenuator repairs between tests can be overly excessive as the manufacturers do not want to risk failure and should not be considered to be indicative of typical repairs. Looking at post-test repair figures would be confusing as well, because without the motivation to pass additional impact tests, manufactures would be focusing on minimizing attenuator repair costs. These repair cost figures would be overly subjective. These tests are for only full test level impact's, repairs characteristics at lower impact magnitudes would still remain altogether nonexistent. However, information on the damage to the attenuator caused by NCHRP crash testing could serve as a mechanism to place the product into its initial category on a provisional basis. Obviously in-service information would have to be gathered and monitored to validate this initial placement.

Initial Data Sources

The most appropriate source for repair cost data would logically be the actual in-service maintenance costs Caltrans experiences on a regular basis. Utilizing the methodology developed in this study as the filter, a set of initial repair cost values will be independently adopted based on the best Caltrans indirect data sources at hand. Starting with initial repair cost figures will enable the tool to be deployed quicker and promote the development of additional data. Repair cost data for the severe duty category is fairly straightforward to accumulate and reasonable initial values could be developed quickly. Collecting initial repair data for repairable and sacrificial attenuators would be provided through case study appraisal on a case by case basis. The research team will have the principle task of obtaining and filtering Caltrans Maintenance data to develop initial values for the tool roll out and use as the starting point for internal data development within the CAL-Cost program. Once the tool is deployed, designers utilizing the tool could implicitly add information to the database as the tool is utilized to replace existing in-place attenuators. Supplementary research will focus on further refining data collection methods to refine the accuracy of the repair cost figures by establishing new resources for both direct and indirect repair data. Ultimately, the tool could be programmed to provide the option for users to access and examine the raw data points as well as the statistical basis of the internal data calculation.

Case Study Data

In the majority of cases, Caltrans designers would be consulting the CAL-Cost tool when replacing an existing attenuator in the field for any of a variety of reasons. The designers are looking to select the most appropriate replacement products, based on site specific life cycle cost analysis. These types of cases provide an opportunity to collect many years of indirect data in regards to site activity and product specific repair costs. An efficient strategy to develop the repair data for non severe duty attenuators would be to examine these existing unit replacement case studies to determine impact frequencies and repair costs. This type of data collection would ultimately be automatically derived by utilizing the tool and not require any extra effort by designers utilizing the tool other than the basic required information to develop a life cycle cost report. The CAL-Cost program would be designed to capture user supplied information and create case study data which after some processing would then be added to the internal data set. Initially, research staff would collaborate with the designers to utilize the tool and develop the required algorithms to correctly categorize and process the gathered data. Once the algorithms are integrated into the CAL-Cost program, designers can operate the tool independently and the data collection capabilities of the tool will be indiscernible to the user.

Case study information provides a suitable basis for determining an expected impact frequency for an existing site. Since non severe duty attenuators, by definition, must be physically reset or repaired after each impact, the impact frequency and relative impact magnitudes at these sites are reasonably well understood by local Caltrans maintenance crews. This is certainly the best possible basis for estimating future impact frequency predictions to calculate the CAL-Cost. Caltrans designers have access to this empirical impact data within their typical District communication channels which is undocumented. Through utilization of the CAL-Cost program, this data will begin to develop into a documented account which can be referenced by users in the future.

Case study data is also an excellent data source for determining repair data for non severe duty attenuators. Once again the common circumstance would be to upgrade an attenuator at a given location; therefore, a clear IMMS data record exists which chronicles actual repair cost for this product. Unfortunately these indirect cost figures represent total Caltrans Maintenance cost and not the necessary bare attenuator repair cost. The cost for crews to safely access the highway site is typically a generic per occurrence generally consistent value. Collaborating with local maintenance crews, a site access cost can be established which can be systematically removed from the total per occurrence IMMS repair cost. The remaining cost is essentially the bare repair cost, while adjusting for special circumstances. Repair events in the case of impacts exceeding TL-3 magnitudes would be an example of a special circumstance to be excluded from the data pool. It would be expected that an excessive impact determination would be fairly obvious based on damage comparison to well documented TL-3 crash tests. It should be expected that repair data could be presented on a specific product basis as a sufficient number of case study data points are determined and averaged to be considered a representative sample.

