



**University of California at Davis
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Development Of New Kinds Of Mobile Safety Barriers

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Abstract

This document reports on two studies supported under the noted task order. The first part of the report discusses the status of intrusion alarms for work zones. An intrusion alarm detects when a vehicle breaches the work zone and alerts people in the proximate area. The main selling point is to capitalize on being rapidly deployed, while providing advance warning to the workers when a vehicle penetrates the work zone. These devices have an audible alarm (typically 130-120 db) to notify workers and the general public when a work zone breach has occurred.

While the concept of an intrusion alarm seems promising, there are many limitations to these systems which make them generally impractical. Additionally, based on the fact that many companies have looked into intrusion alarms and that only one company has an active product line suggests that current systems have significant limitations both from their technical implementation as well as worker acceptance.

Additionally, this report covers the finite element crash test simulations on the low-profile barrier to determine the geometry that had the least permanent deflections and best met construction feasibility. The simulations were completed under the guidelines of test level 2 of the *National Cooperative Highway Research Program (NCHRP) Report 350*. Prior to the crash test simulations, a foundation had to be designed. A 2-dimensional finite element parametric study of various cross-sections for the foundation was studied and one was selected because of its simpler constructability and ability to resist impacts. There were two crash test case studies. The first case tested the maximum permanent deflections (installed in weak soil) whereas the second case tested the barrier structure (installed in rigid soil). The study concluded that both the weak and rigid soil simulations were within acceptable limits.

Executive Summary

This document reports on two studies supported under the noted task order. The first part of the report discusses the status of intrusion alarms for work zones. An intrusion alarm detects when a vehicle breaches the work zone and alerts people in the proximate area. The main selling point is to capitalize on being rapidly deployed, while providing advance warning to the workers when a vehicle penetrates the work zone. These devices have an audible alarm (typically 130-120 db) to notify workers and the general public when a work zone breach has occurred.

While the concept of an intrusion alarm seems promising, there are many limitations to these systems which make them generally impractical. One huge benefit to intrusion alarms is the huge cost savings due to reduced deployment time in comparison to more bulky positive protection systems. From conversations with experts in the field and examination of literature, it seems that one important way to reduce injuries is to better control equipment traffic within the work zone. Additionally, moving the flagger from the critical point of the closure through the implementation of Automated Flagger Assistant Devices (AFADs) could reduce risk significantly. Work zone fatalities could be reduced with better traffic control strategies both for the general motorist and within the work zone itself. A significant reduction in injuries involving workers and the general public could be gained through the development of rapidly deployed positive protection systems, which provide the workers with a higher level of protection. A positive protection system, which gives the workers a real sense of security, will also increase worker production as they can focus more on the task at hand. Additionally, based on the fact that many companies have looked into intrusion alarms and that only one company has an active product line, suggests that current systems have significant limitations both from their technical implementation as well as worker acceptance.

Part 2 of this report discusses the modeling of universal barrier foundations. Specifically, it covers the finite element crash test simulations on the low-profile barrier to determine the geometry that had the least permanent deflections and best met construction feasibility. The simulations were completed under the guidelines of test level 2 of the *National Cooperative Highway Research Program (NCHRP) Report 350*. Prior to the crash test simulations, a foundation had to be designed. A 2-dimensional finite element parametric study of various cross-sections for the foundation was studied and one was selected because of its simpler constructability and ability to resist impacts. There were two crash test case studies. The first

case tested the maximum permanent deflections (installed in weak soil) whereas the second case tested the barrier structure (installed in rigid soil). The study concluded that both the weak and rigid soil simulations were within acceptable limits.

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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

BRIEF STATUS ON INTRUSION ALARMS

Worker safety in temporary work zones is essential and has become a high priority as traffic volumes continue to increase. Many positive protection systems have been developed such as portable concrete barriers (PCB) or water filled barriers. Systems like these take a substantial amount of time and money to set up, but provide a high level of protection to workers. The other end of the spectrum is a work zone which is simply defined by traffic cones. A cone system is convenient since there is minimal deployment time. The downside to a cone system is the lack of positive worker protection. There are a variety of costs and benefits associated with the different work zone systems. The cost can be quantified as a function of equipment and labor. The benefit is the level of protection to the worker and the general public. Comparing the quantifiable “cost” to the qualitative “benefit” in order to justify utilizing a specific work zone protection system is a challenge. Generally, the PCB systems are employed for longer term projects, while cone systems are better suited for short duration work zones.

An intrusion alarm detects when a vehicle breaches the work zone and alerts people in the proximate area. The main selling point is to capitalize on being rapidly deployed, while providing advance warning to the workers when a vehicle penetrates the work zone. These devices have an audible alarm (typically 130-120 db) to notify workers and the general public when a work zone breach has occurred.

The concept of an intrusion alarm is not new. Efforts were made to develop this kind of system as early as 1961 [1]. In the early 1990’s, the Strategic Highway Research Program (SHRP) supported work aimed at developing intrusion alarms [2]. Presentations by Peter Hatzi [3] and by Ken Kochevar [4] discussed many companies who were developing intrusion alarms (both held positions with the Federal Highway Administration [FHWA]). These systems could all be classified in essentially three categories as discussed below.

