University of California at Davis
California Department of Transportation

TEMPORARY BARRIER USAGE IN WORK ZONES

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16. Abstract

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There are currently many new and innovative barriers that have been developed in Europe and tested under the European testing standard EN 1317. These barriers are not tested to the required standard for the United States, NCHRP 350. In order to help facilitate the use of European technology in the United States, a correlation was developed to use test results from EN 1317 tests to estimate the results from NCHPR 350 test 3-11.

A two-dimensional dynamic model was created to simulate a NCHRP 350 crash test. The model was based on a crash test that was already performed to correlate the deflection and exit angle of the vehicle. The model did not accurately predict the results from the actual crash test, but it can still be used to determine the qualitative aspects of a vehicle impact. This model can be used to help analyze the new concepts that AHMCT will develop during the project for conceptualizing new mobile barrier designs.

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Executive Summary

The objective of this document is to report on the creation of a toolbox of safety barriers in order to help Caltrans more easily develop their work zone designs. The current work zone designers do not have a comprehensive set of deployment guidelines for work zone barriers. They rely on previous work zone designs and barrier deployment history. This document provides guidelines for barrier deployment in order to help Caltrans engineers more effectively develop their work zone designs.

A web based version of the toolbox of safety barriers was developed as an example of how the toolbox could be implemented within Caltrans statewide. The toolbox contains all applicable information related to barrier usage to protect temporary work zones. The toolbox is made up of multiple charts that contain information such as the NCHRP 350 test level, lateral deflection, weight, height, and other values that are of interest to the work zone designer.

This toolbox was developed as a web based application so that the most current information can be maintained and disseminated. The web based toolbox would most likely be implemented as an internal communication channel for Caltrans engineers and the work zone designers.

Deployment guidelines were created by using current crash testing information with existing information from the Federal Highway Administration. The deployment guidelines are based on a linear interpolation between two crash test points for each barrier. This interpolation is used to create an equation to calculate the deflection of the barrier. This deflection could then be used with existing documents to create an adequate buffer zone for the barrier installation. The implementation of these deployment guidelines would help Caltrans more effectively design work zones for the safety of their employees and the motoring public.

Currently there are many new and innovative barriers that have been developed in Europe and tested under the European testing standard EN 1317. These barriers are tested under different testing conditions than the required standard for the United States. All the barriers that are used in the United States need to be tested under NCHRP 350 in order to meet the correct approval conditions. In order to help facilitate the use of European technology in the United States, a correlation is developed that uses test results from EN 1317 tests to estimate the results from NCHPR 350 test 3-11. This correlation uses a similar method as that used to determine the barrier buffer zone. In order to use this correlation, a certain amount of crash test information is needed to calculate the required equation for the analysis.

A two-dimensional dynamic model is created to simulate a NCHRP 350 crash test. This model is based on a current barrier that had already undergone NCHRP 350 crash testing. The goal of the model is to determine how well a simple two-dimensional dynamic model could predict the behavior of the barrier. NCHRP 350 test 2-11 is used to determine the accuracy of the model. The model does not accurately predict the results from the actual crash test. This is mainly due to the simplifications that were used in the model in order to reduce the programming requirements. The model can still be used to determine the qualitative effects of the barrier impact. This model can also be used to help analyze the new concepts that The Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center will develop during the project for conceptualizing new mobile barrier designs.

Future research should focus on adoption and deployment of the web based toolbox of safety barriers within Caltrans. Internally, Caltrans engineers could provide more detailed and current information to the toolbox and further formalize deployment guidelines. As testing data

and product approvals are available, the toolbox could provide the means to disseminate this information throughout Caltrans. In-place barrier cost benefit data would be useful information to add to the toolbox and could be calculated internally from existing Caltrans project costs. Also a best practices forum could be linked to provide templates for barrier usage guidelines for various work zone situations. The web based toolbox approach enables such changes and features to be rapidly and easily incorporated and promptly responds to user inputs.

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Disclaimer

The research reported herein was performed as part of the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center, within the Department of Mechanical and Aeronautical Engineering at the University of California, Davis and the Division of Research and Innovation at the California Department of Transportation. It is evolutionary and voluntary. It is a cooperative venture of local, state and federal governments and universities.

The contents of this report reflect the views of the author(s) who is fare and responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the STATE OF CALIFORNIA or the FEDERAL HIGHWAY ADMINISTRATION or the UNIVERSITY OF CALIFORNIA. This report does not constitute a standard, specification, or regulation.

CHAPTER 1
INTRODUCTION

Project Outline

The number of vehicles traveling on the US roadways continues to increase on an annual basis. This increase in vehicles and traffic is causing more wear and tear that will in turn require an increase in road maintenance and construction on our highways. This will lead to an increased number of workers and motorists being at risk in the work zones. In 2003 there were 1,028 fatalities in work zones around America compared to 872 in 1999. In 2002 there were 119 fatalities in California's work zones alone. Besides the fatalities there were also other injuries that occurred which totaled over 40,000 injuries each year on America's roads [1]. With an increasing number of work zones and vehicle traffic these numbers will only continue to rise.

The California Department of Transportation (Caltrans) is in charge of overseeing all construction and maintenance activities on California's state highways. Any time roadwork is performed that is going to impact traffic, a temporary traffic control zone needs to be established. The temporary traffic control zone starts at the first construction zone warning sign and ends at the work zone termination sign. Traffic control zones can be divided up into four segments: the advance warning area, the transition area, the work space, and the termination area. The work space of the traffic control zone contains all the workers and equipment used during the activity. Whenever a work zone needs to be setup on a roadway, a work zone design needs to be created.

Caltrans' design and construction engineers are required to design the work zone to take into account safety and mobility of the personnel and equipment in the work zone. Designing the work zone can be a challenging task due to the infinite number of scenarios that are encountered and a limited number of standards and specifications for work zone layouts. The Federal Highway Administration (FHWA) has developed standards for work zone layouts, but they do not include any detailed information regarding the use of barriers or positive protection devices. Figure 1 shows a temporary traffic control zone that is divided into the typical four sections.

At this point a few basic definitions are in order. First, a barrier or traffic barrier is a device which provides a physical barrier through which a vehicle would not normally pass. Permanent barriers are designed to minimize harm to vehicle occupants; temporary barriers need also to protect construction and maintenance workers. Furthermore, temporary barriers are typically used for a relatively short duration, usually of one year or less [4]. Geometric and operational restrictions in work zones frequently preclude the use of the same design standards for barriers and terminals that apply to permanent systems.

Traffic barriers are designed so that a vehicle hitting the barrier is steered back onto the road. Concrete barriers redirect errant vehicles due to their shape; other barriers often redirect by designing supports so that they break off on impact, allowing the barrier to deform and push the vehicle back on track. All barriers either move on impact, as with concrete barriers, or deform, as with metal barriers. Accordingly, if used to protect work zones, all require a buffer zone between their placement and the area they are intended to protect.

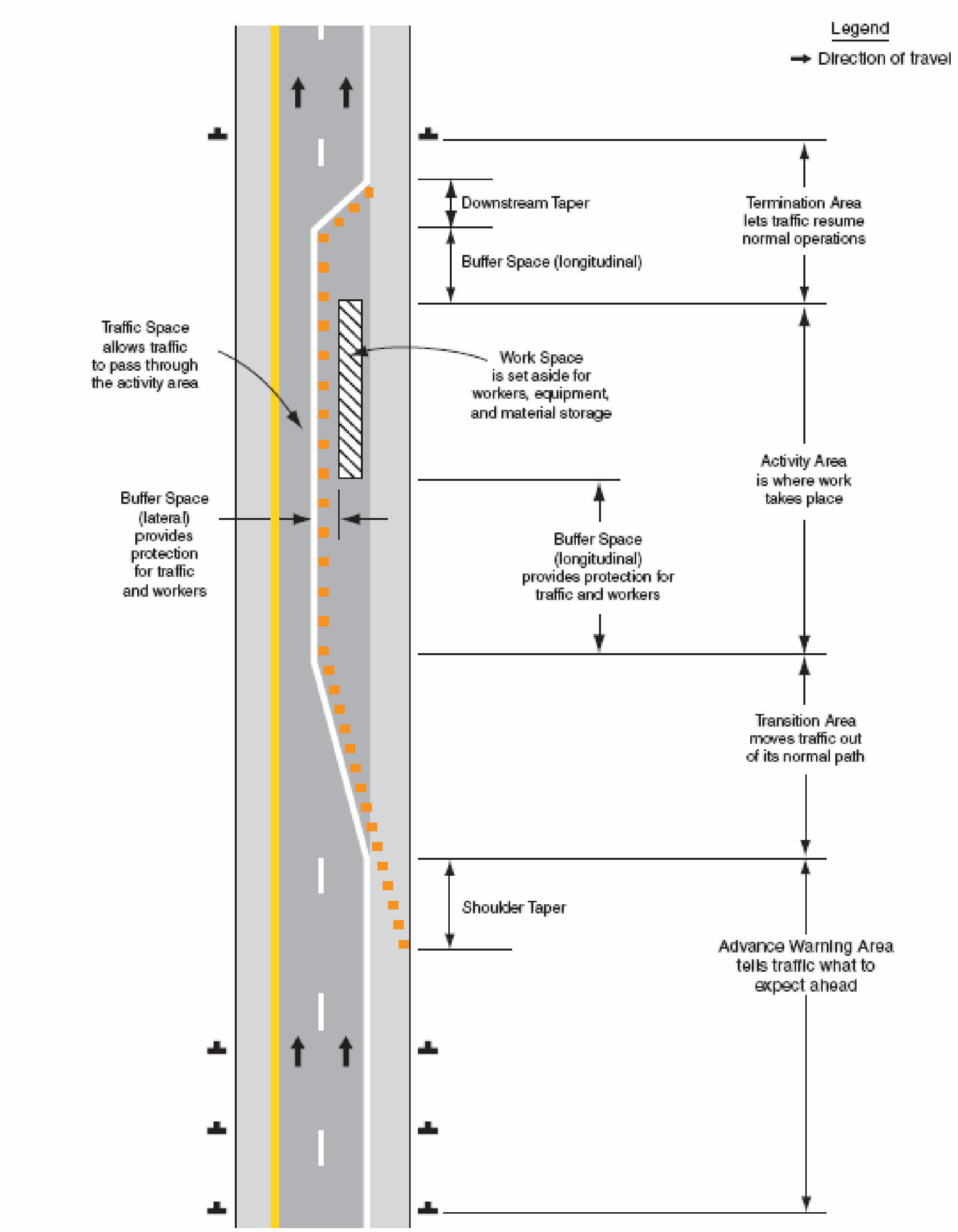


Figure 1 Component Parts of a Temporary Traffic Control Zone [2]

The guidelines for the deployment of barriers and positive protection devices are not well documented. Many design engineers have to make judgment decisions based on experience and past work zone designs for the selection and deployment of barriers. There needs to be more effective guidelines that are used to deploy these barriers in the work zones. In order to help Caltrans more effectively design their work zones, Caltrans charged the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center at UC Davis to research temporary barrier usage in work zones. The project goals were to develop a toolbox of innovative and safety barriers along with detailed guidelines for their cost effective deployment. This toolbox will help Caltrans choose the correct barrier for the selected work zone application.

Current Barriers and Guidelines

The current guidelines for the application of barriers in work zones are very limited. The only guidelines that are currently used for determining if barriers should be used in work zone applications is a benefit cost analysis. This benefit cost analysis takes into account certain road characteristics. Typically the average daily traffic volume and design speeds of a roadway are used as inputs for an algorithm. Using this data and the algorithm, unshielded work zones and work zones protected by a barrier are compared. The two setups are compared based on the costs associated with the barrier: installation, crash, and maintenance costs to the similar unshielded costs. Based on this analysis one can quantitatively determine when it is cost effective to install a barrier on a roadway [3].

The benefit cost analysis helps determine when a barrier should be used on a roadway, but it still does not help determine how to deploy the barrier on the roadway. These guidelines still do not exist and need to be developed to help aide in the deployment of barriers in work zones. The concrete barriers have a history of deployment and therefore experience makes up for the lack of deployment guidelines. However there are many new and innovative barriers that are now available and have been approved by Caltrans for use on California's state highways. The new barriers are typically steel shaped barriers. These barriers tend to have a larger lateral deflection than the concrete barriers. Due to the larger deflection, deployment guidelines are more important to insure the safety of workers and motorists. The creation of deployment guidelines for these new products would give Caltrans' engineers more choices when designing work zones plans. Having multiple choices for work zone barriers combined with deployment guidelines can make work zones safer for everyone.

Testing Standards

NCHRP 350

In order for a barrier to be used on any federal highway it first needs to be approved by the FHWA. The FHWA requires that the barrier be crash tested to ensure that it can safely contain and redirect the impact of the vehicle. The current crash test standards are set by the National Cooperative Highway Research Program (NCHRP). NCHRP 350 is the current report that is used for the safety testing of highway features. For longitudinal barriers, there are six different test levels for which a barrier can be approved. These six test levels vary based on the mass, type of vehicle, and the impact angle of the test.

The most common NCHRP test method used is referred to as Test-Level 3 (TL-3). This test method consists of two crash tests. The first test, test 3-10, consists of an 800-kg (1760 lbs) passenger vehicle moving with a speed of 100 km/hr (91 ft/sec) impacting the barrier at twenty degrees. The second test, test 3-11, uses a 2000-kg (4400 lbs) pickup truck moving at 100 km/hr (91 ft/sec) and impacting the barrier at twenty-five degrees [4]. The small car test is used to determine if the barrier is safe for the occupants of the vehicle. The occupant impact velocities and ridedown accelerations cannot exceed certain values for the test. The longitudinal and lateral impact velocities need to remain below 12 m/s (39.4 ft/s). The longitudinal and lateral ridedown accelerations need to remain below 20 g's [4]. The large pickup truck test is used to determine if the barrier will redirect the vehicle and prevent penetration into the work zone. The large vehicle is also used to determine how much the barrier will deflect laterally. This lateral deflection is important in determining when a barrier can be used for work zone applications.

In order to determine how large of an impact a barrier can withstand, the impact severity can be used. The impact severity of an impact is just the kinetic energy in the lateral direction given by

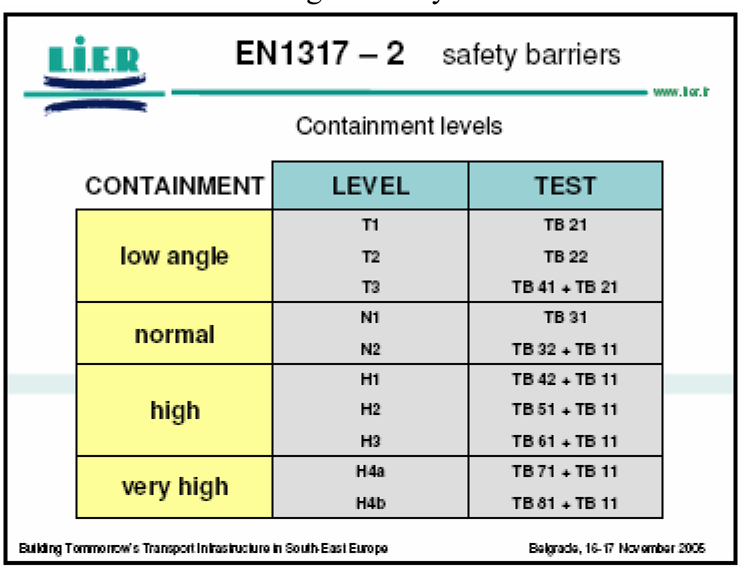
$$IS = \frac{1}{2} m (v \sin \Theta)^2 \tag{1.1}$$

where m is the mass of the vehicle, v is the velocity, and Θ is the impact angle of the crash test. This parameter can be used to determine the difference between barriers by comparing the amount of energy that has to be redirected or contained by the barrier.

The tests for NCHRP 350 TL-3 acceptance are considered the standard and benchmark tests for most barriers used on the roadways. These two tests are intended to be representative of the typical vehicles that are found on the highway. NCHRP 350 has been the standard since 1993 and since that time the vehicles and speeds of the roadways have changed and evolved. Eventually the testing standards will have to change to keep up with the changing vehicles on the roadways.

EN 1317

EN 1317 is the current standard that is used for European roadside safety devices. This testing standard differs from NCHRP 350 testing standards. The main differences relate to the type of vehicle used and the speed and angle of the vehicle in the crash tests. This difference between the European standard and the American standard is mostly due to the difference in the types of vehicles used in the respective regions. European cars tend to be smaller than American cars. Also, in Europe the roadways tend to be somewhat smaller so the expected impact angles are going to be smaller than those on the large freeways that are found in America.