Benchmark Study Data

Determining reset/repair cost data for products in the severe duty category can be fairly straightforward for products like the Smart Cushion™, where a typical impact requires a routine

reset. This firm correlation degrades significantly when examining elastic type attenuators, like the REACT350™, which routinely returns to nearly full reset position in a relatively short amount of time after lower force impacts. The result is that many impacts with these elastic types of attenuators go unreported and unnoticed to Caltrans maintenance. Obviously these unreported impacts represent a significant cost saving to Caltrans, as opposed to a more sacrificial product which surely would have been damaged and would have required repair on the highway. For the CAL-Cost value to be equitable for severe duty category, the elastic nuisance hit cost savings needs to be evaluated and included in the repair figures. The most rigorous method of quantifying the cost savings afforded by elastic/nuisance impacts would be to directly measure attenuator impacts and compare the collected data to IMMS repair data. Direct measurement of this kind of data would require a long-term research strategy. Keeping with the theme of developing initial values in order to expedite the near-term deployment of the CAL-Cost tool, a source for immediate initial valves needed to be identified.

A protocol for benchmark studies was identified which recognizes a source where pertinent IMMS data exists which typifies elastic/nuisance impact cost savings. The benchmark locations have two requirements. First, these are sites where a nearly sacrificial type attenuator has been replaced with an elastic type of severe duty product and secondly, many years of IMMS data is obtainable for both units. If the highway site characteristics have not changed over this data period, than the IMMS data will provide a fundamental basis for quantifying reduction of repair costs for elastic/nuisance impacts. Since highway conditions have remained fairly constant then it is justifiable to assume the impact frequency average remains relatively constant. Therefore a reduction in repair events following the replacement could be attributed to elastic/nuisance impact repair cost savings, including the associated highway access cost savings. Several benchmark sites were identified and the resulting indirect cost savings figures will be averaged together to obtain an estimated cost saving value for the initial CAL-Cost deployment.

STUDY RESULTS REVIEW

The primary goal of this project is to develop a methodology and formula that accurately estimates the in service life-cycle cost of impact attenuators. The methodology and formula developed in this report was circulated to appropriate State, Federal and industry representatives in an effort to acquire reviews and suggestions. These suggestions were incorporated (where relevant) into the final project report. The primary goal of this report is to analyze data to help understand the attenuator life cycle cost and to develop a method of estimation of those costs. The next phase of this project will be primarily to collect repair cost data in order to give more meaningful numbers to the simulation tool which has been developed. Initially severe duty attenuators will be the focus of the study in an effort to maximize maintenance cost reduction. This is due to the fact that by focusing on appropriately implementing these products in short order, immediate cost savings can be realized. However, during the tool development efforts were made to easily incorporate other products into the tool. Another aspect of the tool which would be part of the next phase of the project would be to further develop the tool to allow for the development of an output report which could aid in creating the PIF package to submit to the FHWA in order to receive federal funding.

In summary by installing the correct class of attenuator to the proper location, immediate cost savings can be made. This cost savings works both ways. First, by installing a severe duty

product to areas with high impact frequencies, tremendous savings could be realized due to reduction in maintenance costs. Secondly, by systematically evaluating the location, it may reveal that a sacrificial product could be more appropriate and cost effecting. Ultimately, the most money will be saved by optimizing the category selection in a manner which allows for the location to receive the most appropriate category of attenuator.

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[3]   Federal Highway Administration (FHWA), NCHRP 350

[4]   Nebraska Transportation Center (NTC), Manual for Assessing Safety Hardware (MASH08)

[5]   Viparina, Mary "Finding in the public interest smart cushion™ impact attenuator." Letter to Kenneth Davis. 18 July 2006

APPENDIX A – DEFINITION OF ACRONYMS AND KEY TERMS

Access Cost – The total price of resources required to merely position a repair crew safely at the attenuator for even a short time. The access cost can consist of traffic control, service vehicles and personnel.

ADT – Average Daily Traffic

AHMCT – Advanced Highway Maintenance and Construction Technology Research Center

Attenuator Viability – The ability of an attenuator to absorb an impact and maintain functionality.

Bare Repair Costs – This is the repair cost of the attenuator only and does not include any form of traffic control.

CAL-Cost – Crash Attenuator Life-Cycle Cost

Caltrans – California Department of Transportation

COZEEP – Construction Zone Enhanced Enforcement Program

Cross-over Point – The time in years where the plot of life-cycle cost vs. time of two products/categories intersect or are equivalent.