One approach was to augment the traditional road cone with a tipping sensor which has a means to sound an alarm once the cone is knocked over. Some of these systems have the sensor and alarm incorporated into a single unit. Other systems have a tipping sensor which relays information to a base station where the physical alarm is located. False positives are a key concern as the cones may be tipped over simply by the wind. These sensors represent

point functions, meaning that the alarm will only be triggered if a cone is knocked over. Theoretically, it may be possible for a car to encroach into the work zone without knocking over a cone, and in such an instance, no alarm will sound. Therefore in implementing this kind of system, the traffic control plan (TCP) must take into account the mean vehicle speed and associated vehicle dynamics to ensure that vehicles cannot enter the work zone without hitting a cone. Figure 1 depicts an example of this type of device.



Figure 1. The First Generation of the Sonoblaster^[4]

Another approach is to utilize pneumatic tube traffic counter technology to form a perimeter around the work zone as shown in Figure 2. One example of this system is shown in U.S. patent 5,661,474 [5]. This kind of system forms a continuous perimeter. As a vehicle drives over the tube, a pressure wave is induced in the tube which is detected. One benefit of this style of system is that false positives are greatly reduced. One of the drawbacks to this kind of system (as well as the augmented cone system) is that the worker is not notified when he encroaches into a live lane. Although the system would detect when a worker steps on the pneumatic tube, a worker can just as easily step over the tube. Pneumatic tools are often used within a temporary work zone, so the workers are used to stepping over hoses and may confuse the pneumatic sensing tube for a typical air hose.



Figure 2. Typical Perimeter System Using Pneumatic Tubes^[3]

The third approach is based on developing an electronic barrier in which a transmitter unit and receiver unit are aligned to create the invisible continuous barrier. An example of this type of system is shown in U.S. patent 4,322,722 [6] where a pulsed microwave is utilized. As a vehicle breaches the work zone the line of sight between the transmitter and receiver is disrupted and an alarm is sounded. A worker will break the signal just like a vehicle reducing the chances that they will inadvertently move into a live lane. Transmitter/receiver alignment is the key to these types of systems which must be accomplished during the initial work zone installation. This alignment must also be maintained during the life cycle of the work zone. Such a system is shown schematically in Figure 3. One advantage of this type of system in comparison to an augmented cone system is that when the work zone is breached, the alarm system itself is not in as much danger to being damaged. This is highly desirable as this kind of system is much more expensive on a unit basis than the augmented cone systems.

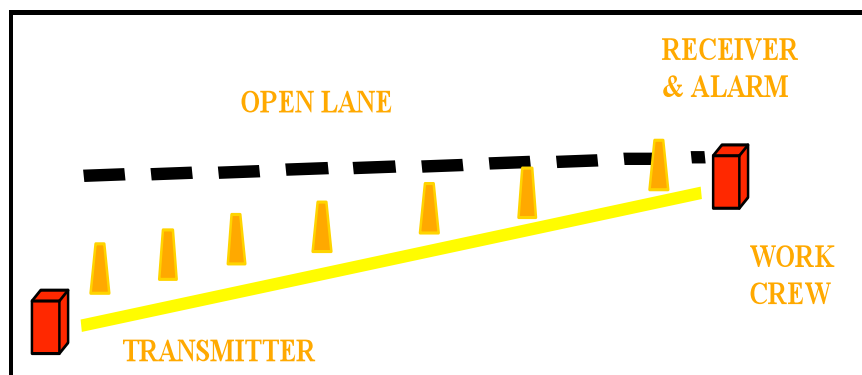


Figure 3. Basic Beam System^[4]

The Hatzi presentation mentions seven different companies which were involved in intrusion alarm development. However, only two were able to be reached: ASTI Transportation Systems (ASTI) and Central Security and Electronic. Efforts were also made to contact Mr. Hatzi directly, but he has since retired.

The ASTI system used a line of sight type system involving a transmitter and receiver which are both shown in Figure 4. An ASTI [7] representative said in a phone conversation that they have the ability to assemble some units, but they are not actively marketing the system. One of the limitations of the system was the alignment. On relatively flat and straight roads, aligning the system is easy, but when the road is uneven, the alignment can be difficult.