CONTAINMENT	LEVEL	TEST
low angle	T1	TB 21
	T2	TB 22
	T3	TB 41 + TB 21
normal	N1	TB 31
	N2	TB 32 + TB 11
high	H1	TB 42 + TB 11
	H2	TB 51 + TB 11
	H3	TB 61 + TB 11
very high	H4a	TB 71 + TB 11
	H4b	TB 81 + TB 11

Figure 2 EN 1317 Containment Levels [5]

Figure 2 shows the containment levels and the tests that are run to test a barrier for that containment level. Figure 3 shows all the EN 1317 tests. Test TB32 is the one that is closest to the tests that are run for NCHRP 350. This test differs from test 3-11 because TB32 uses only a 1500-kg (3300 lb) car impacting the barrier at a twenty degree angle. TB32 uses a car instead of a truck and the car has less mass and impacts the barrier with a smaller angle than test 3-11. However, the speed of the vehicle is increased to 110 km/hr (100 ft/sec) instead of 100 km/hr.

This crash test does not meet the same impact severity that test 3-11 provides. The impact severity of test TB32 is much less than that of test 3-11. This causes some issues when a barrier has been tested in accordance to EN 1317, but one is interested how it will test according to NCHRP 350 test conditions. As such, a correlation between NCHRP 350 and EN 1317 is needed.

LIER

EN1317 – 2 safety barriers

www.lier.fr

Test types

	Vehicle	Mass (kg)	Speed (km/h)	Angle (°)
TB 11	Car	900	100	20
TB 21	Car	1 300	80	8
TB 22	Car	1 300	80	15
TB 31	Car	1 500	80	20
TB 32	Car	1 500	110	20
TB 41	Rigid Truck	10 000	70	8
TB 42	Rigid Truck	10 000	70	15
TB 51	Bus	13 000	70	20
TB 61	Rigid Truck	16 000	80	20
TB 71	Rigid Truck	30 000	65	20
TB 81	Articulated Truck	38 000	65	20

Building Tommorow's Transport Infrastructure in South-East Europe — Belgrade, 16-17 November 2005

Figure 3 EN 1317 Crash Tests [5]

Summary

Caltrans needs an updated and improved method to choose and deploy barriers for their work zones. There are no current charts or databases to compare certain barrier characteristics to each other. Currently all the barriers are chosen based on experience and the history of past work zones. There is also a lack of a comprehensive set of guidelines for the deployment of the barriers in the work zone. These two issues need to be addressed in order to improve the creation of work zones.

One objective of this report is to create a toolbox of safety barriers which will place all the currently approved barriers in an easy to search database to help in selecting barriers for work zone applications. Another objective is to create quantitative guidelines for determining the placement of barriers in work zones. These guidelines will help integrate the new barriers into Caltrans available barriers for work zone activities.

The remainder of this report is organized in the following manner. Chapter 2 is a description of all the current barrier designs that are available for use to add positive protection for workers and motorists. The third chapter is the presentation of the toolbox of safety barriers that can be used to help design temporary traffic control zones. Chapter 4 covers the guidelines for the deployment of temporary barriers in the work zones. The fifth chapter covers the correlation between the EN 1317 testing standard and NCHRP 350 standard. Chapter 6 is a two-dimensional dynamic model that was created to analyze how well a simple dynamic model could account for the effects of a car impacting a barrier under NCHRP 350 test conditions. Chapter 7 will provide conclusions and recommendations for further research in the area of temporary barrier usage in work zones. It will also cover some roadway issues that need to be addressed with a parallel AHMCT Research Center project in which new mobile barriers for construction and maintenance work are being conceptualized.

The following chapter will introduce the current barrier types being used on the roadways and also introduce new and innovative products. The characteristics of each barrier type will be presented along with the pros and cons of each. Deployment considerations for each barrier type will be addressed including mobility issues and work zone access. Some of the new and innovative products will be discussed with their added advantages and disadvantages. Understanding these barriers is crucial to developing a standard for the deployment of these barriers in work zones.

CHAPTER 2
TYPES OF TEMPORARY BARRIERS

This chapter introduces the different types of barriers. It is a general introduction to each type of barrier that explains the characteristics along with the advantages and disadvantages of using each type of barrier in a work zone. Each barrier type has its own characteristics that need to be accounted for when designing a work zone. Within each barrier category there are also many differences between the different barriers' performances. This chapter will only discuss the differences between the general types of barriers and the performance characteristics that each type of barrier offers.

Understanding these barrier characteristics helps when designing a work zone. Each barrier type is going to offer different levels of containment that need to be addressed when determining which type of barrier to use in a work zone. Other barrier characteristics that need to be considered are the mobility of the barrier at the work zone site and the reusability of the barrier after an impact. Depending on the work zone, the barrier installation time and cost need to be analyzed to determine if the type of barrier can be used for certain work zones. The following is a description of all the barrier characteristics to help in understanding what type of barriers should be used for certain work zones.

Concrete Barriers

The current and most widely used temporary barriers on the roadways today are concrete barriers. Concrete barriers have been used on roadways for construction for some time. They continue to be the choice for most construction projects because of their high level of containment, where containment is defined as restraining errant vehicles from entering the work zone, protection for the workers, and their relatively inexpensive cost. The one drawback of concrete barriers is their size and weight. Concrete barriers weigh a considerable amount and once they are placed in a work zone they are very hard to relocate quickly and efficiently.

There are many different types of concrete barriers that exist. These concrete barriers vary in height, width, length, weight, and shape. There are two different shapes that have become the standard for concrete barriers, the New Jersey shaped barrier and the F-Shaped barrier. The New Jersey shaped barrier is the more commonly used barrier of the two shapes, but the F-Shaped barrier is the better performing and safer of the two [6]. However, because of the wide use of the New Jersey barrier and its performance record, it is more widely used than the F-Shaped barrier. Figure 4 shows a New Jersey shaped barrier in a deformed position after a crash test.

Figure 4 Concrete Barrier [7]

These concrete barriers have some distinct advantages over other types of barriers. There is one main advantage to using concrete barriers over the other new and innovative barriers that are available; concrete barriers are typically the least expensive for long duration projects. They are generally inexpensive for the departments of transportation to buy, and they are also easy to maintain. These barriers need little or no maintenance while they are installed on a roadway. In most circumstances, if the barrier is hit while in place at a worksite, it can be easily moved back into position, for example these barriers can be moved back into position by using a crowbar or a work vehicle to push it back into line. Under most impact conditions concrete barriers are completely reusable. Most vehicles only cause cosmetic damage to the barrier during an impact and the structural integrity of the barrier is left intact. However, this can change if the impact is with a larger vehicle or at a more extreme angle. In such cases the barriers are cheap to replace. The main issue is that heavy equipment is needed to remove the old barrier and install the new section of barrier in its place. This replacement could be costly due to the large equipment that would be needed to replace the section of barrier.

Another advantage of using concrete barriers is the containment that they obtain. The containment offered by concrete barriers is the best as compared to any other type of barrier available. Concrete barriers offer a very low deflection value that is usually around 1 m (3.28 ft). This containment cannot be found in the other types of barriers. When high containment and a low deflection are needed, there is no other feasible choice besides concrete barriers.

While concrete barriers offer great containment, they do have some disadvantages. While concrete barriers are typically the least expensive, they can be less cost effective on short-term construction projects. Some projects may last a couple days while some larger projects can last for years. Concrete barriers are almost always installed on projects that last for long periods of time. However, barriers are typically not installed on short projects that only last for a few days or a couple of weeks due to the relatively large effort and cost to install the concrete barriers. Typically these projects are only protected with cones, which do not add any positive protection.

Concrete barriers are not used in moving work zones. Some work that is performed on the roadways involves work zones that need to be continually moving or stationary for a short time and then moved into a new location. Concrete barriers cannot be used for this type of work. Once concrete barriers are installed on a section of roadway, they are usually left there until the completion of the road work. Concrete barriers weigh too much and require heavy equipment in order to move them. Their use is not cost- or time-effective for moving work zones. Moving work zones employ truck mounted attenuators (TMAs) for protection.

Steel Shaped Barriers

Steel safety shaped barriers are new barriers that are available to be used on federal highways. There are two companies producing steel barriers in the United States, Barrier Systems Inc. and Energy Absorption Systems Inc. These barriers are not widely used for construction projects on the roadways. This is due to the lack of experience and historical usage information regarding these types of barriers. Figure 5 shows the Safeguard Link System deployed on the roadway.

Figure 5 Safeguard Link System [8]

There are some advantages to the steel barriers that make them an attractive choice for shielding work zones. These steel barriers are easier and cheaper to install than the concrete barriers. This is because they are lighter and easier to connect together than concrete barriers. Barrier Systems Inc. claims that their steel barrier, Safeguard Link System, can be deployed at a rate of 60.96 m (200 ft) to 91.44 m (300 ft) in 30 minutes [8]. This is much faster than what can be attained when installing a concrete barrier. For this reason, steel barriers have the added advantage that they can be setup and taken down quickly and efficiently. This makes them candidates for short term work zones that could last a few days to a couple of weeks. This would provide the positive protection to the workers while maintaining a cost effective installation process.

Some of the steel barriers are designed to be more mobile. Both the Safeguard Link System and Vulcan Barrier have wheels installed on the bottom of the barrier. This makes the barrier easily transportable at the work zone location. The barrier can be towed longitudinally along the roadway while the barrier segments remain intact. This greatly reduces the time needed to setup the barrier at the new worksite. Since the barrier is on wheels the barrier can be setup for a short duration and then towed to a new location using a work truck. The barrier can be lifted up onto the wheels by using a pneumatic attachment or a hand crank. This depends on which barrier is used. Since the barriers are on wheels, they can easily be moved around by workers unlike concrete barriers that are almost immobile once they are deployed.

Another advantage to having the barrier on wheels is that it allows for an access point into the work zone. In some of the barriers, any segment of the barrier can be opened up to allow access into the work zone. These same barriers can also be used as links between concrete barrier segments. Typical concrete barriers do not allow for access points in the middle of the barrier installation, but with the addition of a steel barrier it can create an access point wherever it is needed. This access point allows for easy access of maintenance and construction equipment into the work zone without having to enter from the beginning or the end. This makes moving equipment into and out of the work zone much easier and safer.

These steel barriers weigh less than concrete barriers. This decrease in weight means that the steel barriers are going to have a larger deflection than concrete barriers. This larger deflection could cause some concern for designers if the work zone needs very high containment. If more containment is needed and steel barriers are desired to be used for the work zone, the barriers can be anchored at the end of the segments. This would allow for a smaller deflection of the barrier and provide the work zone with higher containment than just having the barrier freestanding. If the barrier is impacted in the work zone, there is not much that needs to be done to fix the barrier. Most steel barriers under typical impact conditions will only be damaged cosmetically. The structural integrity of the barrier would normally remain intact. The barrier will need to be repositioned to reestablish the original work zone layout. This could be done by extending the wheels and pushing it back into place or by using vehicles and equipment to push the barrier back into line. Steel barriers offer a well balanced alternative to the traditional concrete barriers that are widely used on the roadway today.

Water-Filled Barriers

Water-filled barriers are another new barrier design that is starting to be used on the roadways. Water-filled barriers have not been approved by Caltrans. It is also noted that Caltrans has reviewed water-filled barriers in the past and an internal memo was sent to the Caltrans New Products Coordinator stating the intention not to review future submittals of these products due to large deflection [41].

There are many companies that are producing different types of water-filled barriers. Water-filled barriers are made in different ways. All of the water-filled barriers are made of a polyurethane shell which gives the barrier its shape. However, in order to make the barrier crashworthy as a longitudinal barrier, it needs to have some type of supports. The Triton Water Filled Barrier by Energy Absorption has a steel endoskeleton which gives it strength to contain and redirect vehicles [9]. However, some of the other water-filled barriers like the Yodock Water Wall use a steel exoskeleton to add strength to the barrier [10]. Both of these designs accomplish the same goal which is to add strength to the barrier so it can withstand an impact by a vehicle. Figure 6 shows the Triton Water-Filled barrier deployed along a roadway.

Figure 6 Triton Water-Filled Barrier [7]

Water-filled barriers have a distinct advantage over other barriers. When the barriers are empty they are very light and can be moved around quickly and easily. Single units of most water-filled barriers weigh less than 90.7 kg (200 lbs) when empty. Barriers this light can be moved around by a single individual without the need for heavy machinery and equipment. This lightweight makes the installation of these water-filled barriers a lot cheaper and quicker than concrete or steel barriers. However, there are some issues that arise with water-filled barriers because they have to be filled with water.

One installation issue that arises with water-filled barriers is that water needs to be transported out to the work site to fill the barriers. This is an added factor that is not needed for the other types of barriers. Depending on the installation length, more than one water truck may be needed to bring enough water to the work zone. Another issue that arises when the water is added to the barrier is that the barriers gain a lot of weight. Once the barriers are filled with water they are then like concrete barriers. They cannot be moved without large equipment or without draining the water out of the barrier. Draining the water out of the barrier in order to move the barrier is not efficient. Another issue that is present with the water is where the water goes when the barriers need to be emptied. The easiest and most cost effective method for draining the barriers would be to pull the plug and let the water drain out. However in some states, especially in California, this is considered to be an environmental hazard. If it is an environmental hazard then the water needs to be transported to a safe location where it can be disposed. Pumping the water in and out of the barrier for each work zone project is a lot of extra work compared to the benefits that water-filled barriers provide.

One of the major issues that arise with the use of water-filled barriers is containment. The containment offered by water-filled barriers is not as good as the other types of barriers. Some water-filled barriers can deflect as much as 5.79 m (19 ft) [9]. This is almost the width of two freeway lanes. If a work zone design has to assume a deflection this great, it makes it very difficult to use this barrier for typical activities. There is not enough space to ensure the highway workers and motorists safety. The deployment guidelines that will be introduced later will help to alleviate this problem and make water-barriers suitable for work zone situations.

Impacts are also different with water-filled barriers. When water-filled barriers are impacted by an encroaching vehicle they sometimes redirect the vehicle and sometimes bring the vehicle to a stop. In lower impact angle situations, the water-filled barriers will have a greater tendency to redirect the vehicle, while with higher impact angles, the barrier will tend to spin the car around and bring it to a stop. Water-filled barriers have a tendency to break up when they are impacted by vehicles. The plastic shells of the barrier break apart to absorb the energy of the impact. Sometimes this can cause the vehicle to snag and spin around during the impact. Since the barrier breaks apart when it is impacted the barrier is not as reusable as the other barriers. When the barrier breaks apart all the water drains out and it needs to be replaced. Replacing the broken barriers can become costly because once the barrier is broken it is not reusable like concrete and steel barriers. Water-filled barriers need to be analyzed and deployment guidelines need to be created so they can be deployed safely in work zones.

Balsi Beam

There is one new and innovative device which looks nothing like the contemporary barriers that are currently being used. This device was designed and created by Caltrans and it is called the Balsi Beam. This positive protection device offers mobile protection for short duration work zones. The Balsi beam consists of a trailer that contains two high strength steel beams on either side. Using hydraulics these steel beams can be rotated to either side of the trailer and extended an extra 4.6 m (15 ft) to provide 9.1 m (30 ft) of work zone protection [11]. The steel beams can be rotated to either side of the trailer to allow for roadwork to be performed on either side of the roadway. This trailer is towed around by a tractor truck which makes it highly mobile. With the barrier being towed by the truck it can be towed anywhere the truck can go. There is no heavy equipment needed to set up the trailer for operation; the barrier can be set up from the cab of the truck. This makes the Balsi Beam extremely safe for people setting up the work zone and all workers in the work zone. Figure 7 shows the Balsi Beam in its driving configuration.

Figure 7 Balsi Beam in driving configuration [12]

There are some disadvantages to the Balsi Beam. The Balsi Beam is highly mobile compared to any other barrier available. This is because the Balsi Beam can be towed to any work zone and setup to perform work on the roadway. The one thing that the Balsi Beam cannot do is move with the work zone. The Balsi Beam performs great for stationary work zones or work zones that remain stationary for a period of time before moving along the roadway. Each time the Balsi Beam moves it has to retract the steel beams and lock them in the driving position. This is highly ineffective for continuously moving work zones.

Another issue that is present with the Balsi Beam is its size. When work is being performed on small roadways there may not be ample room to turn around the vehicle. The work zone designers need to take into account the fact that the Balsi Beam needs to return to a location at the end of the day. There needs to be an area where the truck can be turned around once the work is completed at the work zone. This limits the types of areas that the Balsi Beam can be used. It probably cannot be used in rural two lane highways where there is limited space for maneuvering the truck. However, it is fine to use on freeways where the next exit could be used for turning around the vehicle.

Summary

This chapter has discussed the types of barriers that are available to be used on the roadways. Each barrier type has certain advantages and disadvantages as does each specific barrier within a given type. Concrete barriers are best used for longer duration work zones that need high containment. Steel and water-filled barriers are best used for shorter duration work zones that do not require as much containment. Concrete barriers can not be used for mobile work zone applications because of the time and equipment needed to set up the barriers. Steel and water-filled barriers have less setup time and can be used for mobile or short term work zones.

The next chapter will discuss the toolbox of safety barriers. The toolbox contains multiple tables of all the barriers available for purchase or in development. These tables are designed in order to allow for easy comparison between multiple barriers for the work zone designer. The toolbox contains all the details of each barrier in order to make an accurate decision for the barrier to use in a work zone. Along with all the details of the barrier, there are also comments and suggestions as to each barrier’s use.