DOT – Department of Transportation (Usually mentioned in association with a state)

Direct Data – This is cost data which is collected in a manner that allows it to be directly incorporated into the computation of parameters used in the life-cycle analysis. In general this encompasses data that is collected primarily for this purpose.

FHWA – Federal Highway Administration

IMMS – Caltrans Integrated Maintenance Management System

In-Service Cost – Sum of all direct post-installation costs associated with maintaining attenuator in full working order on travelway. Costs include repair, access, maintenance and replacement.

Indirect Data – This is data that have been collected for various purposes that can be used in order to help define the parameters used in the life-cycle analysis. However, as these sources are not primarily generated for the purpose of this project, they should be considered as a "best guess" estimate until sufficient direct data is collected.

Life Cycle Cost – The total cost of the attenuator which is the total of the installation cost and the in-service cost due to the amount of impacts the system is subjected to.

MASH – Manual for Assessing Safety Hardware

MAZEEP – Maintenance Zone Enhanced. Enforcement Program

Mean Time Between Hits (*MTBH*) – The mean time between hits is an inverse of the impact frequency which is expressed as the expected time interval between impacts. MTBH is calculated by dividing the historical number of impacts by the time period of the record.

Mode of Operation – The resulting state of the attenuator after an impact in respect to recovery.

MTBH – Mean Time Between Hits

NCHRP – National Cooperative Highway Research Program

QPL – Qualified Products List

Nuisance Hits – Vehicle impacts resulting in minimal attenuator damage not requiring scheduled repair work.

PIF – Public Interest Finding

Repairable Duty Attenuator – An attenuator classification that requires the product to be cost effective to repair and not replace for typical impacts.

Sacrificial Duty Attenuator – An attenuator classification where the attenuator is typically cheaper to replace instead of repair.

Severe Duty Attenuator – An attenuator classification that requires a product to be quickly reset in order to restore TL-3 certification for typical impacts. In order to be included in this category typical repair must have the following properties
1. The time it takes to perform the typical repair is well understood
2. Any parts required to repair the product are not highly specialized

Severe Duty Locations – Locations with higher than normal in-service costs; typically as a result of high impact frequency, extreme access cost, or a combination of both factors.

TCP – Traffic Control Plan

TL-3 – NCHRP Test Level 3 Designation

Virtual Gore Point – This is the point where the white lane lines from the off-ramp/on-ramp connect to the through lane line. This is useful to understand when trying to assess the accessibility of a location.

APPENDIX B – THE COMPUTATION OF THE OPTIMUM CATEGORY

For the purposes of this selection tool, there are at most 3 equations to look at. This would mean that there would be at most 3 intersection points. The three equations are presented below.

$$LC_{Sac} = m_{Sac}x + B_{Sac}$$
$$LC_R = m_R x + B_R$$
$$LC_{SD} = m_{SD}x + B_{SD}$$

As stated above, there are at most 3 intersection points. How ever this set is reduce by the number of parallel line sets. For example if $m_{Sac} = m_R$ then there would only be 2 intersection points. Now we need to solve for the intersection points in general, this is done by finding the x value which makes the following statements true:

$$LC_{Sac} - LC_R = 0$$
$$LC_{Sac} - LC_{SD} = 0$$
$$LC_R - LC_{SD} = 0$$

This is done by solving the following equation

$$\begin{Bmatrix} 0 \\ 0 \\ 0 \end{Bmatrix} = \begin{bmatrix} m_{Sac} - m_R & 0 & 0 \\ 0 & m_{Sac} - m_{SD} & 0 \\ 0 & 0 & m_R - m_{SD} \end{bmatrix} \begin{Bmatrix} x_a \\ x_b \\ x_c \end{Bmatrix} + \begin{Bmatrix} B_{Sac} - B_R \\ B_{Sac} - B_{SD} \\ B_R - B_{SD} \end{Bmatrix} = [A]\{X\} + \{B\}$$