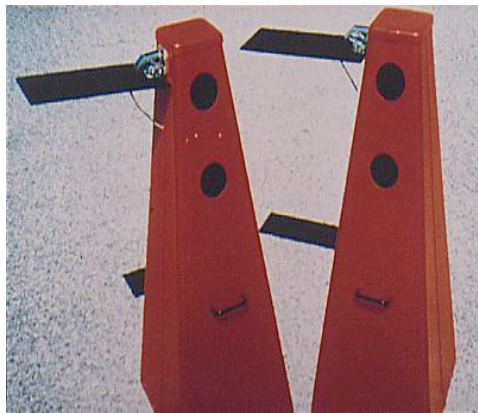


Figure 4. Beam Style Intrusion Alarm^[3]

Central Security and Electronics (CSE) has also been contacted. Their system was based on a pneumatic tube traffic counter. Their representative, Nic Barrack [8], informed me that CSE is no longer manufacturing the system. The system uses radio telemetry to communicate between the sensor and a remote system which has the alarm. The difficulty is getting a radio receiver system which would respond fast enough to be useful. Radio telemetry systems are widely used in security systems. The frequency response of security systems can be relatively slow, resulting in a time lag on the order of 100 ms. At a speed of 26.8 m/s (60 mph), a 100 ms time lapse corresponds to 2.682 m (8.8 ft) of vehicle travel. Thus, precious time for worker response is wasted simply by the reaction time of the system. Therefore, in the development of the CSE system, which is shown in Figure 5, efforts were made to decrease the system response time in order to maximize the time that the worker has to react to a work zone breach. This drove up the system cost. Mr. Barrack felt that the system was practical to use for work zones which last ½ day minimum in order to justify the additional deployment cost. Mr.

Barrack also felt that the system would be unprofitable due to the large marketing cost needed to reach a relatively small specialized market. Therefore the system has not been widely sold and was never mass marketed. Mr. Barrack said that he is capable of making more units, but he would not do so unless there was a large enough volume to justify his time as the radio units were highly specialized and difficult to fabricate. On a side note, during the conversation with Mr. Barrack, he said that Virginia requires intrusion alarms to be utilized for work zone enclosures. However, they are working on eliminating this requirement as obtaining an intrusion alarm is currently difficult since they are no longer readily available.

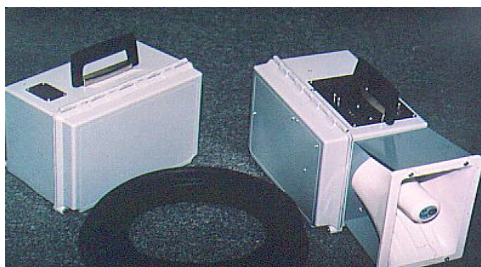


Figure 5. CSE System^[3]

Ken Kochevar reported three additional companies involved in intrusion alarm development in his presentation: Safety Line, International Road Dynamics (IRD), and Logic Systems. However, through email contact, Mr. Kochevar said he had difficulty getting any current information about the systems from these companies, and he has stopped actively promoting these systems.

The Safety Line system appears to be similar in principle to the ASTI system. In looking for additional facts about the Safety Line system, a research update on the SHRP intrusion alarm confirmed that Safety Line was merely a distributor of the ASTI system [9]. The system uses an infrared beam which uses line of sight between the transmitter and receiver. When the line of sight is disrupted, the alarm is activated. This report also mentioned that a significant amount of time was required to initially line up the transmitter and receiver.

The Sono-Blaster system (see Figure 1), mentioned in the Kochevar presentation, was an International Road Dynamics (IRD) product. A phone conversation with IRD [10] revealed that a limited number of units are still available, however the product is discontinued. They felt that the system was not profitable enough to justify continued support. Their units were selling for about \$300 each. The system has a patented tipping sensor [11, 12] which activates

a horn when knocked over. Each unit was independent and utilized a compressed CO₂ cartridge for horn activation. The rights to this product have changed to Transpo Industries, who have created a second version of the Sono-Blaster (see Figure 6). Transpo has indicated thru a telephone conversation [13] that efforts are being made to provide each state DOT with approximately 50 units at a cost of \$50-\$60 each for evaluation purposes. The deployment time frame for this is unclear as the manufacturing details are still being worked out.



Figure 6. Second Generation of the Sonoblaster^[13]

Logic Systems also tried to develop a wireless intrusion alarm system which they patented [14]. The idea of this system was to augment road cones with a wireless communication system with tipping sensors. The proposed equipment included an alarm box, as well as devices that each individual worker could wear (such as a hard hat, pager type unit, or integrated hearing protection) which would alert the worker of a breach in the work zone. The owner of the company [15], who also invented the system, did not completely develop it, he has since sold the company, and is looking to sell the patent rights.

Efforts were also made to identify any other companies who are developing intrusion alarms. With the exception of the Transpo system mentioned above, no other intrusion alarms were identified. Table 1 summarizes the identified companies which have worked on various intrusion alarm concepts. Most of these companies could not be located and it is believed that they are out of business and are no longer developing their respective systems.