CHAPTER 3
TOOLBOX OF WORK ZONE BARRIERS

This chapter will discuss the toolbox of safety barriers that was created to aide in the efficient deployment of temporary barriers for work zone applications. The toolbox is made up of multiple charts that contain useful information for determining which barrier to use in a work zone. The toolbox charts contain information for both the barriers and attenuators that are used to shield the barriers from vehicle impacts. This toolbox contains all the characteristics of each barrier that a work zone designer needs in order to design a work zone.

This toolbox will be an interactive chart that will be available in a website format. This will allow Caltrans engineers easy access to all the information they need to develop their work zones. The toolbox is made up of seven charts. Four of the charts cover information regarding temporary barriers and the other three cover the impact attenuators used to protect the temporary barrier installations. This toolbox includes all of Caltrans' approved products for use on California's State highways. Additional barriers that are not approved by Caltrans are included at the end of the chapter. Some of these barriers are the water-filled barriers that Caltrans has not approved and some are new and innovative devices that have been developed in Europe, but have not been crash tested under NCHRP crash test conditions.

Temporary Barriers

The first barrier chart shown in Figure 8 displays some of the pertinent information for each barrier. The chart contains the product name along with the manufacturer of each barrier. The column labeled NCHRP shows the highest crash test rating that the barrier received from the FHWA approval committee. The FHWA's Acceptance Letter contains information on the crash testing of the barrier along with comments. The Caltrans New Products committee issues an Approval Letter for use of the temporary barriers on California's State highways. The deflection for the barrier is listed as the deflection for the containment level specifically listed. The dimensions, installation guidelines, and notes sections contain links that, if this was in a web layout, will take the user to the selected pages where this information would be contained. The cost for the barrier is the cost per each barrier segment. In order to compare the cost of each barrier, the cost was normalized by the length of each barrier and it is supplied accordingly.

More information can be found in Figure 9 which shows all the dimensions for the barriers. These dimensions include the weight, width, height, length, and full weight. This chart does not contain any water-filled barriers because Caltrans has not approved any of them, but the full weight is included to make the addition of water-filled barriers simple. Figure 10 shows the guidelines for installing each of these barriers on the roadways. The guidelines contain the beginning length of need (BLON) for each barrier, which is the point at which the redirective feature of a longitudinal barrier or end treatment begins [13]. The guidelines also contain the minimum installation length that needs to be installed for the barrier to perform at its tested NCHRP 350 test level. The next column represents whether the barrier can remain freestanding or needs to be anchored on the roadway. The anchorage requirements that are listed are required to obtain the deflection shown on the chart. The delineation column identifies whether the barrier comes with delineation included. The deflection equation, which will be explained in Chapter Four, allows the user to determine the deflection of a barrier for a given impact severity.

Figure 11 contains additional notes for each barrier. The additional notes explain deployment considerations for each barrier along with other information that is not included in the charts. For the Safeguard Link System this additional information includes the cost of the manual version of the barrier. The notes section contains other information regarding the maximum curvatures for some barriers and where the barriers would be best suited for a work zone.

Product	Manufacturer	NCHRP	Federal Acceptance Letter	Caltrans Approval Letter	Deflection ft(m)	Dimensions	Installation Guidelines	Cost	Cost per foot	Notes
Safeguard Link System [8,15]	Barrier Systems Inc.	TL-3	Click Here		6.5 (1.98)	Click Here	Click Here	$ 16,750.00	$ 598.21	Click Here
BarrierGuard 800 [8,15]	Barrier Systems Inc.	TL-4	Click Here		6.5 (1.98)			$ 5,925.00	$ 150.00	
Vulcan Barrier [9,16]	Energy Absorption	TL-3	Click Here		13 (3.96)					
Concrete Reaction Tension System (CRTS) [8,17]	Barrier Systems Inc.	TL-3	Click Here		2 (0.61)			$ 821.50	$ 250.46	
Steel Reactive Tension System (SRTS) [8,17]	Barrier Systems Inc.	TL-3	Click Here		2.3 (0.7)			$ 2,600.00	$ 792.68	
GPLINK Portable Barrier Railing [18,19]	Gunner Prefab AB	TL-3	Click Here		5.8 (1.76)					
K Rail [20]		TL-3	Click Here		3.6 (1.1)					
Balsi Beam [11,21]	Caltrans	N/A	Click Here		0.25 (.08)					

Figure 8 Barrier toolbox

	Weight lbs(kg)	Width in(cm)	Height in(cm)	Length ft(m)	Full Weight lbs(kg)
Safeguard Link System	3700 (1678)	28 (71.1)	33 (83.8)	28 (8.53)	N/A
BarrierGuard 800	2400 (1088)	21.5 (54.6)	31.5 (80)	39.5 (12.04)	N/A
Vulcan Barrier	870 (395)	21.5 (54.6)	32 (81.3)	13.5 (4.11)	N/A
Concrete Reaction Tension System (CRTS)	1500 (680)	18 (45.7)	32 (81.3)	3.28 (1)	N/A
Steel Reactive Tension System (SRTS)	1500 (680)	13 (33)	32 (81.3)	3.28 (1)	N/A
GPLINK	6172 (2800)	9.45 (24)	34.25 (87)	19.7 (6)	N/A
K Rail	8000 (3630)	24 (61)	32 (81)	20 (6.1)	N/A
Balsi Beam	N/A			30 (9.14)	N/A

Figure 9 Barrier dimensions

	BLON ft(m)	Minimum Installation ft(m)	Freestanding	Anchorage Requirements	Delineation Included	Deflection Equation
Safeguard Link System	112 (34.14)	224 (68.28)	Yes		No	$D = 1.27\text{x}10^{-5}\text{x(IS)} + .13$
BarrierGuard 800	237 (72.24)	240 (73.15)	No	Each End	No	
Vulcan Barrier	324 (98.76)	864 (263.35)	Yes		No	$D = 2.27\text{x}10^{-5}\text{x(IS)} + .70$
Concrete Reaction Tension System (CRTS)	124.7 (38)	246 (75)	No	Each End	No	
Steel Reactive Tension System (SRTS)	124.7 (38)	246 (75)	No	Each End	No	
GPLINK			Yes		No	
K Rail	120 (36.6)	240 (73.2)	Yes		No	

Figure 10 Barrier installation guidelines

	Notes
Safeguard Link System	Can be used as a link between PCB's for entrance into work zones. Can be towed on wheels. Cost displayed is for the pneumatic and manual barrier. The manual barirer only costs $15,362.00. 200 - 300 ft can be set up in 30 min. The quick installation time and ease of mobility make the Safeguard Link system suitable for short duration work zones.
BarrierGuard 800	1000 feet can be set up in about 1 hour. There is a volume discount if more than 1 mile of barrier is purchased. Since anchoring is required for the barrier, the BarrierGuard 800 would be better suited for a longer duration work zone. Curved joints can be purchased for navigating curves on the roadway. The maximum curve is a 40 meter radius.
Vulcan Barrier	Can be used as a median gate. Can be towed on wheels. Can follow curves up to six degrees per four meter segment. Due to it's low weight per segment and short length the deflection of this barrier is larger than other steel barriers. Due to the higher deflection this barrier should be used where larger deflections are acceptable.
Concrete Reaction Tension System (CRTS)	Can be used with barrier transfer machine to move barrier up to two lanes at 10 mph. The CRTS is suitable for work zones where traffic considerations exist. The CRTS can be moved out 1 to 2 lanes of traffic when work is being conducted and then moved back to the shoulder to allow more lanes for peak traffic. This is ideal for a night only work zone where more lanes can be used by motorists during the day and construction can be resumed at night. The CRTS can be used as a freestanding barrier is 80 segments are placed upstream and downstream in lieu of the anchored configuration.
Steel Reactive Tension System (SRTS)	Can be used with barrier transfer machine. The SRTS is suitable for the same places as the CRTS, but the steel frame makes the SRTS smaller. This makes the SRTS suitable for workzones where mobility is needed and minimal lane width is available. The SRTS can be used as a freestanding barrier is 80 segments are placed upstream and downstream in lieu of the anchored configuration.
GPLINK	The GP Link barrier is useful where minimal deflection is needed along with narrow lane width. GP Link is very heavy and would be better suited for longer duration work zones.
K Rail	K-rail provides very high containment and low deflection. K-rail would be suitable for work zones that have minimal space for deflection and where high containment is needed. K-rail is very suitable for work zones on bridges because there is a minimal amount of room for work. Two differnt types of pin connections can be used. The deflection with the pin connection is 1.1 m. If bolts are used to connect the barriers together the deflection is then 1 m.
Balsi Beam	Provides 30 feet of protected work space for workers. Box beams can be deployed on either side of the vehicle depending on the location of the work zone. The Balsi beam cannot be moved once the beam is deployed and has to retract the beam before moving on the roadway. Due to the large size of the tractor trailer ample space is needed to turn the truck around.

Figure 11 Barrier notes

Attenuators

Barrier installations need to be shielded on either end to prevent adverse injuries to vehicle occupants should they hit the barrier end. The barrier ends can be shielded in two ways. The barrier end can either be flared away from the roadway or an attenuator can be used to shield the barrier end from a vehicle impact. For temporary barrier installations, temporary attenuators can be used. Like the barrier charts, the attenuator charts contain detailed information on each attenuator that help the work zone designer determine which attenuator should be used for a specific work zone.

Figure 12 shows a representative portion of the attenuator toolbox that lists the attenuators that are used to shield temporary barriers. Note that the toolbox is a dynamic document and the following data may not necessarily correlate with the current toolbox nor are all links herein active. This chart contains the product and the manufacturer of each attenuator. The NCHRP column contains the highest crash test rating that the attenuator received from the FHWA. The Acceptance letter column contains a link to the Caltrans approval letter. Both the dimensions and notes columns contain links to two additional charts with additional information on each attenuator. The gating column lists whether the attenuator allows gating or not. Gating is a characteristic of an attenuator that allows a vehicle to pass through the attenuator if the impact is at an angle [13].

Figure 13 shows the dimensions for each attenuator. These dimensions include the width, height, length, empty weight, and full weight. The full weight is included because the Absorb 350 is a water filled attenuator and the Energite III System, Fitch Barrels, and TrafFix Barrels are sand filled barrels. The dimensions of the barrels are not included because the barrels come in different sizes depending on the stopping power needed for the situation. The weight of these barrels also varies due to the size of the barrel and the amount of sand that is placed in each barrel. Figure 14 shows the notes chart for the attenuators. The notes section includes any information that is not included in the first two charts. It includes some deployment considerations for the deployment of the attenuators along with other pertinent information.

Product	Manufacturer	NCHRP	Approval Letter	Dimensions	Gating	Notes
Absorb 350 [8]	Barrier Systems Inc.	TL-3	Click Here	Click Here	Yes	Click Here
ADIEM [22]	Trinity Industries Inc.	TL-3	Click Here		No	
Energite III System [9]	Energy Absorption Inc.	TL-3	Click Here		Yes	
Fitch Barrells [9]	Energy Absorption Inc.	TL-3	Click Here		Yes	
TrafFix Barrells [23]	TrafFix Devices Inc.	TL-3	Click Here		Yes	

Figure 12 Attenuator toolbox

	Width in(cm)	Height in(cm)	Length ft(m)	Empty Weight lbs(kg)	Full Weight lbs(kg)
Absorb 350	24 (70)	32 (81)	32 (9.7)	85 (39)	670 (304)
ADIEM	32 (81)	28 (71) at nose 48 (122) at hazard	30 (9.1)	11,500 (5225)	N/A
Energite III System	N/A	N/A	N/A	Varies	Varies
Fitch Barrels	N/A	N/A	N/A	Varies	Varies
TrafFix Barrels	N/A	N/A	N/A	Varies	Varies

Figure 13 Attenuator dimensions

	Notes
Absorb 350	The measured weight is per element. Nine elements are needed for TL-3 crash rating. This is a water filled attenuator that can be used to protect most temporary barriers. It should be used where gating is allowable and where a narrow attenuator is needed.
ADIEM	Can be placed on exisitng surfaces. Pinned anchorage allows unit to be moved and relocated quickly. BLON is 15 feet. Due to its heavy weight it is not easily transported to other locations. This attenuator should be used when gating is not desired.
Energite III System	These are all sand barrels that can be used to shield all types of temporary barriers. They come in various sizes and weights for the desired stopping power. These should only be used where gating is allowable. These barrels are filled with sand until the desired stopping power is reached.
Fitch Barrells	
TrafFix Barrells	

Figure 14 Attenuator notes

Unapproved Barriers and Innovative Designs

There are many barriers that have not been approved by Caltrans for use on California's roadways. For example, water-filled barriers have not been approved by Caltrans. One reason that these barriers have not been approved is due to their large deflections. These barriers are included in the water-filled barrier chart, so all of the information is available for Caltrans in case they desire to use these barriers at a later time.

There are also new and innovative devices that have been designed. These new and innovative devices were developed in Europe and tested under EN 1317 standards. Due to this reason, they are not marketed or easily transferred to the United States because they would have to undergo more testing. These barriers are included so Caltrans can research the barriers further and decide if the barriers are worth pursuing.

Figure 15 contains all the water-filled barriers. This chart contains all the information for Caltrans to determine if these barriers would be useful in the future. Figure 16 shows all the new and innovative devices that have been developed in Europe. All these barriers were tested under the EN 1317 testing standards so the containment levels correspond to this test. This chart allows Caltrans to view the important information about each barrier in order to make a decision about whether the barrier could be useful for Caltrans.

Name	Company	NCHRP	Deflection (ft)m	Width (in)cm	Height (in)cm	Length (ft)m	Weight (lbs)kg	Full Weight (lbs)kg	BLON (ft)m	Minimum Installation (ft)m	Freestanding	Delineation	Cost per Unit	Cost per foot	Notes
Model 2001 [10,24]	Yodock Wall Company	TL-3	14 (4.27)	17 (43.2)	46 (116.8)	6 (1 83)	330 (150)	1735 (787)	48 (14 63)	150 (45.72)	Yes	No	$ 660.00	$ 110.00	Model 2001 requires steel reinforcement kit for TL-3 compliance. The barrier and reinforcement kit are sold seperately and the price includes both.
MB-350 [25,26]		TL-3	11 (3.35)	24 (61)	42 (106.7)	6 (1.83)	125 (57)	1800 (818)		198 5 (60 5)	Yes	No	$ 533.00	$ 88.83	206 Gallons of water needed for each barrier. Steel kit and barrier sold seperately and the price includes both.
SB1-TL [27,28]	Safety Barriers Inc.	TL-3	15 (4.57)	24 (61)	42 (106.7)	7 (2.13)	164 (74)	1840 (835)	49 (14 94)	140 (42.67)	Yes	No		$ -	Uses a steel cable for reinforcement. 1 5 minutes required for installation of each barrier.
Trinton Water Filled Barriers [9,29]	Energy Absorption Systems Inc.	TL-3	19 (5.79)	21 (53.3)	32 (81.3)	6 5 (1.98)	140 (64)	1350 (612)	65 (19 81)	195 (59.44)	Yes	No		$ -	Serves as its own end treatment. Up to 650 ft/hr can be deployed.

Figure 15 Water-filled barrier chart

Name	Type	Containment Level	Deflection ft(m)	Width in(cm)	Height in(cm)	Length ft(m)	Weight lbs(kg)	Freestanding	Website	Company
Vario Guard [30]	Steel	H2	11.5 (3.5)	15.7 (40)	35.4 (90)	13.1 (4)	882 (400)	No	http://www.vo kmann-rossbach.com	Volkmann Rossbach
Mini Guard [30]	Steel	T2	6.9 (2.1)	19.7 (50)	19.9 (50.5)	4.9 (1.5)	132 (60)	No	http://www.vo kmann-rossbach.com	Volkmann Rossbach
STGW 4200 [31]	Steel	T1	3.3 (1)	15 (38)	21.7 (55)	6.6 (2)	209 (95)	Yes	http://www.stahlschutzwaende.de	P. Berghaus GmbH
VIP [32]	Steel	N1	3.4 (1.04)	9.5 (24)	27.6 (70)	39.4 (12)	1667 (756)	Yes	http://www.sesar.fr/uk	Roadis
SMS [33]	Steel	H1		21.7 (55)	80 (31.5)	19.7 (6)	1323 (600)	Yes	http://www.somaro.fr/	Somaro
Delta Bloc 50S [34]	Concrete	T2	3.5 (1.08)	14.2 (36)	19.7 (50)	19.7 (6)	2557 (1160)	Yes	http://www.deltabloc.com	Delta Bloc
Delta Bloc 65S [34]	Concrete	H1	4.3 (1.3)	15.4 (39)	25.6 (65)	19.7 (6)	3682 (1670)	Yes	http://www.deltabloc.com	Delta Bloc

Figure 16 New and innovative barrier chart

Summary

This toolbox will allow Caltrans work zone design engineers to easily choose the correct barrier for the selected work zone situation. The final design for the toolbox will be a web based application that will be easily accessible for Caltrans employees. This will also make updating the data and disseminating the information simple. The toolbox's charts contain all the information that may be useful in designing a work zone. The charts for water-filled barriers are also included should Caltrans decide to use this type in the future. The new and innovative barriers are included to help Caltrans identify innovative designs that could be used on California's roadways.