In the case of two lines being parallel the equation would be eliminated from the system of equations above. There are two things which must be done to accomplish this. First this problem must be detected. This can be done by determining if [A] is non-singular which means the det[A]≠0. If this is true, and since [A] is diagonal, this can only be true if there is a diagonal entry of 0 or if a value for 'i' exists such that A(i,i)=0. Once 'i' is determined the equation above can be simplified by eliminating the corresponding row and column values. For example if 'i'=2

$$\begin{Bmatrix} 0 \\ 0 \\ 0 \end{Bmatrix} = \begin{bmatrix} m_{Sac} - m_R & 0 & 0 \\ 0 & m_{Sac} \; m_{SD} & 0 \\ 0 & 0 & m_R - m_{SD} \end{bmatrix} \begin{Bmatrix} x_a \\ x_b \\ x_c \end{Bmatrix} + \begin{Bmatrix} B_{SD} - B_R \\ B_{Sac} \; B_{SD} \\ B_R - B_{SD} \end{Bmatrix}$$

By the reduction illustrated below, the equation reduces to the following:

$$\begin{Bmatrix} 0 \\ 0 \end{Bmatrix} = \begin{bmatrix} m_{Sac} - m_R & 0 \\ 0 & m_R - m_{SD} \end{bmatrix} \begin{Bmatrix} x_a \\ x_c \end{Bmatrix} + \begin{Bmatrix} B_{Sac} - B_R \\ B_R - B_{SD} \end{Bmatrix}$$

It should also be noted that for the process above, this would be the smallest set of equations for our system. If 1//2 and 2//3 by deduction, we can assume that 1//3. In this case, the category with the lowest life-cycle cost would be the product with the lowest installation cost.

43

Next we need to establish our intervals of interest. The first part of this is to reorder the [X] vector in ascending order. This will be denoted as {x1 x2 x3}.

Now we need to apply some practicality to the solution. 'x' represents the number of impacts it takes to for the life cycle cost of two categories to be equal. Since we cannot have negative impacts any negative x values are thrown out. Additionally, for the purposes of the graph the tool will enforce an upper bound.
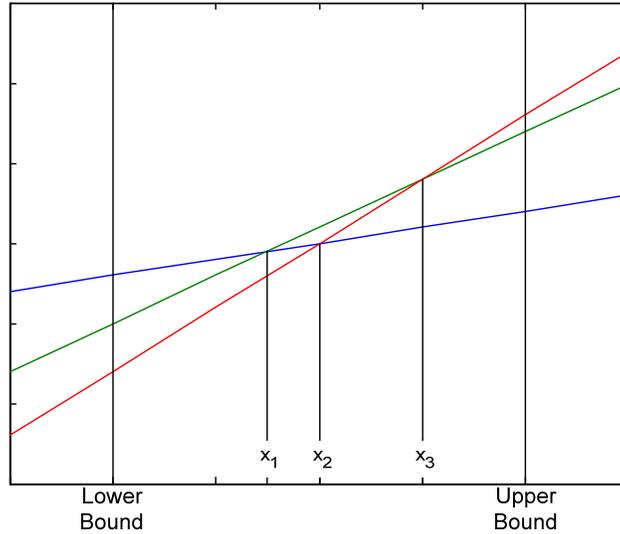
Next we need to figure out the lowest category within the intervals. If you look at the three curves throughout each interval and rank them from lowest to highest, the order will be the same anywhere on the interval. The order only changes after the lines cross at a point of intersection. The minimum value can be determined by evaluating the equation using a value of x that lies within the interval of interest and finding the minimum life cycle cost. Now looking more specifically on the interval from [Lower Bound x_1] the red graph is the lowest. Now on the interval [x_1 x_2] the green and the blue have switch, but the red line is still the optimal solution. On the next interval [x_2 x_3] the blue curve now becomes the optimum value.

44

APPENDIX C - SAMPLE DATA COLLECTION WORKSHEET

This form is intended to collect data for the impact attenuator selection tool developed by the Advanced Highway Maintenance and Construction Technology Research Center (AHMCT) at the University of California Davis. The goal of this project is to aid in the deployment of the optimum crash attenuator category for a given location based on in-service data and location specific costs. Please email completed forms to blank@ucdavis.edu or mail to :