Table 1. Summary of Intrusion Alarm Systems

System	Company	Type	Source/Availability
Infrared Intrusion Alarm	ASTI Transportation Systems	Line of sight	Hatzi/Unavailable
Microwave Intrusion Alarm	Traffic Management Systems Corp.	Line of sight	Hatzi/Unavailable
Pneumatic Tube & Radio	Safe-Lite Systems	Pneumatic Tube	Hatzi/Unavailable
Pneumatic Tube Intrusion Alarm	Central Security and Electronic	Pneumatic Tube	Hatzi/Unavailable
Pneumatic Tube Intrusion Alarm	Columbia Safety Corporation	Pneumatic Tube	Hatzi/Unavailable
Pneumatic Tube Intrusion Alarm	Action West	Pneumatic Tube	Hatzi/Unavailable
Watch Dog Perimeter Work Zone Intrusion Alarm	Kenco International	Pneumatic Tube	Hatzi/Unavailable
Safety Line SL-D12	Road-Tech Safety Services, Inc.	Line of sight	Kochevar/Unavailable
Wireless Warning Systems	Logic Systems	Augmented Cone	Kochevar/Unavailable
Sonoblaster	International Road Dynamics	Augmented cone	Kochevar/Unavailable
Sonoblaster	Transpo Industries Inc.	Augmented Cone	Internet Resource/Available

Over the process of investigating intrusion alarms, some interesting issues were also identified that have bearing on work zone safety. Many of these issues were exposed in a conversation with Chad Dornsife [16], founder of the highway safety group. These include sources of work zone injuries and lane closure design. His organization is primarily focused on public safety on highways. However, there is a strong relationship between public safety and work zone safety.

Mr. Dornsife stated that a large percentage of work zone fatalities do not involve the general public. This is supported by reviewing the list of highway work zone fatality investigation reports on the National Institute for Occupational Safety and Health (NIOSH) [17] website which cites many cases where the worker on foot was injured by work equipment. The remedy for this would be to have better traffic control of equipment used within the work zone.

Mr. Dornsife stated a situation in which the worker accidentally walked into a live lane and was killed by a passing motorist. If there was some method of constraining the worker to the work zone, this fatality could have been avoided. This supports the need to protect the moving traffic from worker encroachment. However, it is obvious that the worker is more at risk since they are more vulnerable to severe injuries.

Work zone injuries could also be reduced by developing better practices for traffic control plans. According to Mr. Dornsife, a large percentage of work zone deaths are to flaggers who

are typically placed in parts of the work zone where traffic is in a state of chaos. Mr. Dornsife argues that instead of putting a person at the critical point, efforts should be made to use automated flagger assistant devices (AFADs). These devices do not eliminate the job of the flagger, however, they allow the flagger to perform their duties from a much safer location.

Time is a critical factor which must be maximized for an effective intrusion alarm. The worker needs time to perceive the alarm, calculate where to go, and finally physically move to a safe location.

There are many factors which affect the workers ability to perceive the alarm. Experience shows that people who are used to working next to live lanes become desensitized to the inherent dangers of their work environment. This allows them to become more involved in the task at hand and lose some awareness of their surroundings. Furthermore, false alarms would hamper the system's effectiveness. Too many false positives will cause the worker to lose faith in the system and increase the time needed for the worker to perceive a real threat. The increase in time is due to the added process of determining whether the alarm is real or false.

Workers also face the added difficulty in determining a safe location when an intrusion alarm is set off. One of the first steps in determining where to go is determining where not to go. People have the ability to generally determine the location from where a noise is coming from. However, this is impaired by many of the systems mentioned above, as the alarm and the sensor are not co-located. In systems where the sensor and alarm are co-located, the sound intensity where the workers are located will be greatly reduced due to the spatial distance between the alarm and the functional portion of the work zone. This significantly reduces the systems effectiveness as mentioned in early evaluation efforts by the Strategic Highway Research Program (SHRP) [9]. Clearly the worker has some indication as to where the danger is coming from based on the typical flow of traffic. On the other hand, the worker needs to have a very clear sense of where the danger is located in order to determine a safe location to migrate to.

After determining where to go based on the intruding object's trajectory, the worker must then physically move to a safe location. This is difficult as there could be obstacles in the work zone which may impede the workers ability to move quickly.

In order to have a better sense of the situation, a vehicle traveling at 26.8 m/s (60 mph) will travel 26.8 m (88 ft) in 1 second. As such, the system must be able to sense intrusions a significant distance in advance of the workers. The sooner the alarm system can detect a breach,

the more time the workers have to react to the threat. In the discussion above, the frequency response of the alarm itself was discussed. Any lag in the system between when the breach occurs and the alarm is sounded, directly reduces the time the worker has to respond.

While the concept of an intrusion alarm seems promising, there are many limitations to these systems which make them generally impractical. One huge benefit to intrusion alarms is the huge cost savings due to reduced deployment time in comparison to more bulky positive protection systems. From conversations with experts in the field and examination of literature, it seems that one important way to reduce injuries is to better control equipment traffic within the work zone. Additionally, moving the flagger from the critical point of the closure through the implementation of AFADs could reduce risk significantly. Work zone fatalities could be reduced with better traffic control strategies both for the general motorist and within the work zone itself. A significant reduction in injuries involving workers and the general public could be gained through the development of rapidly deployed positive protection systems, which provide the workers with a higher level of protection. A positive protection system, which gives the workers a real sense of security, will also increase worker production as they can focus more on the task at hand. Additionally, based on the fact that many companies have looked into intrusion alarms and that only one company has an active product line suggests that current systems have significant limitations both from their technical implementation as well as worker acceptance.