The next chapter will discuss the deployment guidelines for placing barriers in work zone applications. The deployment guidelines are a way of determining the deflection of a barrier installation for a given work zone scenario. Since these barriers have different lateral deflections, each barrier cannot be placed the same at a given work zone. The deployment guidelines will help in determining how to place each barrier for a given work zone situation.

CHAPTER 4
GUIDELINES FOR THE DEPLOYMENT OF TEMPORARY BARRIERS

This chapter will discuss the deployment guidelines that help determine the placement of barriers in work zone situations. The deployment guidelines are a way of determining the expected deflection of a barrier given certain impact conditions. The first step in determining the expected deflection is determining a work zone speed and an anticipated impact angle. From these values an impact severity value is determined along with the expected deflection. The method of determining this value will be discussed in detail along with the generation of general deployment guidelines for any barrier.

Many of the new and innovative barriers do not have a deployment history. These barriers lack a safety and performance record like the concrete barriers. One reason is because these new barriers do not have any deployment guidelines that aide in their installation for road work applications. These deployment guidelines will help the work zone designers deploy the barrier for each work zone application by the deflections that would be expected by the barrier.

Each barrier that is used has a different lateral deflection value, which is crucial when designing a work zone. The workers need to be shielded from the motorists and the motorists need to be shielded from heavy equipment and structures. However, the lateral deflection value that is available is usually only the deflections from the performed NCHRP 350 crash tests. These crash tests are not typical of all of the impacts that will occur in a work zone situation. Most impacts will occur at smaller angles than test 3-10 or 3-11. Therefore, determining the deflection for a certain work zone scenario is needed in order to properly deploy the barrier for the workers and motorists safety.

Anticipated Impact Angle and Impact Severity

The first step in determining the expected deflection from a barrier is to find the anticipated impact angle for the impact. However, before this can be done, a work zone speed needs to be established. This work zone speed is typically selected based on the judgment of the work zone designers. Normally a work zone is set slightly lower than the normal roadway speed. For freeways, a work zone speed is usually around 90 km/hr (55.9 mph). Once a work zone speed is selected, the anticipated impact angle is then determined.

The anticipated impact angle for the work zone is found based on the speed of the vehicle and the number of lanes separating the vehicle and the barrier. Figure 17 shows a chart relating the work zone speed and the number of lanes separating the vehicle and barrier to determine the expected impact angle. As the speed of the vehicle increases, the impact angle of the vehicle is reduced, but as the speed of the vehicle decreases, the impact angle increases. This causes a conflict because reducing the work zone speed will lead to a lower impact severity, but also causes the impact angle to increase, thus leading to a higher impact severity. As such, the speed of the work zone should be selected based on the desired impact severity.

Speed, km/h (mph)	Maximum Attainable Angle (deg)		
	1 Lane	2 Lanes	3 Lanes
80 (49.7)	13	22.7	29.4
90 (55.9)	11.6	20.1	26.1
100 (62.2)	10.4	18.1	23.4
110 (68.4)	9.5	16.4	21.3

Figure 17 Impact Angle Chart [35]

The chart of Figure 17 was created by using a point mass analysis with an assumed maximum steer angle. The coefficient of friction between the pavement and the tire was taken to be 0.7. For these impact angles the barrier is assumed to be at the inside of the outside lane [35]. A one lane offset means that the vehicle is traveling in the lane directly next to the barrier.

Figure 17 can be used to determine the anticipated impact angle for a barrier deployed in a work zone. For a four lane divided highway, a vehicle traveling with a one lane offset at 100 km/hr (62.2 mph) can only attain a 10.4 degree impact angle. This is less than half of the impact angle used for NCHRP 350 test 3-11. By using this chart to determine the anticipated impact angle, the new and innovative devices can be more easily deployed on the roadway for construction projects.

The chart in Figure 17 is only valid for a straight roadway section. There are ways to obtain a higher impact angle than the angles listed in the chart. Vehicles can veer off of the roadway away from the barrier and then overcorrect, thus increasing the offset distance and the impact angle. Larger impact angles can also be obtained if the barrier is set up along a curved section of roadway. However, some curves that are found on most freeways can be assumed to be straight. If a curve is present in the work zone, it would have to be analyzed to determine how much of an effect the curve will have on the impact angle of the vehicle. Under no condition will the curve not have an effect, but the effect may be neglected if its contribution is very small.

After the work zone speed and anticipated impact angle have been determined, the impact severity for the impact can be calculated. This is done by using equation (4.1) and solving for the impact severity. The impact severity is the kinetic energy of the vehicle in the lateral direction, which represents the amount of energy that the barrier must contain and redirect. This anticipated impact severity can be used to determine what type of barrier to use for the work zone. If the impact severity is very large, then a barrier with high containment, like a concrete barrier, is needed for the work zone. However, if the impact severity is low, then a new barrier with increased mobility might be better suited.

Expected Deflection

The expected deflection of the barrier is the key in determining the placement of the barrier in the work zone. This expected deflection allows for the work zone designer to create an adequate buffer zone for workers and motorists' safety. An equation relating the impact severity and the deflection has to be used to determine the required buffer zone. This equation, which has been named the deflection equation, is determined from the crash tests of the barrier. The deflection equation is determined by using NCHRP 350 crash tests 3-10 and 3-11. These deflection values are plotted on a graph of deflection versus impact severity. Figure 18 shows the two crash tests plotted on a graph for the Safeguard Link System.

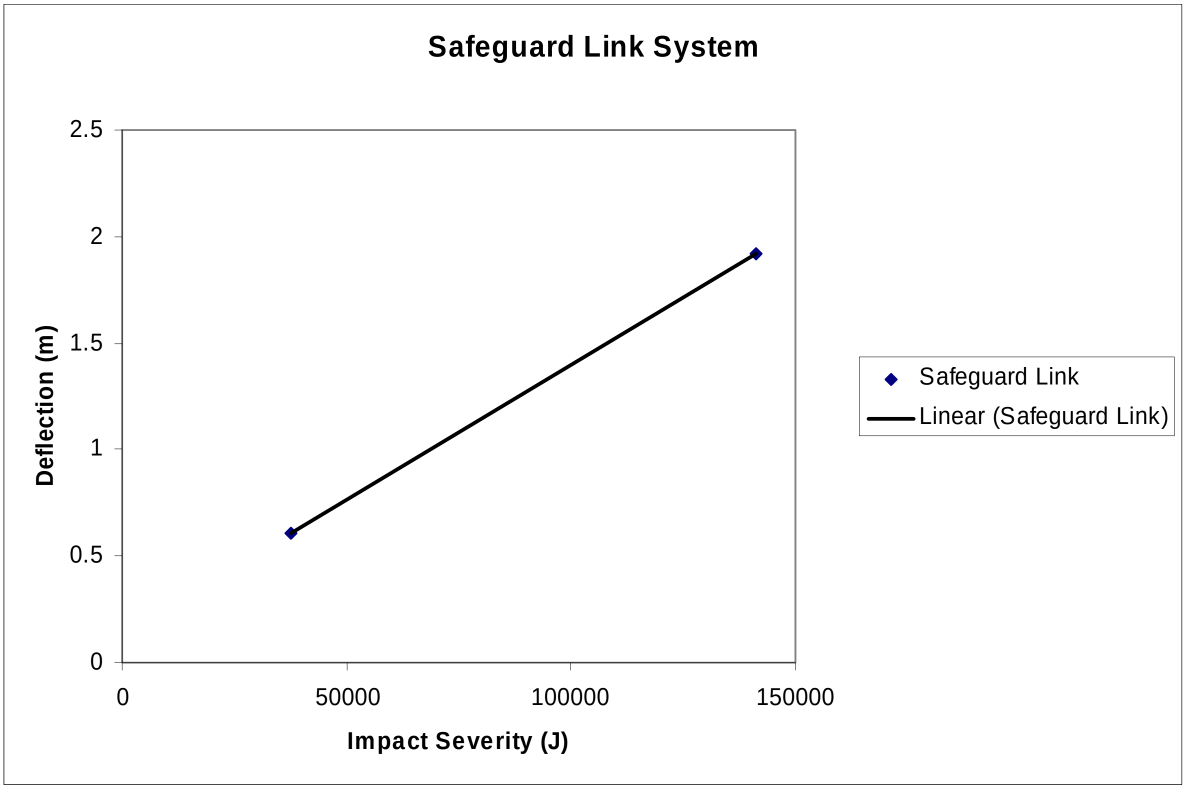


Figure 18 Deflection versus impact severity for the Safeguard Link System barrier

The point on the right represents test 3-11. The values for this test were an impact severity of 141.1 KJ (104,070 ft-lb) and a deflection of 1.92 m (6.3 ft). The point on the left represents test 3-10, which had an impact severity of 37.8 KJ (27,880 ft-lb) and a deflection of .610 m (2 ft) [14]. These two points were then used to fit a line between the two points. The equation for the line is the deflection equation that relates the impact severity and the deflection. For the Safeguard Link System the deflection equation is

$$Deflection = 1.27 \times 10^{-5}\left(IS\right) + .13 \qquad (4.1)$$

where *IS* is the impact severity, in kilojoules, of the anticipated impact. This equation gives the deflection in meters.

The deflection equation that is found from this method does have some limitations. This equation is only valid between a certain range of impact severity values. For this particular example, the range is between 37.8 KJ (27,880 ft-lb) and 141.1 KJ (104,070 ft-lb). This is due to the shape of the curve for which the line is fit. This graph is based on the kinetic energy of the vehicle in the lateral direction. The equation for kinetic energy is

$$KE = \frac{1}{2} m v^2 \qquad (4.2)$$

where m is the mass of the vehicle and v is the velocity. The kinetic energy varies linearly with the mass of the vehicle, but it varies with the velocity squared. The kinetic energy equation is a second order equation. Fitting a straight line to the two crash test points forms a linear approximation to the kinetic energy equation for the impact severity range. This approximation causes the deflection equation to overestimate the deflection of the barrier. Figure 19 shows a kinetic energy curve along with a straight line to show why the impact severity range needs to be included.

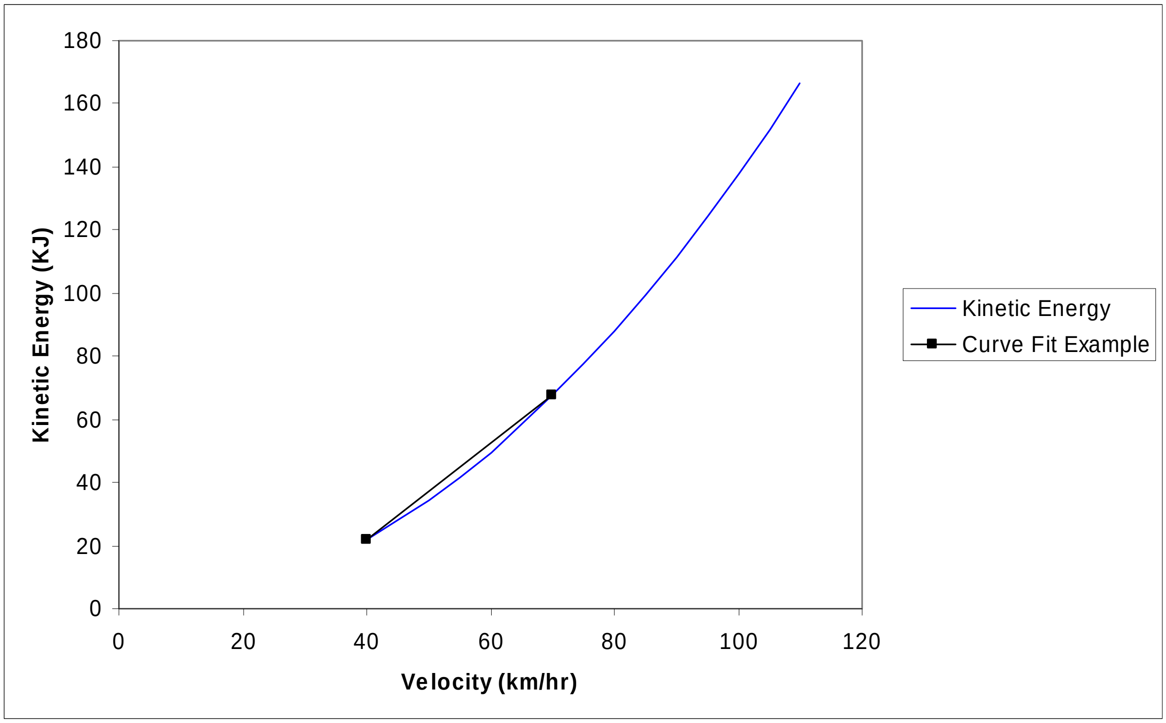


Figure 19 Example kinetic energy plot with example curve fit

Figure 19 shows the inaccuracies of the curve fit for determining the deflection equation. However, an overestimate of the deflection in the range is allowable because it is safer for the workers and motorists. The deflection equation could also be extended beyond the current limits, but the curves will start to diverge and the deflection equation will underestimate the barriers deflection which could lead to a work zone injury. An error of five percent is probably allowable, but in the interest of safety, the impact severity range should be observed.

This method of determining the deflection equation for a certain barrier can be used for any barrier. All that is needed is the results of two crash tests for a certain barrier configuration. Tests 3-10 and 3-11 are the preferred tests because these tests encompass a large range of vehicles used on the roadway. Most barriers have undergone these tests as long as they are tested to NCHRP 350 TL-3.

Deployment Considerations

Using the noted deflection equation along with the current work zone layouts, Caltrans can conduct safe deployment of these new and innovative barriers in work zones. The deflection equation will provide for the calculation of a buffer space for the work zone layout. The Manual on Uniform Traffic Control Devices for Streets and Highways [2] contains some typical work zone layouts that can be used with the expected deflection. Figure 20 shows an example of a lane closure on a roadway with a temporary traffic control barrier.

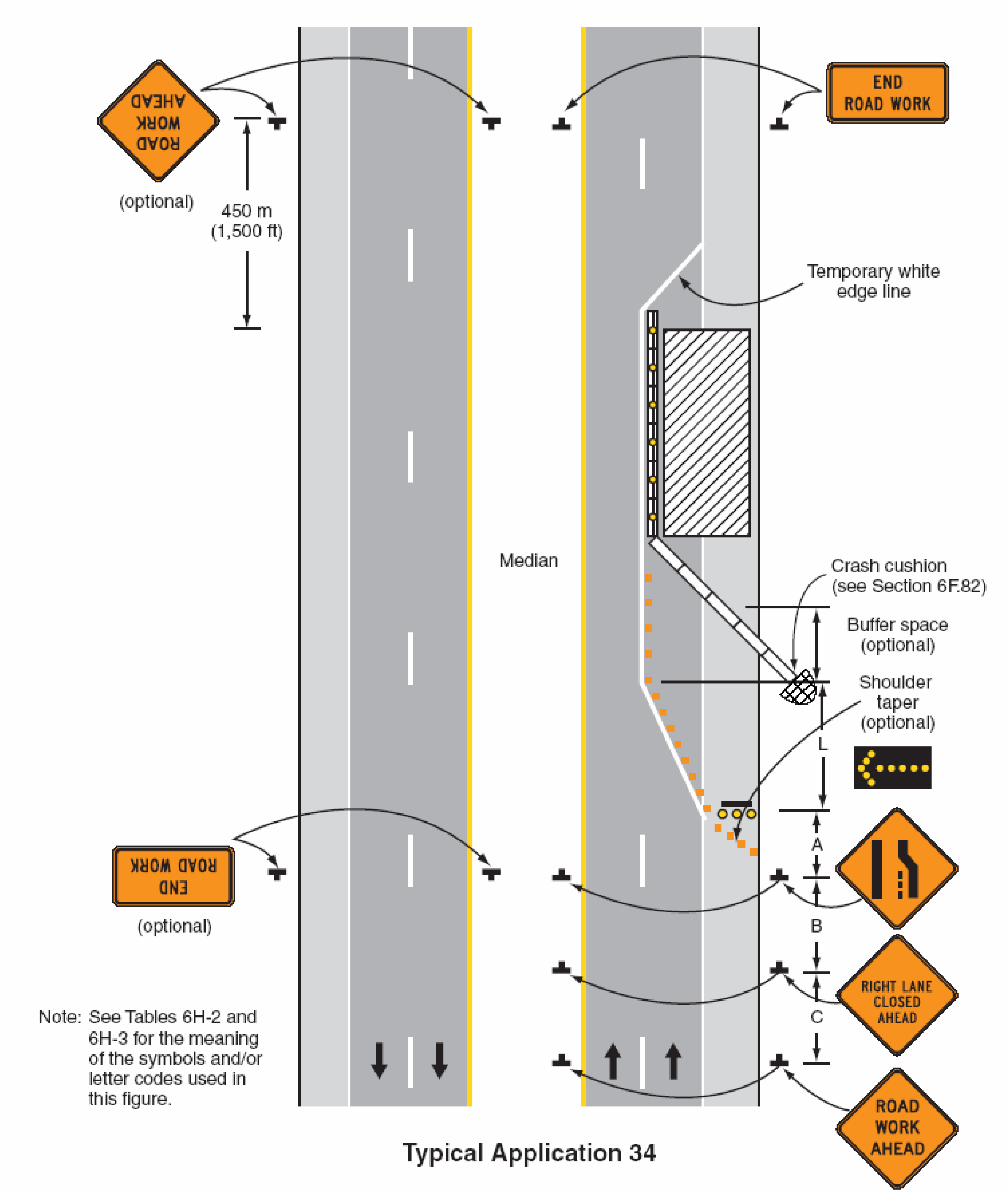


Figure 20 Lane closure with temporary traffic barrier [2]

The main issue with the deployment of a barrier configuration is the containment offered by the barrier. With the use of the deflection equation, an accurate buffer space can be developed to increase the safety. The buffer space is the lateral distance between the work space and the barrier. Figure 20 only shows one possible situation for barrier deployment in a work zone. There are many other work zone layouts that can be used with this added lateral buffer zone.