Date:		Supervisor:	
Product:		Phone Number:	
IMMS Ref. #:		Email:	
Location	Postmile	From:	
		To:	
	GPS Lat. (Optional)		
	GPS Long. (Optional)		
	Description		
Traffic Control	Labor	# of People (setup and removal):	
		# of People (maintaining wz):	
	Equipment	# of Equipment (setup and removal):	
		# of Equipment (maintaining wz):	
		Time (setup and removal of wz):	
	Description		
Repair	Total Parts Cost:		
	Description of Parts		
		Number of People (repair only):	
		Number of Equipment (repair only):	
		Time (repair only):	
	Description		
Impact	Type (Circle One):	Side Front Unknown	
	Description		

For more information please see the report on the AHMCT website: www.ahmct.ucdavis.edu

45

APPENDIX D – SAMPLE PIF

U.S. DEPARTMENT OF TRANSPORTATION	FEDERAL HIGHWAY ADMINISTRATION	CALIFORNIA DEPARTMENT OF TRANSPORTATION

REQUEST FOR APPROVAL OF COST EFFECTIVENESS/PUBLIC INTEREST FINDING

COST EFFECTIVENESS DETERMINATION REQUIRED	PUBLIC INTEREST DETERMINATION REQUIRED
☐ Experimental Contracting methods (23 CFR 635.204) ☐ Informal Bid (Less than three week advertisement) (23 CFR 635.204) ☐ Use of force account (day labor) (23 CFR 635.204) ☐ Use of publicly owned equipment (23 CFR 635.106) ☐ Other: _____	☐ Use of State-furnished materials (23 CFR 635.407) ☐ Mandatory use of borrow/disposal sites (23 CFR 635.407) ☒ Use of patented and proprietary materials (23 CFR 635.411) ☐ Waiver to Buy America Requirements (23 CFR 635.410) ☐ Other: _____

FEDERAL-AID PROJECT NO	CLASS OF FEDERAL FUNDS ☐ IM ☒ NH ☐ STP ☐ OTHER:		
	STEWARDSHIP: ☒ STATE AUTHORIZED (EXEMPT) ☐ FULL OVERSIGHT		
EA	DIST-CO-RTE-PM	ESTIMATED COST	FEDERAL FUNDS
07-182201	07-LA-91-KP 9.7/22.7 (PM 6.0/14.1)	$70,916,000	$62,782,000

GENERAL LOCATION Route 91 From Vermont Avenue to Downey Avenue Undercrossing	GENERAL DESCRIPTION OF WORK: Replacing: the HOV AC section with PCC section, bridge approach and departure slabs, damaged PCC pavement, existing median barrier. Constructing: the ramp termini. Upgrading traffic signs and metal beam guard railing.

REASONS THAT THE REQUESTED APPROVAL IS CONSIDERED TO BE COST EFFECTIVE OR IN THE PUBLIC'S BEST INTEREST (STATE):

Crash Cushion (Type REACT 9SCBS)

This project proposes to install crash cushions at various locations to shield fixed objects with Crash cushion (Type REACT 9 SCBS) at 7 locations. The REACT 9SCBS was developed and tested as a NCHRP 350, Test Level (TL-3) crash cushion and successfully passed the Safety Performance Test. The system is quick and easy to install and maintain. It is also cheaper to replace compared to other systems available because parts of the system can be reused. Caltrans standard special provision 83-967 has been written for this item.

Since it is easy and fast to replace, it reduces the exposure of highway maintenance staff, requires minimal traffic closure time and as a result, increases public safety. Therefore, it is in the public's best interest to allow the use of crash cushion (Type REACT 9SCBS) to provide the public and CT staff with the highest safety. Use of non-pre-approved systems would result in testing delays and increased costs.

Therefore, it is in the public's best interest to allow the use of REACT 9SCBS to provide the public and the Caltrans staff with the highest safety.

APPROVED BY CALTRANS' DISTRICT REPRESENTATIVE	DISTRICT REPRESENTATIVE NAME AND TITLE:	DATE:
APPROVED BY CT FEDERAL RESOURCES REP. (State Auth. Projects)	FEDERAL RESOURCES REP. NAME AND TITLE: Randy Steen Federal Resources Engineer	DATE: 3/9/2005
REMARKS (FHWA):		
APPROVED BY FHWA'S REPRESENTATIVE (Full Oversight Projects)	REPRESENTATIVE NAME AND TITLE:	DATE:

NOTE: FHWA'S SIGNATURE NOT REQUIRED FOR STATE AUTHORIZED PROJECTS, EXCEPT FOR "BUY AMERICA".