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CHAPTER 2 DEVELOPMENT OF UNIVERSAL BARRIER FOUNDATIONS

Summary

This chapter covers the finite element crash test simulations on the low-profile barrier to determine the geometry that had the least permanent deflections and best met construction feasibility. The simulations were completed under the guidelines of test level 2 of the *National Cooperative Highway Research Program (NCHRP) Report 350* [5]. Prior to the crash test simulations, a foundation had to be designed. A 2-dimensional finite element parametric study of various cross-sections for the foundation was studied and one was selected because of its simpler constructability and ability to resist impacts. There were two crash test case studies. The first case tested the maximum permanent deflections (installed in weak soil) whereas the second case tested the barrier structure (installed in rigid soil). The study concluded that both the weak and rigid soil simulations were within acceptable limits.

Background

The crash test simulations were tested under the conditions of test 2-10 of the *NCHRP Report 350* guidelines. It requires an 820-kg vehicle to impact the barrier at a speed of 43.5 mph (70 km/h) at an angle of 20°. The occupant risk criteria of Table 5.1 of the *NCHRP Report 350* served as a guideline for generally acceptable dynamic performance.

The software used to simulate crash testing on the low-profile barrier was LS-DYNA. It is a simulation software package that computes using nonlinear transient dynamic finite element analysis using explicit time integration.

Research Work Performed

This section reports on research work performed by subcontractor ARA during the project period. The section is divided into three phases as described below:

Phase I

During the first phase, three main objectives were identified as follows:

1. Calibration of a soil model
2. A 2-dimensional study for foundation cross-section designs
3. A 3-dimensional full-length impact with a C2500 (820-kg) pickup

The approach in modeling the soil was to use a solid continuum in the 2D models to effectively capture realistic soil behaviors important in determining the barrier response, in

addition to the passive resistance criteria. These models include elasticity, compaction or permanent set, shear failure, and inertial resistance. The soil design criteria were as follows:

1. Loose sand with a density of 110 pcf.
2. Coefficient of passive lateral earth pressure, $K_p = 3$
3. Deflection to depth ratio = 0.04. This is the approximate relative movement at the top of a retaining wall to reach the maximum passive earth pressure in loose sand, per table C5.5.1-1 of the *Caltrans Bridge Design Specifications, April 2000* [4], Sect. 5.
4. For 475 mm deep x 30 mm wide block in soil model, total force at 19 mm lateral deflection is 175 N or 39 lbf.

The next step after calibrating the soil model was to determine the most effective foundation cross-section in resisting vehicle impacts. A parametric design study of various cross-sections of the foundation was performed using LS-DYNA to determine effective sizes and geometries. Ten different foundation cross-sections were modeled. The parametric study narrowed the selection of the cross-sections down to sections 3, 8, and 9 (See Figure 7).

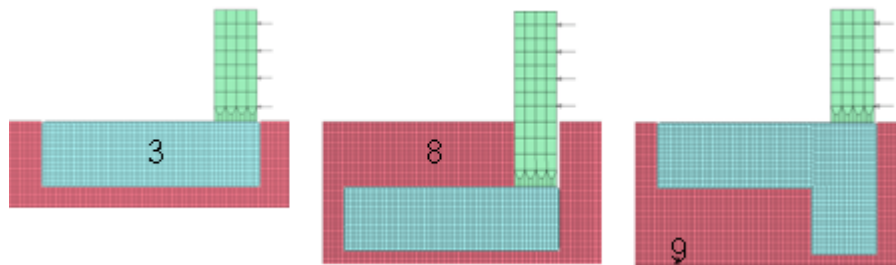


Figure 7. Cross-Sections 3, 8, and 9

The full length rigid barrier impact with a C2500 pickup was completed on cross-section 9 (See Figure 8). The 3-dimensional simulation of section 9 yielded deflections that were lower than the 2-dimensional parametric cases.