There are also many work zone layouts that are not available due to the infinite number of work zone possibilities that can be created given the situations. The layouts available from the manual are general layouts that provide basic guidance. By using the layouts and combining them with the expected deflection of the barrier in the work zone, work zones can be created for the safety of motorists and workers.

There are other considerations that should be considered when using the deflection equation. The minimum buffer space that should ever be used is the deflection at the minimum impact severity range. If higher impact severities are expected in the work zone, then a barrier with a very high containment should be used. Sometimes an impact angle greater than 25 degrees could be expected. This is beyond the tests conducted for NCHRP 350 approval, but having a barrier is safer than not having a barrier. If such a large impact angle is likely, then a barrier that offers high containment should be used. However, this barrier may not perform as expected from the NCHRP 350 crash tests, but it will add a form of positive protection to the work zone.

Benefit Cost Programs

Benefit cost analyses could be used to help determine when a barrier should be used for a work zone scenario. The benefit cost program helps determine when a barrier should be used, but it does not determine how to place the barrier on the roadway. One such benefit cost program that could be used for the deployment of temporary barriers is called the Roadside Safety Analysis Program (RSAP) [36]. This program uses a benefit cost algorithm to determine the cost effectiveness of placing a barrier for a given work zone design. However, this benefit cost program does not take into account some important factors for temporary barrier usage in work zones. One disadvantage of the RSAP is that it can only analyze work zones that last for a year or more. This means that it would work well for work zones that last longer than a year, but most temporary work zones last a matter of weeks or months. Another limitation of the RSAP is that it does not distinguish between each temporary barrier. In order to create an accurate benefit cost analysis, each barrier should be analyzed in the program. The RSAP could be used to help determining when a barrier should be used for longer duration work zones, but for temporary barrier usage in work zones, the RSAP is limited in its usefulness.

Summary

The deployment of barriers in work zones is a difficult process. There are many factors that influence the barrier choice for a work zone. All of these factors cannot be accounted for because there are an infinite number of possible work zone scenarios. These deployment guidelines do not account for all work zone scenarios, but they do help in determining how a barrier should be deployed. The use of the deflection equation and the current deployment layouts can be used to help deploy the new and innovative barriers for work zone operations.

The next chapter will discuss the development of a correlation between barriers that were tested under EN 1317 and NCHRP 350. Some of the new and innovative barriers were developed and tested in Europe under the EN 1317 standard. In order to use this barrier in the United States, it would have to be tested under NCHRP 350. The next chapter will discuss how the barriers' deflection can be estimated for NCHRP 350 test 3-11 from the EN 1317 tests. This value can then be used to determine if the barrier is suitable for use under NCHRP 350 testing conditions.

CHAPTER 5
CORRELATION BETWEEN EN 1317 AND NCHRP 350 TESTING STANDARDS

This chapter will discuss a correlation between the EN 1317 and NCHRP 350 testing standards. This correlation will determine the NCHRP 350 test 3-11 crash test deflection by using the EN 1317 crash test results. This process is similar to the previously discussed method used for determining the buffer zone for barrier deployment. The first step is obtaining the EN 1317 crash test information for the barrier. Then by plotting the crash test data on a graph, a line can be plotted and the deflection for crash test 3-11 can be determined.

The barriers that have been designed and tested in Europe were tested under EN 1317 testing standards. These testing standards are different than the standards that are set by NCHRP 350. In order for a barrier to be used on the U.S. federal highways, it needs to be approved by the FHWA. The FHWA needs to approve a barrier based on NCHRP 350 crash testing. A barrier that is tested to EN 1317 could be crash tested to NCHRP 350, but this can be very expensive especially if the barrier does not gain FHWA approval. By using this correlation, the NCHRP 350 crash tests results can be estimated. If the results are desirable, then NCHRP 350 crash tests can be performed so the FHWA can review the barrier for use in the United States.

EN 1317 Crash Tests

In order to determine the performance of a barrier under NCHRP 350 testing conditions, two EN 1317 crash tests need to be used. For the two crash tests, one needs to have an impact severity above 137 KJ (101,046 ft-lb), and the other needs to be below that level. These two points need to encompass the impact severity for NCHRP 350 test 3-11 so that a straight line can be fit between them. EN 1317 containment levels H1 and H2 use two crash tests that meet these requirements. From Figure 2, containment level H1 uses tests TB42 and TB11 to determine the crashworthiness of the barrier. The crash tests for a containment level of H2 are TB51 and TB11 [5]. Test TB11 has an impact severity of 40.6 KJ (29,945 ft-lb), which is very close to the impact severity for NCHRP 350 test 3-10. Test TB42 has an impact severity of 126.6 KJ (93,375 ft-lb) and test TB51 has an impact severity of 287.3 KJ (211,902 ft-lb).

If a barrier has been tested to EN 1317 H1, it does not have a crash test with an impact severity greater than 137 KJ (101,046 ft-lb). However, the impact severity of test TB42 is very close to that of NCHRP 350 test 3-11. Test 3-11's impact severity is 10.4 KJ (7,671 ft-lb) greater than TB42, which is an eight percent increase over TB42. However, because the difference is small, this crash test can be used to help determine the prediction for the deflection under NCHRP 350.

Developing the Correlation

The same basic method will be used to develop the correlation that was used for determining the expected deflection. In order to develop the correlation between the EN 1317 results and the NCHRP 350 results, the two crash test data points need to be plotted on a graph of deflection versus impact severity. A straight line has to be fit between the two points and the deflection equation needs to be found. The deflection equation that is created by using the EN 1317 points is used to determine the deflection for the impact severity of test 3-11. Once the equation has been found, the impact severity of test 3-11, which is 137 KJ (101,046 ft-lb), is plugged into the equation to determine the deflection of the barrier.

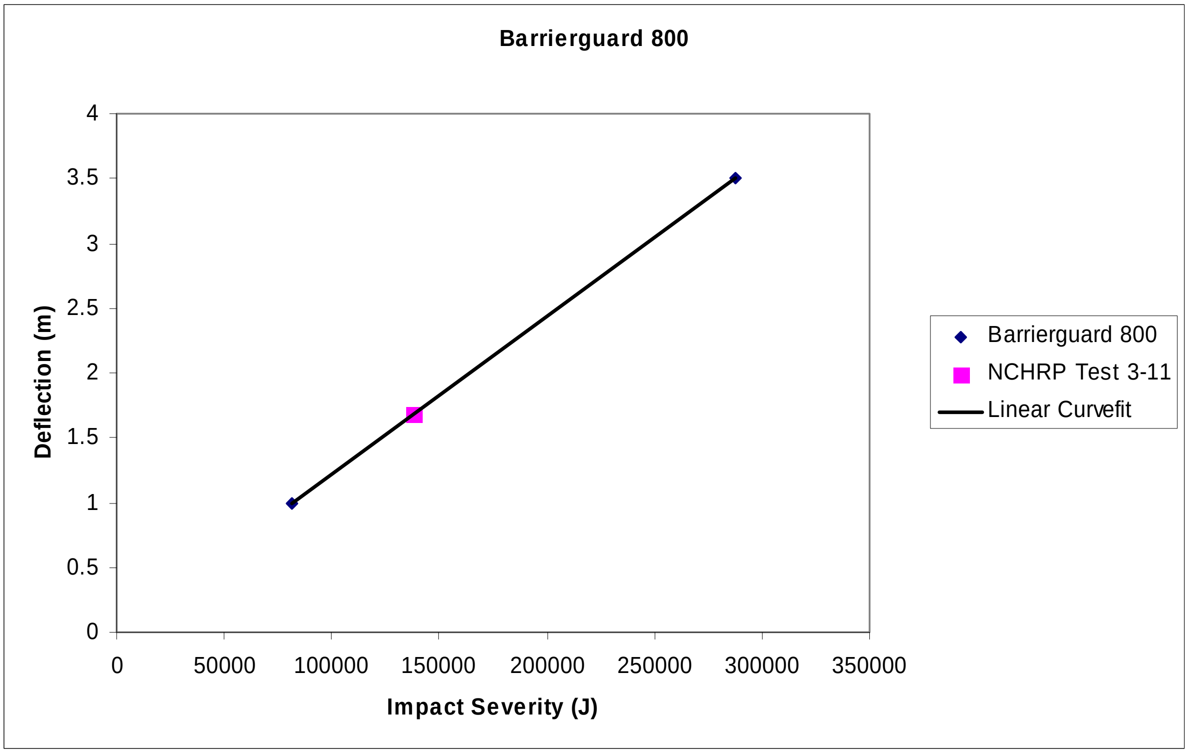


Figure 21 BarrierGuard 800 Correlation Example

Figure 21 shows an example of the method that was used to determine the NCHRP 350 performance characteristics. The BarrierGuard 800 barrier was tested to EN 1317 H2 containment level. The point on the right end of this line represents test TB51 and the point on the left end of the line represents test TB32. For containment level H2 only test TB51 and TB11 need to be tested, but they also ran test TB32, which has an impact severity of 81.9 KJ (60,406 ft-lb). Since the impact severity of TB32 is lower than 137 KJ (101,046 ft-lb) it can be used as a substitute for test TB11. The deflection equation for the straight line approximation for the BarrierGuard 800 barrier is given as

$$Deflection = 1.22 \times 10^{-5}(IS) + .004 \qquad (5.1)$$

where *IS* is the impact severity of test 3-11. This equation is then used to determine the deflection of test 3-11, which is 1.68 m (5.51 ft). This deflection value is very close to the predicted value for the BarrierGuard 800 that was determined by the FHWA approval committee, which was 1.5 m (4.92 ft) [15]. The estimated value that was determined from this analysis overestimates the actual deflection of the barrier by about ten percent.

There is also the possibility of creating a higher order model to more accurately estimate the crash test results. If three crash test data points were available for a certain barrier, a second order curve fit could be used to determine the deflection equation for the barrier. This curve fit would help limit some of the error involved in the linear approximation. This was not performed for this barrier because only the two crash test data points were known.

Analysis Error and Limitations

The overestimate of this deflection is allowed in the analysis because it is a conservative estimate. Figure 22 shows a second order plot of kinetic energy with different linear approximations. The approximation labeled Small Gap shows the effect of a small range of impact severity when making a linear approximation. Large Gap shows the linear approximation of a large range of impact severities. These two approximations show that a smaller range of impact severities produces a more accurate linear approximation, while a large range of impact severity produces a less accurate linear approximation. The example for the BarrierGuard 800 is actually more accurate using tests TB32 and TB51 than using TB11 and TB51 because the linear approximation range is smaller.

The approximation of test 3-11 with the crash tests for containment level of H1 will underestimate the expected deflection of the barrier, due to the fact that the impact severity for test TB42 has a lower impact severity than test 3-11. The overestimate occurs from the linear approximation of the second order kinetic energy equation. Beyond the impact severity range of the deflection equation, the linear approximation becomes increasingly inaccurate. However, the impact severities of TB42 and 3-11 are very close and the approximations are still valid for determining the expected deflection.

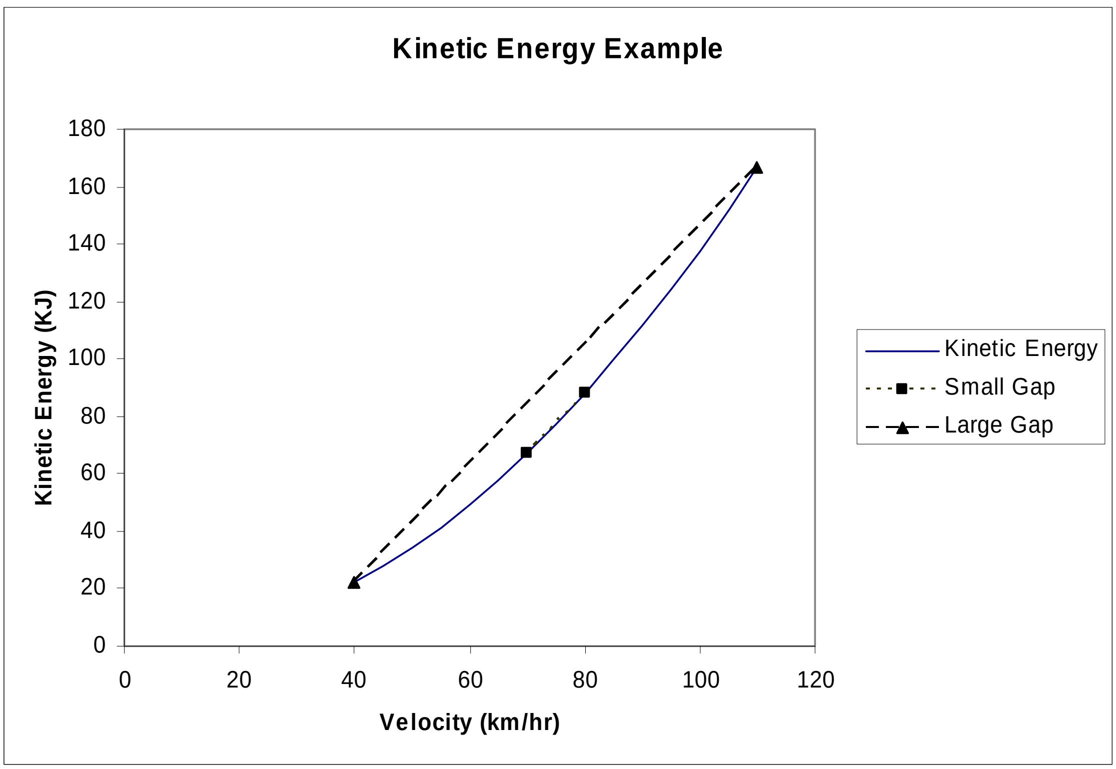


Figure 22 Kinetic Energy Curve Example

There are some limitations to this analysis. The analysis needs two EN 1317 crash tests that surround test 3-11's impact severity. Due to the EN 1317 crash tests that are performed for the barriers, only barriers that have been tested to H1 or higher containment levels can be used to determine the deflection equation. Not all of the innovative products and devices are going to be tested to H1 or higher and this analysis limits some of the products that could be analyzed with this simulation. Many barriers that are tested under EN 1317 test conditions are only tested to a containment level of N2. The FHWA did approve tests TB32 and TB11 for the BarrierGuard 800 barrier as acceptable substitute tests for test 3-10 [15]. However, the standard in the United States has been set at TL-3. Most barriers that are used on the roadways need to be TL-3 tested and approved.

Summary

This correlation between EN 1317 and NCHRP 350 provides an easy way to estimate important deflection information without performing an actual crash test. Crash tests are expensive and time consuming. This analysis is quick and easy and can be performed by a single individual with little time and effort. This allows for new and innovative barriers developed in Europe to be easily analyzed for use in the United States. However, not all of the barriers that are developed in Europe can be tested using this method because of the difference between the crash tests of the two standards.

The next chapter will discuss the creation of a two dimensional dynamic model of a barrier impact. The dynamic model is a multi-body dynamic model of the Safeguard Link System. This model was created to determine how well a simple two dimensional model could account for the complex effects of a vehicle impacting a barrier. The goal of the model was to determine if the actual deflection values of the barrier could be calculated by using the model. The AHMCT Research Center is also conceptualizing new types of mobile barriers. This model can be used to help analyze the new barriers to determine how they react to vehicle impacts.

CHAPTER 6
TWO DIMENSIONAL DYNAMIC MODEL OF BARRIER CRASH TEST

This chapter will discuss a two dimensional dynamic model that simulates a temporary barrier crash test. The dynamic model was developed to determine how accurately a two-dimensional model could represent a crash test. This model was based on the Safeguard Link System where the actual crash test data is known. The main goals were to determine if the model could accurately predict the lateral deflection and the exit angle of the vehicle, along with information about how the barrier reacts during the vehicle impact.

In order for the FHWA to approve a barrier for use on the roadways it needs to undergo full scale NCHRP 350 crash testing. This crash testing is expensive and time consuming. During the design process it is cheaper to perform computer simulations to determine the crashworthiness of the barrier before the actual full scale crash tests. Currently most of the computer models that are being used to evaluate barriers are created with non-linear finite element programs like LS-DYNA or DYNA3D. These simulations are very accurate and give great results, but they are both computationally expensive and time consuming. A simple dynamic model will not produce the same type of accuracy of results that non-linear finite element programs can produce, but it can still produce useful information with less computational and time expense.

This dynamic model was created using a multi-body dynamics program called AUTOLEV [37], which uses Kane's method [38] to determine the equations of motion for the dynamic system. AUTOLEV develops the equations of motion and then outputs them into a Matlab file for analysis. Matlab is used to solve the differential equations and output the results for analysis.

Dynamic System Overview

A multi-body dynamic model was created to simulate the NCHRP 350 2-11 crash test for the Safeguard Link System. This barrier is a steel safety shaped barrier that is connected with hinges between each segment. Test 2-11 is a test that uses a 2000 kg (4,409 lb) pickup truck moving at 70 km/hr (43.5 mph) with an impact angle of 25 degrees [4]. For the actual crash test four barrier segments were used, with each barrier segment measuring 8 m (26.2 ft) in length.

There are certain assumptions that need to be made about the multi-body system in order to model the barrier. Each barrier segment was assumed to be of constant mass throughout the segment. This allowed the barrier to be modeled as a thin rod, making the calculation of the moment of inertia simple. Barrier segments are also assumed to be connected by pin connections. The Safeguard Link System uses a hinge design for its connection, which can be modeled as a pin connection. The hinge connection will not allow the barrier to rotate to extreme angles while a pin connection would allow the barrier to rotate a full 180 degrees. However, the angles that occur during the crash test will be small enough that the pin connection is an acceptable assumption.

In order to use AUTOLEV to solve for the equations of motion for this system, reference frames and coordinate systems for the model were created. The reference systems for this model consist of the generalized coordinates and the generalized speeds. The Newtonian reference frame for the system was the N frame. The generalized coordinates were chosen to reduce the numbers of degrees of freedom for the system. Reducing the degrees of freedom for the system will eliminate some of the dynamic equations and reduce the computational time. The first barrier segment rotation angle was the rotation in the N frame. The other barrier rotation angles were the rotation angles relative to the barrier before it.

Figure 23 shows the Newtonian reference frame and the angles that were selected for the barrier configuration. Figure 24 shows the angular speeds that were chosen for the barrier. Figure 25 shows the barrier angles when the barrier is in its typical deformed configuration. Figure 26 shows a sequence of drawings that illustrate how the car hits the barrier and is redirected away from the barrier.

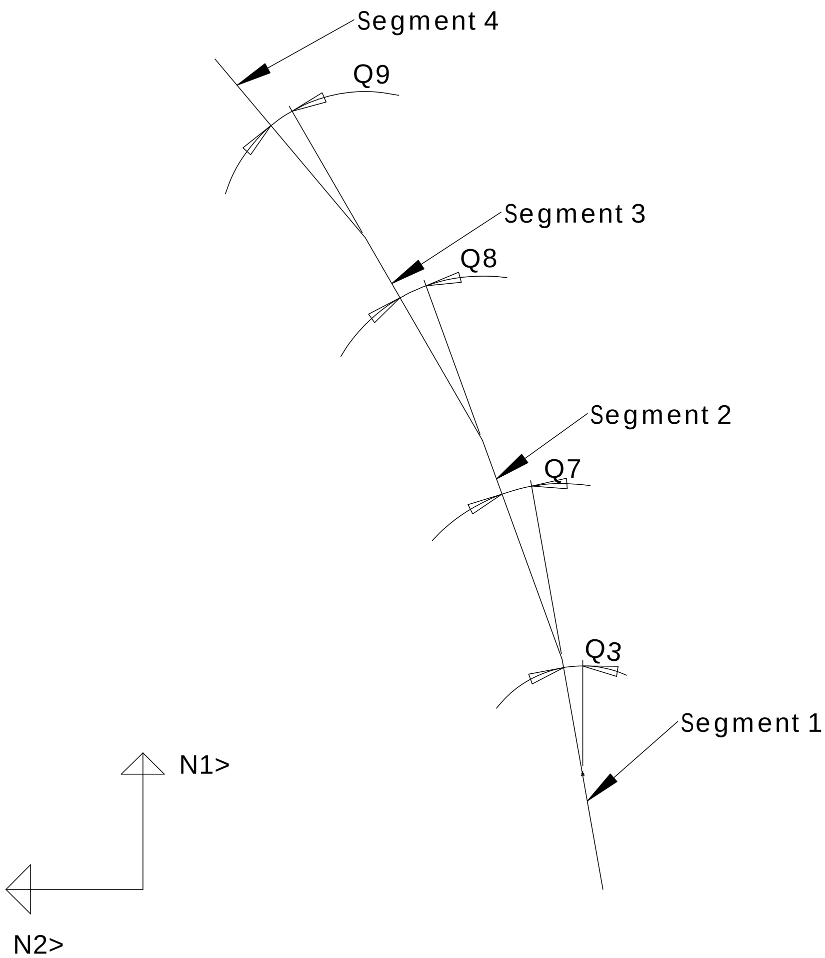


Figure 23 Barrier angles

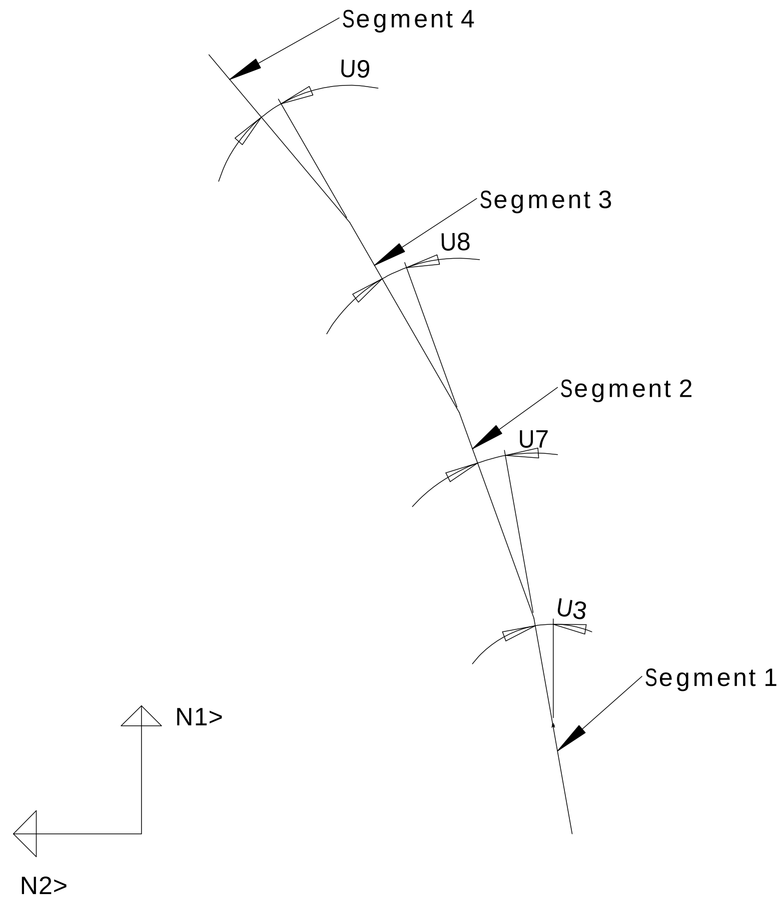


Figure 24 Barrier generalized speeds

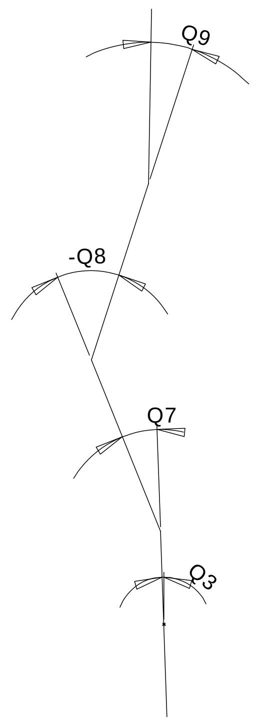


Figure 25 Typical barrier deformation

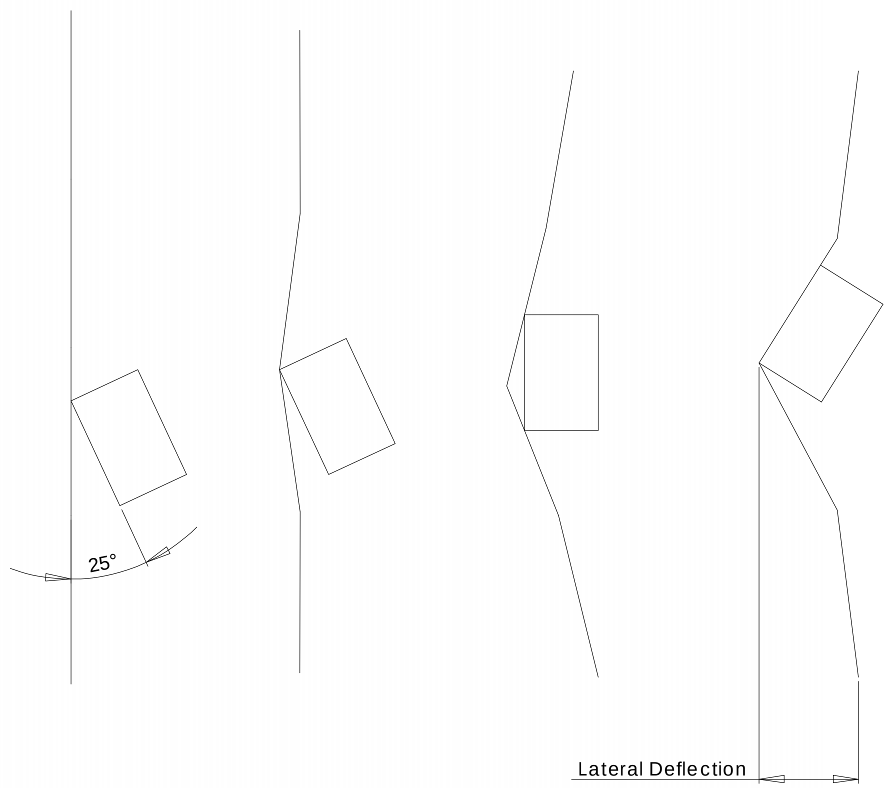


Figure 26 Typical barrier impact sequence

Some other assumptions in the system also had to be made regarding friction. Each of the barrier segments has friction acting between the barrier and the roadway. To simplify the model, it was assumed that friction would only act at either end of the barrier segment rather than all along the barrier. The friction that occurs between the roadway and the barrier is both static and dynamic. The complexity of programming the change from static to dynamic friction is complex. As such, the static friction was not included in the analysis and the dynamic friction was defined as a function of the velocity of the friction point. The friction force was defined to be linear up until a critical velocity and then remain a constant value. The critical velocity for the friction force was set at .01 m/s (.03 ft/s). This is essentially a step input for the friction force; however, a step response will not compute well in the ordinary differential equation solver in Matlab.

There are also friction forces between the vehicle and the barrier. These friction forces are all dynamic friction forces that would normally act between the whole contact area between the vehicle and the barrier. However, for this model, two contact points that were chosen for the vehicle, the front left and rear left bumpers. These two points are used for the friction and contact forces that act between the vehicle and the barrier.

The contact forces were defined as a function of the distance that the contact points on the vehicle move past the barrier. The vehicle is allowed to move through the barrier, so once the point moves past the barrier line, a force is applied to the contact points until the contact point is forced back away from the barrier. The force linearly increases up to a certain value and then remains constant. This function helps account for the crush of the vehicle in the model. The crush of the vehicle is more complex than this function, but it is very difficult to represent in a model.

There are also some simplifications made to the vehicle. The vehicle was modeled as a moving mass with a given moment of inertia. The vehicle model does not contain any vehicle dynamics or suspension effects. The friction between the roadway and the tires is not included in the model, so the car will continue to rotate once it leaves contact with the barrier. This vehicle is not truly accurate, but it works well enough to provide the impact for the barrier in order to determine the barrier's deflection.

Model Results

Three different crash tests were simulated to determine the accuracy and validity of the model. The first test was for crash test 2-11. In order to determine how accurately the model was working, the speed was increased to 100 km/hr (62 mph) with the same impact angle. After this test, the last test was run with a speed of 100 km/hr (62 mph) and an impact angle of twenty degrees. These three tests take into account all of the variables that will affect the deflection of the barrier.

Figure 27 shows the barrier angles from the first test. The first barrier angle is Q3 which is almost unchanged. The angle Q7 is positive which represents the barrier deflecting from the impact. Angle Q8 shows that the third barrier segment is deflected, but the angle is negative. This is because the barrier is rotated in the opposite direction of the defined angle. Angle Q9 shows the barrier rotating the same directions as the first and second segments. Figure 25 shows the barrier in its deflected configuration, which helps explain the barrier angles.

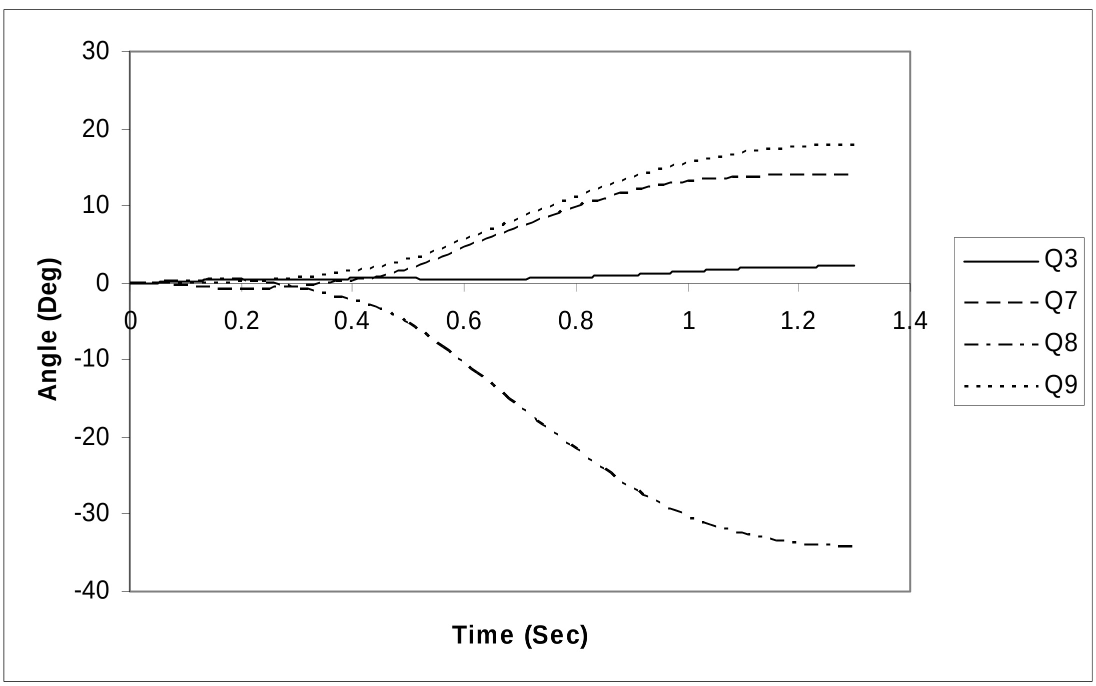


Figure 27 Barrier angles for simulated test 2-11

Figure 28 shows a graph of deflection versus time for simulated test 2-11. The deflection was calculated at the point between the second and third barrier segments. This is the point of maximum deflection for the barrier installation. According to Figure 28, the maximum simulated deflection for crash test 2-11 was 2.38 m (7.8 ft). According to the actual crash test, the maximum deflection for test 2-11 was 1.07 m (3.5 ft).