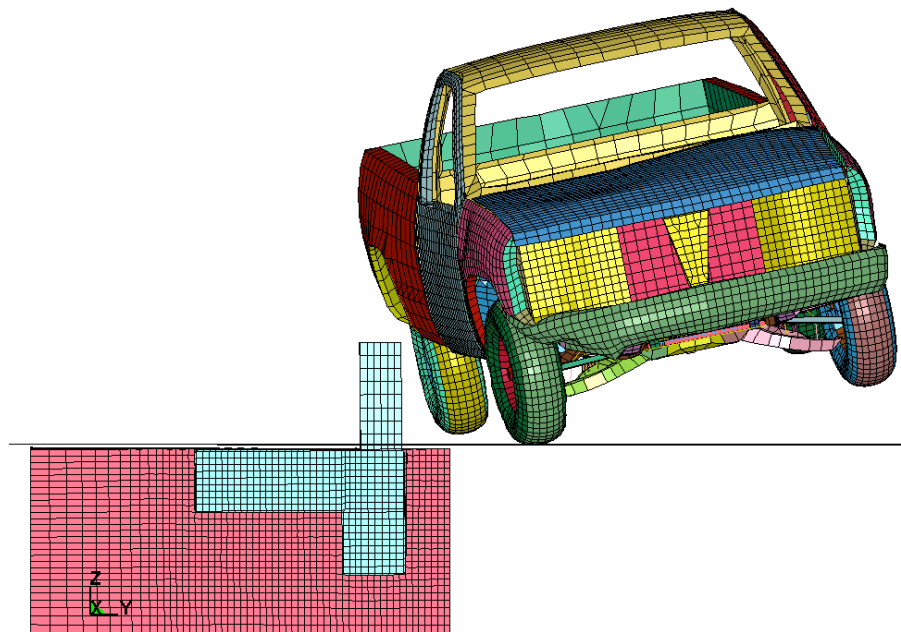


Figure 8. C2500 Pickup Impact on Cross-Section 9

Although the L-shape keyed foundation (cross-section 9) was the most resistant to impacts, a decision was made to use cross-section 3 since it was easier to construct and yielded similar results [1].

Phase II

During the second phase of the project, the crash test simulations (in 3-dimensions) were conducted with two soil extremes. The low-profile barrier was installed on the cross-section 3 foundation for the full crash test simulations (See Figure 9).

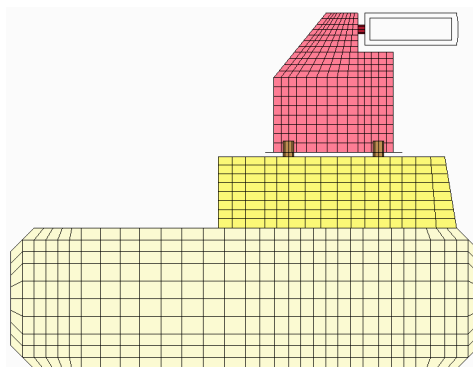


Figure 9. Cross-Section 3 foundation with Low-Profile Barrier Installed

The low-profile barrier model was impacted by the pickup truck in weak soil (loose sand) and in rigid soil to evaluate deflections and foundation strength. Only 50 feet of the low-profile

barrier was modeled to reduce computation time (See Figure 10). Note that a 100 feet long test section will be built and crash tested to validate the simulation in a later project

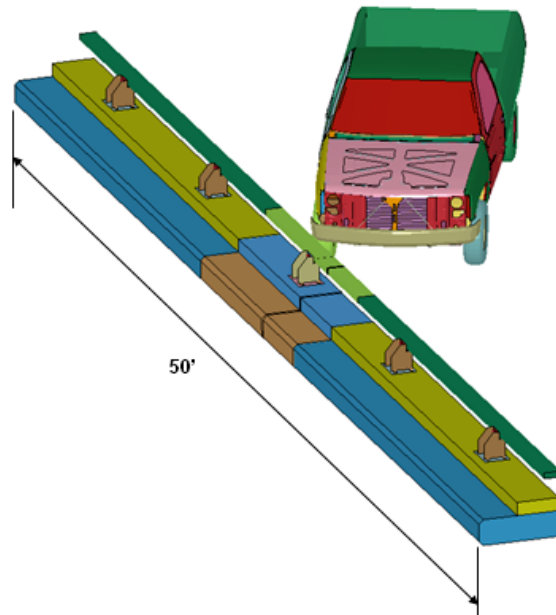


Figure 10. 50 Feet Long Simulated Test Section

The rigid soil test simulation concluded that the low-profile barrier structure met the evaluation criteria. The bolts were able to carry the loads sufficiently. However, subsequent impacts in the same location could cause steel parts to rupture and possibly fail at the anchor and rail bolts, which would require repair or replacement (See Figure 11).