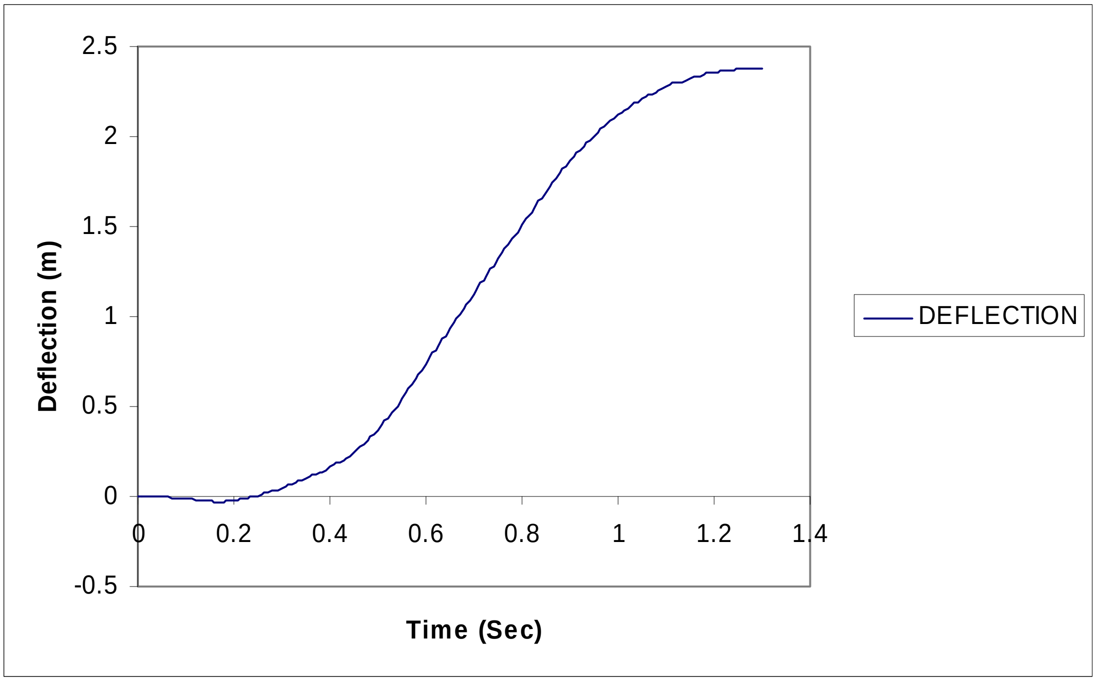


Figure 28 Maximum barrier deflection for simulated test 2-11

Figure 29 shows the angular velocities of the barrier angles. These angular velocities show how each barrier moves during the impact. This plot confirms the findings that the barrier is moving in the correct manner. This also can show how the barrier is accelerating with the vehicle impact and the other barrier sections.

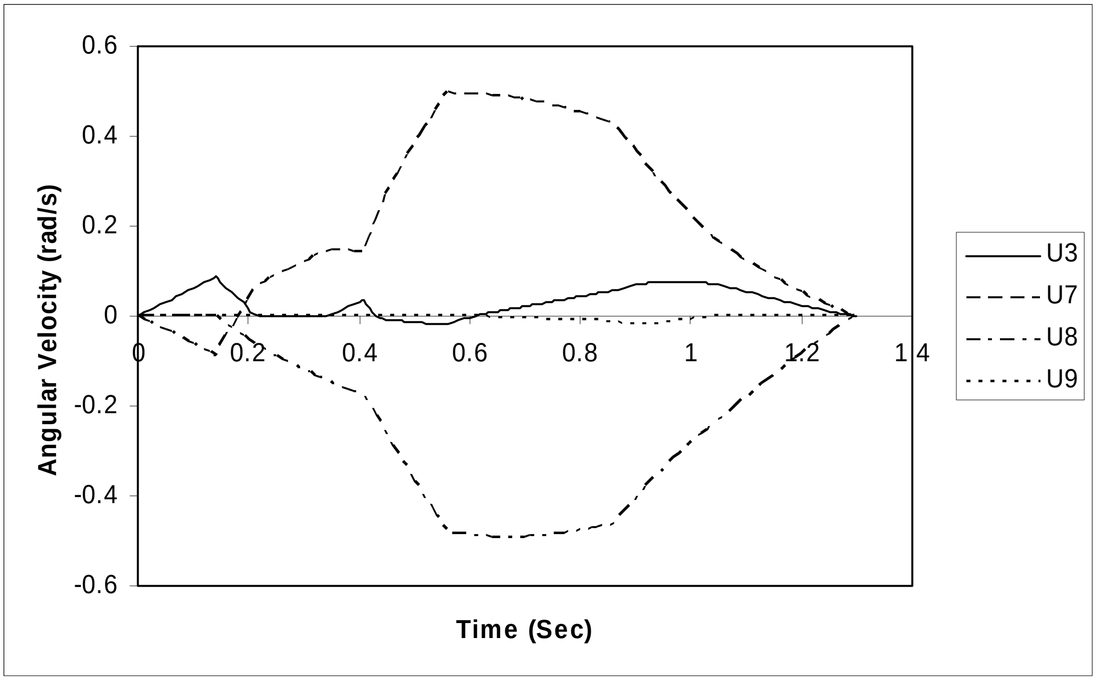


Figure 29 Barrier angular velocities for simulated test 2-11

Figure 30 shows the barrier angles for a 25 degree impact angle at 100 km/hr (62 mph). This test was simulated to determine how well the model worked for the crash test analysis. With the increasing speed, the barrier should deflect more as there is more kinetic energy that needs to be dissipated. This also means that the barrier angles should be greater for these impact conditions. Figure 30 shows that the barrier angles are not as great as the barrier angles for simulated test 2-11.

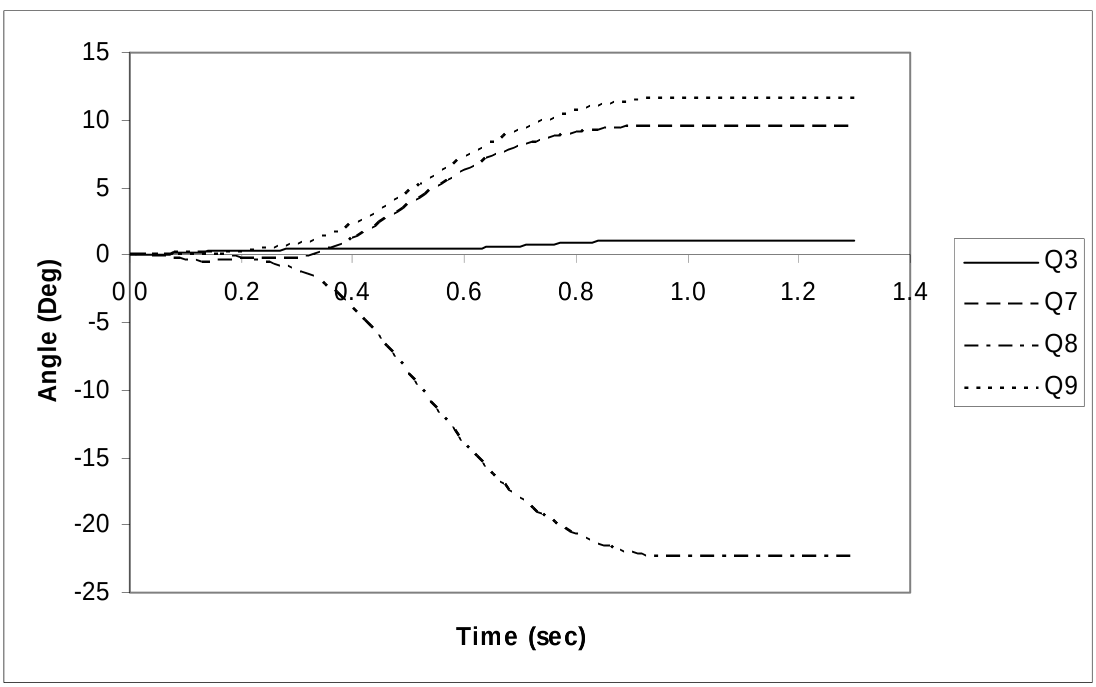


Figure 30 Barrier angles for simulated 25 degree impact at 100 km/hr (62 mph)

Figure 31 shows the deflection of the barrier for the test at the higher speed. This deflection should be greater than the deflection that was found from simulated test 2-11. The deflection for this test was found to be 1.56 m (5.1 ft) while the deflection for the original test was 2.38 m (7.8 ft). The test with the faster speed produces a lower deflection using this model. This will be explained in the next section.

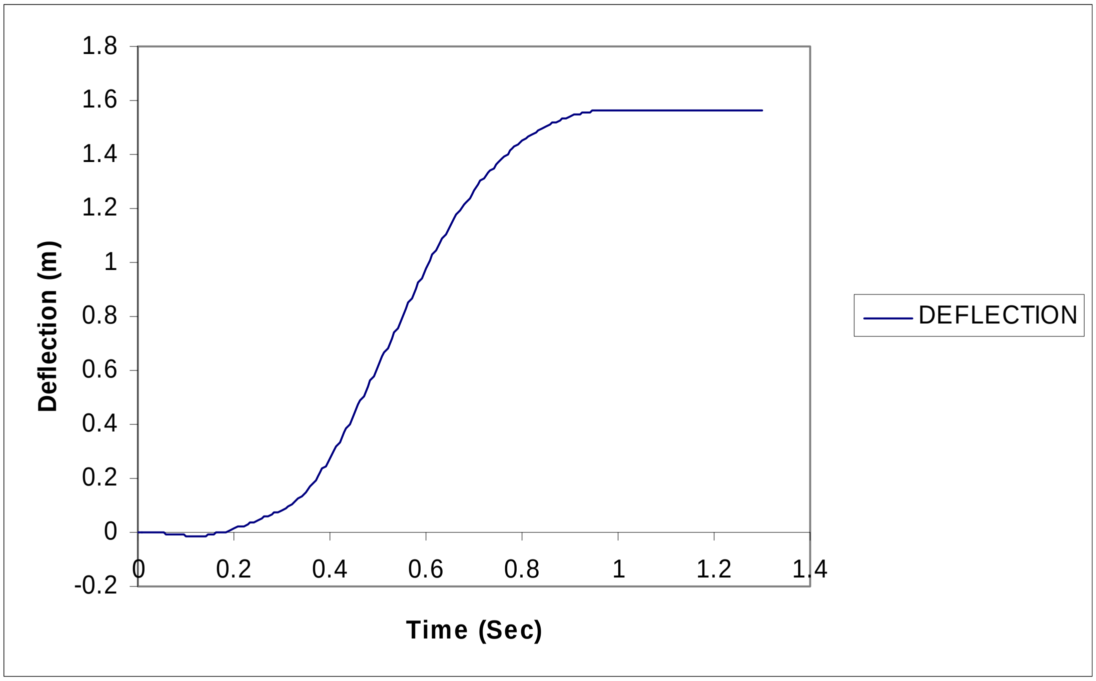


Figure 31 Barrier deflection for simulated 25 degree impact at 100 km/hr (62 mph)

Figure 32 shows the barrier angular velocities for the higher speed impact. These barrier velocities look the same as test 2-11, but the values are a little smaller. They also occur over a shorter period of time. This means that the vehicle was not in contact with the barrier as long as it was for test 2-11.

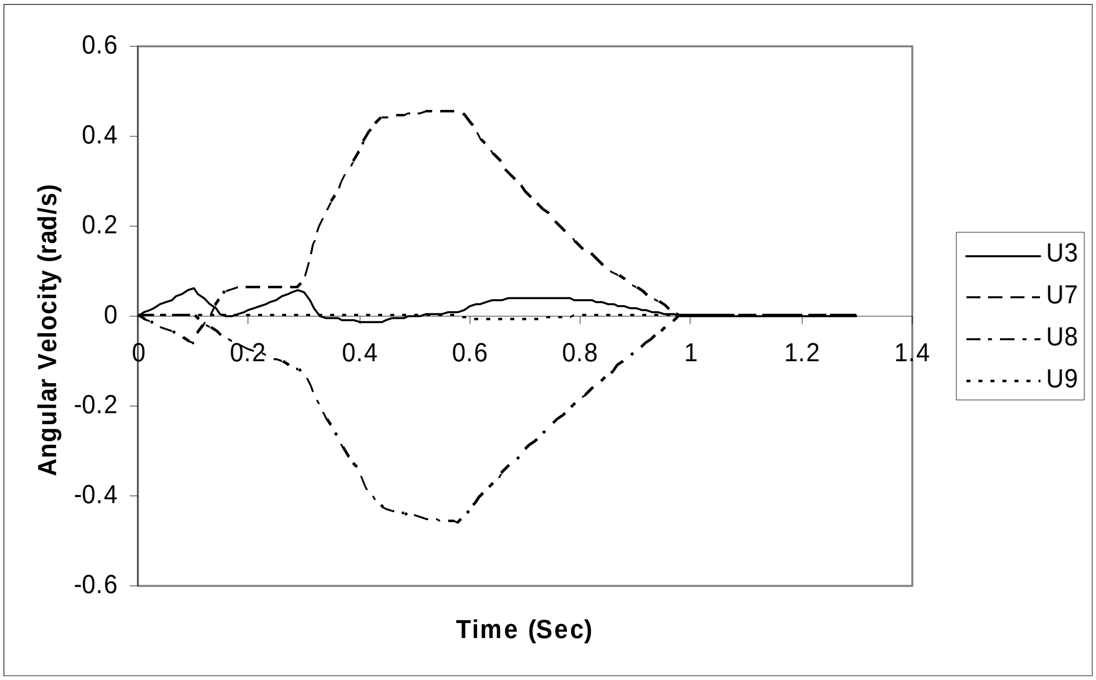


Figure 32 Barrier angular velocities for simulated 25 degree impact at 100 km/hr (62 mph)

The third test simulated used a 20 degree impact angle at 100 km/hr (62 mph). This test was run to determine if a change in the impact angle would produce the correct results. A smaller impact angle should result in a smaller deflection for the barrier because the kinetic energy of the impact is reduced. Figure 33 shows the barrier angles for the smaller angle test. The barrier angles are smaller than the 25 degree angle test which means that the smaller impact angle produced a smaller deflection as expected.

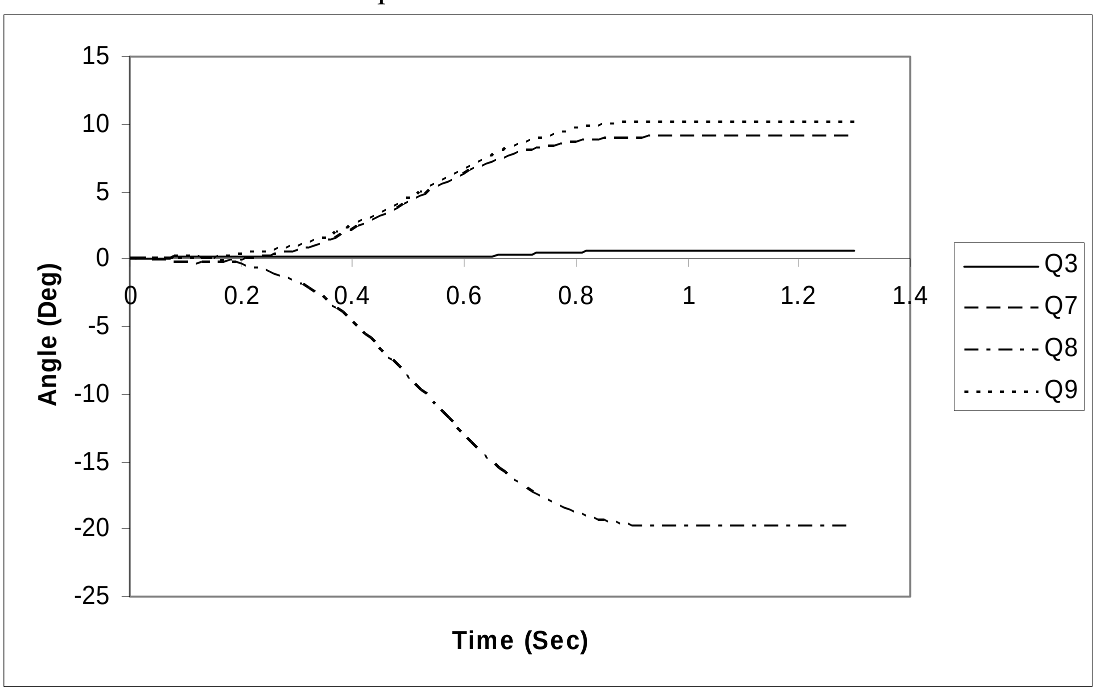


Figure 33 Barrier angles for simulated 20 degree impact at 100 km/hr (62 mph)

Figure 34 shows the barrier deflection for a simulated 20 degree impact test. The deflection for this test was found to be 1.38 m (4.5 ft) which is less than the deflection for the 25 degree impact test. This shows that the model properly accounts for impact angles in barrier crash tests.

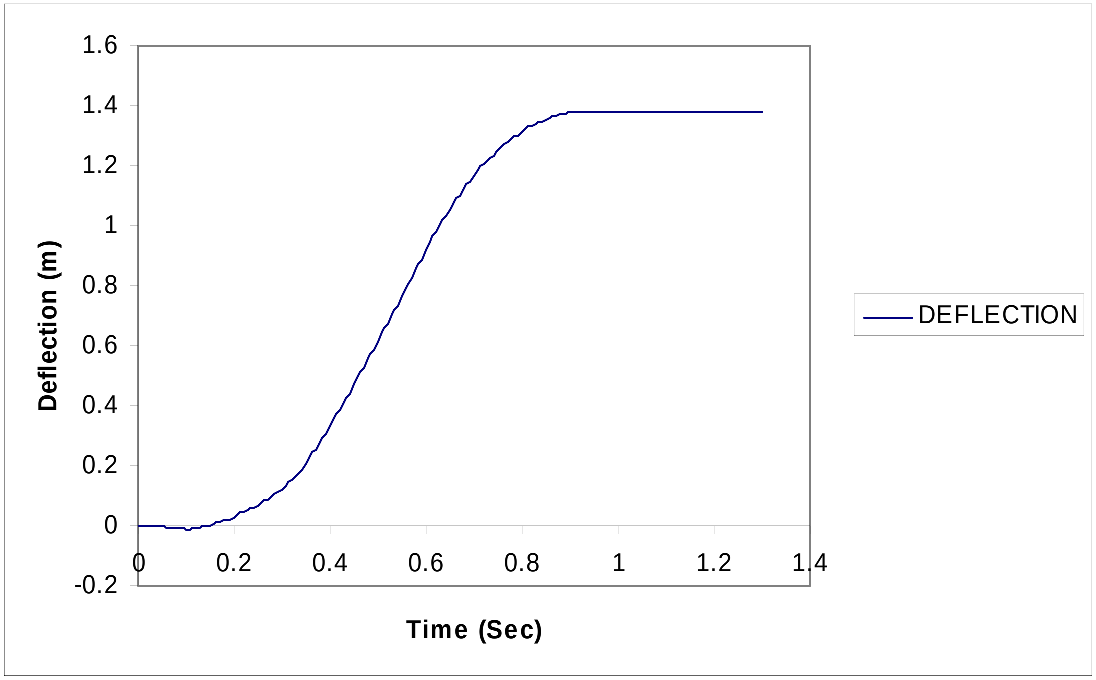


Figure 34 Barrier deflection for simulated 20 degree impact at 100 km/hr (62 mph)

Figure 35 shows the barrier angular velocities for the 20 degree impact. These barrier angular velocities are smaller than the 25 degree test. The barrier has a smaller deflection so the velocities would be expected to be smaller. The velocities also occur over a smaller period of time because of the reduced kinetic energy that has to be dissipated.

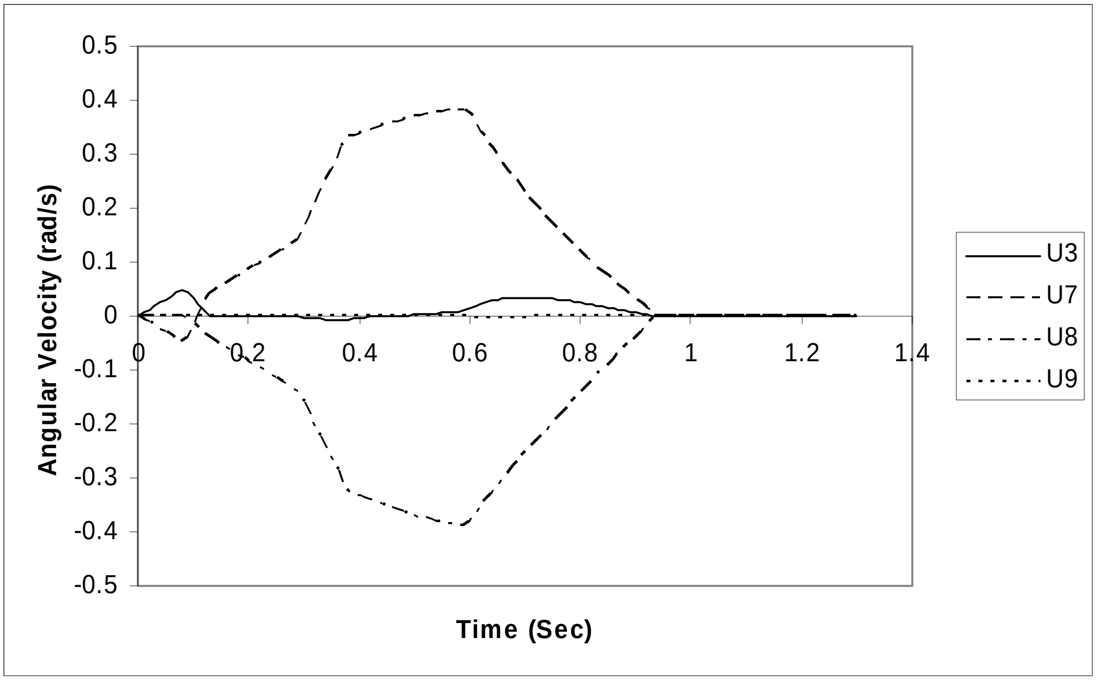


Figure 35 Barrier angular velocities for simulated 20 degree impact at 100 km/hr (62 mph)

The other information that is of use from the simulation is how the car reacts to the barrier impact. The vehicle will rotate as it impacts the barrier. This rotation can be plotted as a function of time during the impact. Figure 36 shows the vehicle heading angle with respect to the N reference frame. This angle would normally stop decreasing after the car leaves contact with the barrier, but there is no friction between the pavement and the tires of the vehicle, so the vehicle just keeps yawing in the same direction. Figure 36 shows that the barrier redirects the car as expected with the crash test results.

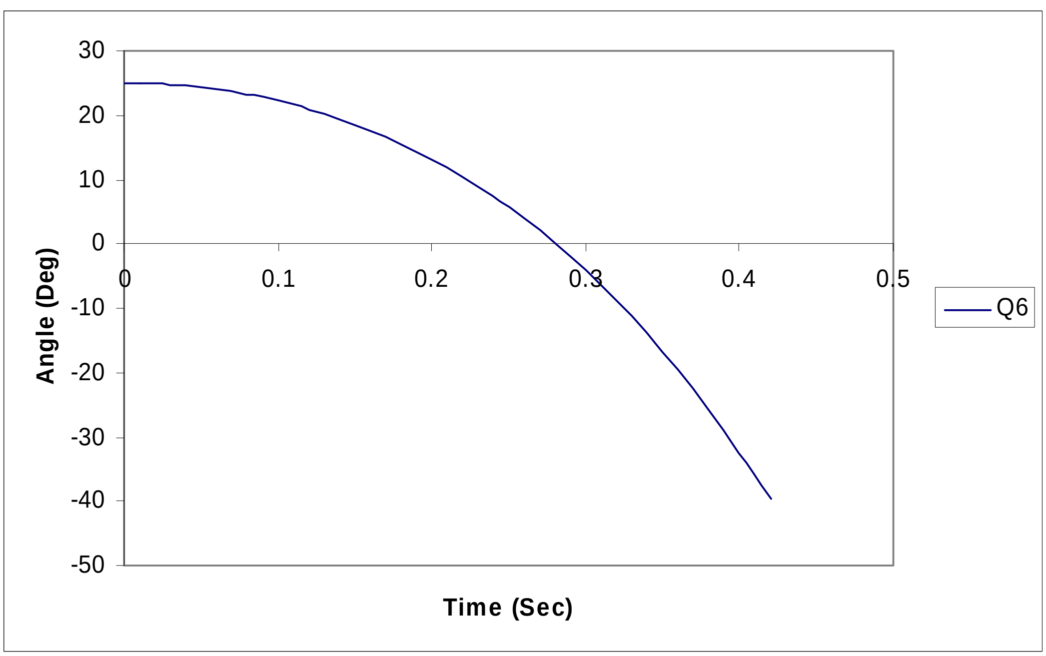


Figure 36 Simulated vehicle heading angle

Discussion of Results

The results for the simulated crash tests of the barrier show where the model excels and where the model falls short of achieving its goals. The main goal of developing this model was to determine the deflection of the barrier from specified impact conditions. The model did not produce the same deflection as the actual crash test for the barrier. This model predicted a deflection of 2.38 m (7.8 ft) for test 2-11 while the actual deflection for the crash test was 1.07 m (3.5 ft). The predicted deflection is over double the actual measured deflection. The shortfall in the deflection prediction of the model probably occurs due to the way the forces between the vehicle and the barrier are defined. The force between the barrier and the vehicle is not totally realistic. It is defined as a linear spring until it reaches a certain value where it remains constant. The crush stiffness that was used for the model might not be correct for the vehicle that was used for the crash test. These values are hard to determine and the crush of the vehicle is not going to be the same in all crash test situations. Another reason for the overestimation of the deflection is due to the friction model that was used. If static friction was used in this model, the deflection would be less because then the barrier to road friction would have to change from static to dynamic friction which would dissipate more energy. Other reasons could also be with the vehicle model. The vehicle model is very simplistic and there is no friction between the vehicle and the roadway. The overestimation of the deflection by the model is caused by a combination of these effects.

Another issue with the dynamic model is the fact that the deflection for the 100 km/hr (62 mph) impact, shown in Figure 31, is smaller than the deflection for test 2-11. This should not be the case. The reason this happens is due to how the forces between the vehicle and the barrier are defined. The force between the vehicle and the barrier is a function of the distance that the front or rear bumper point moves beyond the barrier. When the vehicle is moving slower, the point is beyond the barrier for a longer period of time, so more force is applied to the vehicle and the barrier. When the vehicle is moving faster, the vehicle is not able to exert as much force on the barrier. This is a drawback of how the force was defined for this model. This limits the model's ability to determine a barrier's performance under different testing conditions. In a true crash test, if the speed of the vehicle is increased, the deflection of the barrier should increase. However, in this test the deflection of the barrier actually decreased. Therefore, if a barrier is being tested with this model, the speed of the vehicle needs to remain constant for the results to be compared.

Another limitation to the model is its use of a pin connection between each barrier segment. Not all barriers are going be connected by a pin connection. Many concrete barriers would rotate as a pin connection for a very small rotation until the concrete barriers come in contact with each other. The rotation location then changes to where the concrete barriers are in contact with each other [39]. This model does not take into account any rotations other than the rotation around the pin connection. For the Safeguard Link System this pin connection assumption is acceptable, but for other barriers it is probably not acceptable.

The model also has trouble predicting the vehicle behavior. Due to the fact that the vehicle model does not have any friction between the tires and the roadway, and there are no vehicle dynamics taken into account, the vehicle continues to move at a constant speed and heading angle after the barrier impact. The lack of friction between the vehicle and the roadway allows the vehicle to yaw continuously after leaving contact with the barrier. This does not allow for the prediction of the vehicle motion after the impact with the barrier, but it does not affect the prediction of the barrier motion and deflection.

The model did seem to properly account for changes in the impact angle. If the impact angle of the vehicle is reduced, the deflection should also be reduced. The deflection for the 25 degree impact test was 1.56 m (5.1 ft) while the 20 degree impact test had a deflection of 1.38 m (4.5 ft). This is exactly what is expected.

This model does not do a good job of predicting the deflection for the barrier impact test, but that does not mean the model cannot be useful. It does a good job of predicting how the barrier deflects during the impact simulation. This means that the model could be used to determine how a new type of barrier will deflect during an impact. This model will work well as an initial design tool for developing a new barrier. However, if the deflection of the barrier needs to be estimated a non-linear finite element program would do a much more accurate job than this model.

Summary

The creation of the two-dimensional model was intended to assess the model's ability to predict the barrier behavior during a crash test. The model did a good job of qualitatively predicting the barrier behavior, but a poor job of actually predicting the correct values of the barrier deflection. This makes the model useful for the next project that the AHMCT Research Center is working on with the development of new mobile barrier concepts. The new mobile barrier concepts can be tested with this model to determine how the new concepts deform under the impact situations. Most of the model's errors are from simplifications and assumptions that were made to make it easier to use the model. If these simplifications and assumptions were refined, the model would be able to more closely represent the barriers characteristics.

The next chapter will discuss the conclusions for this report and also discuss some recommendations for a parallel AHMCT Research Center project regarding new concepts for mobile barrier applications. The new mobile barrier is going to be designed for use with completely mobile work zones. These could be maintenance activities along the roadway or slow moving road repair work to guardrails, or pot-hole patching. Based on the analysis of this report, there are some considerations and further research that should be addressed in the future.

CHAPTER 7
RECOMMENDATIONS AND CONCLUSION

This chapter will discuss the recommendations and conclusions from the research. The recommendations will consist of comments for the next research project that the AHMCT Research Center is working on, which is conceptualizing a new type of mobile barrier. There will also be recommendations about further research for temporary barrier usage in work zone to make the work zones safer for the motorists and workers. Conclusions on this research will also be discussed.

Recommendations

The following recommendations should provide ideas for the conceptualization of new mobile barrier designs and recommendations for further research on temporary barrier use in work zones.

Mobile Barrier Ideas

The only current mobile barrier available for use is the Balsi Beam. However, the Balsi Beam has limitations that limit its use to certain work zone situations. Designing a new mobile barrier that could be used in more work zone situations is a key aspect that needs to be addressed. The Balsi Beam cannot be used for continuously moving work zones, which excludes a lot of maintenance activities that occur on the roadways. The new barrier concept needs to be completely mobile. The barrier should be set up and moved as a barrier without having to take down the barrier before moving. The Balsi Beam also only allows for 9.14 m (30 ft) of protected work space. The new barrier should look into using a larger protection area which would make the barrier more versatile in the work zones it can protect.

The Texas Transportation Institute (TTI) designed two versions of its own mobile barrier. These designs used existing vehicles combined with steel guardrail or beams to provide positive protection for the work zone. Figure 37 shows the first TTI mobile barrier that was developed. This barrier used five vehicles along with steel guardrail in order to provide redirective capabilities for work zone protection. Figure 38 shows the second mobile barrier that TTI designed. This barrier used two dump trucks that were connected by a steel beam to provide the positive protection for the work zone. Each of these designs uses the same concept as the Balsi Beam, which is a mobile vehicle that uses steel beams to achieve positive protection. In order to develop a new mobile barrier system, new ideas and designs are needed.

Figure 37 First TTI mobile barrier [40]

Figure 38 Second TTI mobile barrier [40]

There are other concepts that have been developed for use as barriers on a roadway. One of these interesting concepts is know as the Dragnet [41]. The Dragnet is a cable barrier that can be deployed to close off the entrance to a lane. The ends are connected to energy absorbing terminals so when a vehicle runs into the net it is safely brought to a stop. Currently the technology cannot be used for a longitudinal barrier, but the technology does create interesting ideas. If a cable barrier system could be combined with a mobile barrier design, it would have the ability to contain the errant vehicle instead of redirecting it back into traffic. The containment of a vehicle would reduce any chances of a secondary collision which would make the work zone safer for the workers and occupants of the vehicle.

Combining the current technologies would allow the barrier to utilize the advantages that each technology has to offer. Currently, steel barriers are the most mobile barriers besides the Balsi Beam. These barriers provide great redirective capability and work zone containment. The cable barrier system provides great energy absorbing capabilities. A combination of these technologies could provide a new mobile barrier capable of protecting work zones with greater safety than what is currently available.

Recommendations for Further Research

Based on the results of the research and analysis of this report, recommendations are made for future research. The use of temporary barriers in work zones is continually advancing as new technology becomes available. Continual research in the area of temporary barrier usage will help keep the new technology available for use on the roadways and maintain safe and efficient work zones.

Research needs to continue in developing guidelines for the deployment of temporary barriers in work zones. The guidelines in this report help in determining how to deploy barriers for work zone applications, but there are more complex work zone scenarios that cannot be accounted for with the guidelines presented. In order to create guidelines that can be used for all work zone scenarios, a computer program should be developed that could be used to determine the layout for the work zone. This program would determine the deflection of the barrier and perform statistical analysis for certain scenarios. With the computational power available, there is no reason not to have a computational algorithm to determine the deployment guidelines for barrier installations.

The costs of the barriers that are given in the toolbox are the cost of each barrier. These costs do not include the installation cost that the contractor charges. The costs of installing a barrier for each work zone situation will depend on the installation site and it is subject to contractor bids. This makes the true installation cost hard to obtain because each bid is individualized depending on the deployment of the barrier in the work zone. Further research in the installation costs of these barriers would help determine the cost effectiveness of each barrier for work zone protection. This is a difficult task to undertake as all work zone designs are different and therefore installation costs will vary. However, if enough information is obtained, an average cost could be calculated and used to help in determining the installation cost of a barrier for a work zone. This cost would be very beneficial to Caltrans in determining the expected costs for a specific work zone design.

Another area of research interest is developing a more advanced benefit cost analysis program. Currently there are no benefit cost algorithms that work well for temporary barrier usage in work zone situations. The benefit cost algorithms are set for long durations of time and do not distinguish between each barrier. A benefit cost program would be a great addition to Caltrans deployment guidelines. This program could also be integrated into the deployment guidelines program, which would allow for determining when and how to deploy a barrier for a work zone situation. This program would use an algorithm to analyze the unlimited number of work zones that exist. It would need to be easy to update so new barriers could be added as they were developed. The use of a computer program to develop and analyze the work zone would greatly benefit Caltrans.

Conclusion

The goal of this work was to develop the toolbox of innovative safety barriers for temporary barrier usage in work zones. The final toolbox will be available as a web based application that can be easily updated to add information as it becomes available. This web based utility will allow Caltrans to easily disseminate information to its employees. This website will contain all the information needed for developing work zones. New technology of barriers is not just created in the United States. Foreign countries are creating new and innovative products that could aide in the protection of work zones in the United States. The technology available for work zone protection is continually evolving. The guidelines for barrier use need to evolve with the technology. This will create the safest work zones possible with the most current technology available.

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