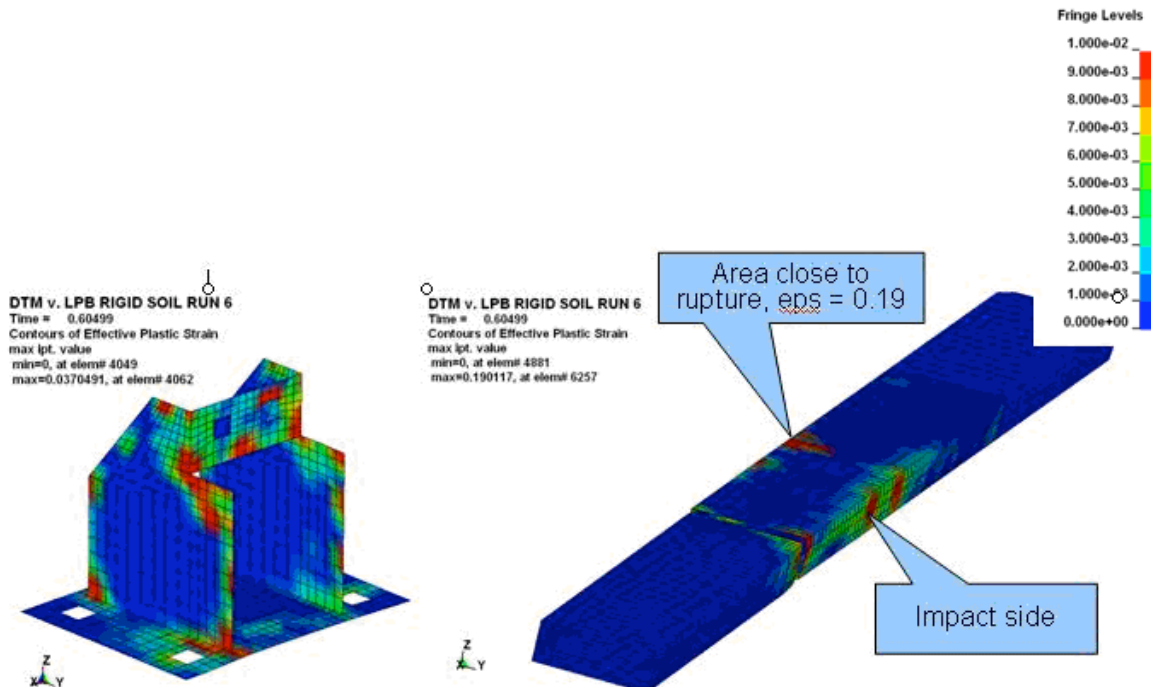


Figure 11. Impact side and Area close to rupture

The steel parts deformed plastically but not enough to cause snagging or pocketing concerns for subsequent impacts. However, the high rail strain at the center post from the splice bending needed to be strengthened or redesigned.

The weak soil test simulation was the same in the rigid soil except that the barrier was placed in a 90 pcf (pound per cubic-foot) sand block. The test concluded that the anchor and rail connector bolt maximum forces were less than the rigid soil test. Plastic strains in the post plates and rail were also less than the rigid soil test. This simulation focused on evaluating deflections of the barrier, reinforcing steel stresses in the foundation, and vehicle response.

The vehicle was redirected and did not roll, snag, or pocket. The lateral occupant impact velocity (OIV) was 5.03 m/s. The longitudinal OIV was 4.3 m/s. The preferred value in *NCHRP Report 350* is 9 m/s. The lateral and longitudinal ridedown accelerations were 8.2 g and 5.1 g. The preferred value is 15 g. The maximum lateral permanent rail deflection was 66 mm (See Figure 12) [2].

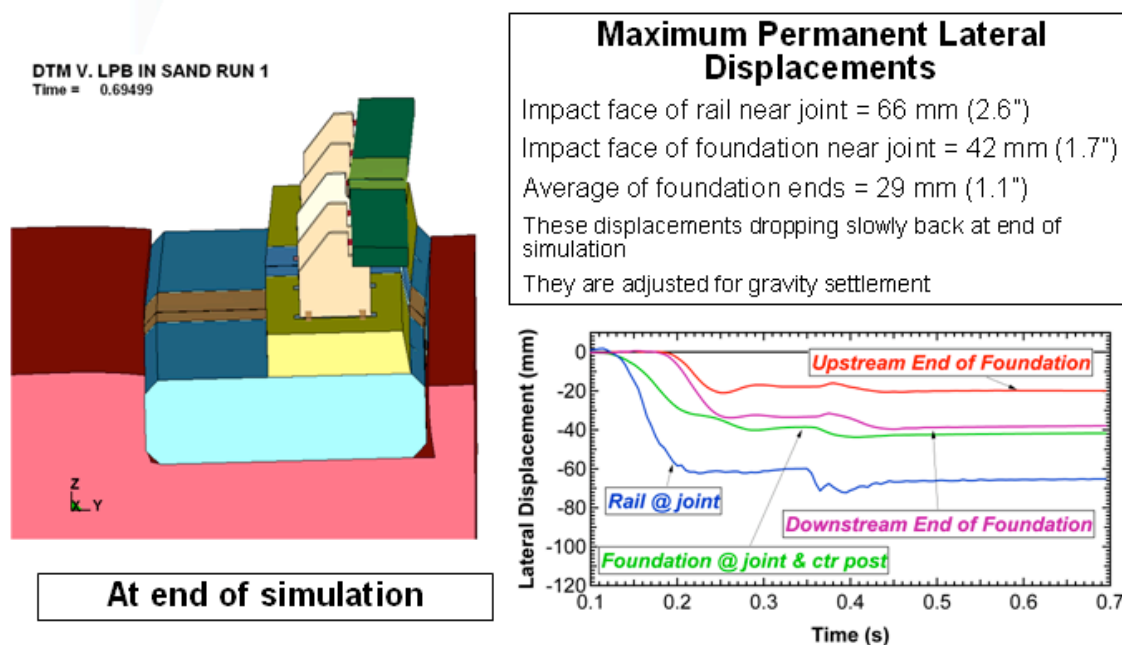


Figure 12. Maximum Permanent Lateral Displacements

Phase III

The focus of the work for the third phase was on crash simulation at the post and at the mid-span of low-profile barrier with the modifications to the rail post connection and anchor bolts strengths. Both the rigid and weak soil cases were simulated. The rail post connection was reinforced with double plate and higher strength bolts were used.

For the rigid soil simulation, the addition of the double plate greatly reduced the peak plastic strains seen in the rail when impacted at the post (19% to 2.2% plastic strain for impact at the post) (See Figure 13).

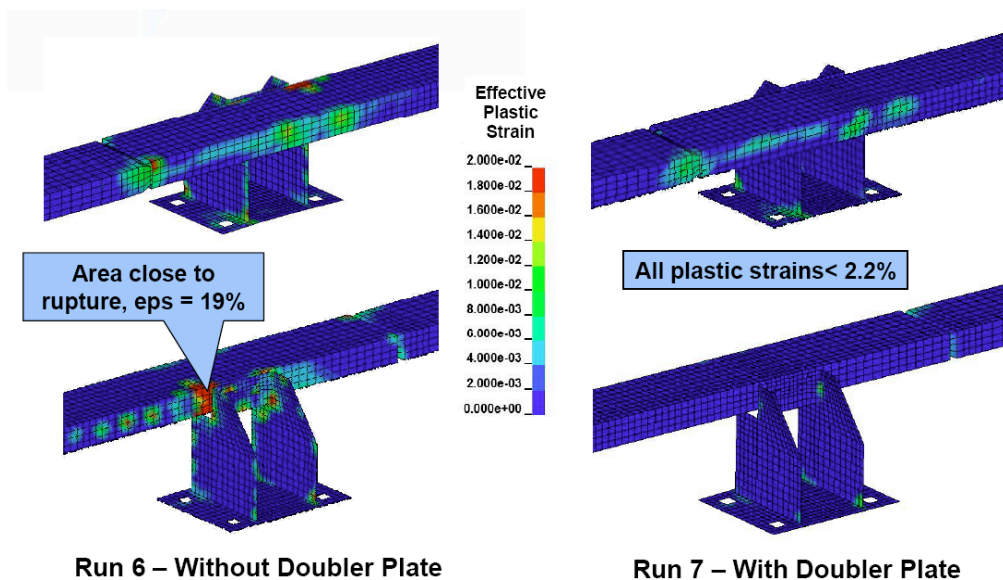


Figure 13. Plastic Strains at Post

The largest plastic strains were seen in the upper corner of the downstream post for the mid-span impact (4% plastic strain) (See Figure 14).

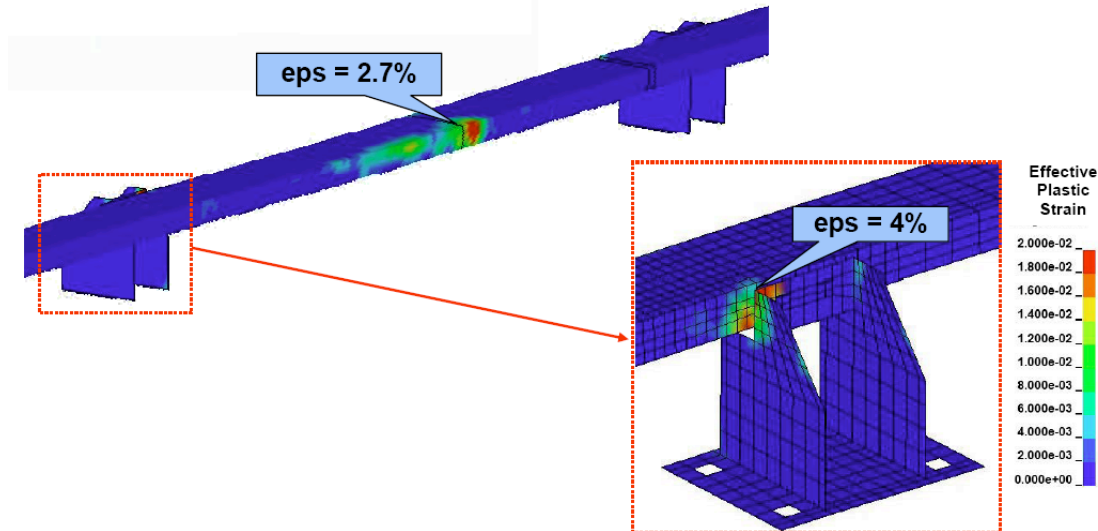


Figure 14. Plastic Strains at Mid-Span

For the weak soil simulation, the vehicle's response for impact at the post and mid-span between the posts were acceptable. The vehicle was directed and did not roll over or snag. The lateral and longitudinal OIV was 4.8 m/s and 4.4 m/s. The mid-post impact yielded a higher lateral ridedown acceleration (10.2 g vs. 8.2 g). The permanent lateral rail deflections increased by 11 mm from the impact at the post (66 mm to 77 mm lateral deflection) (See Figure 15) [3].

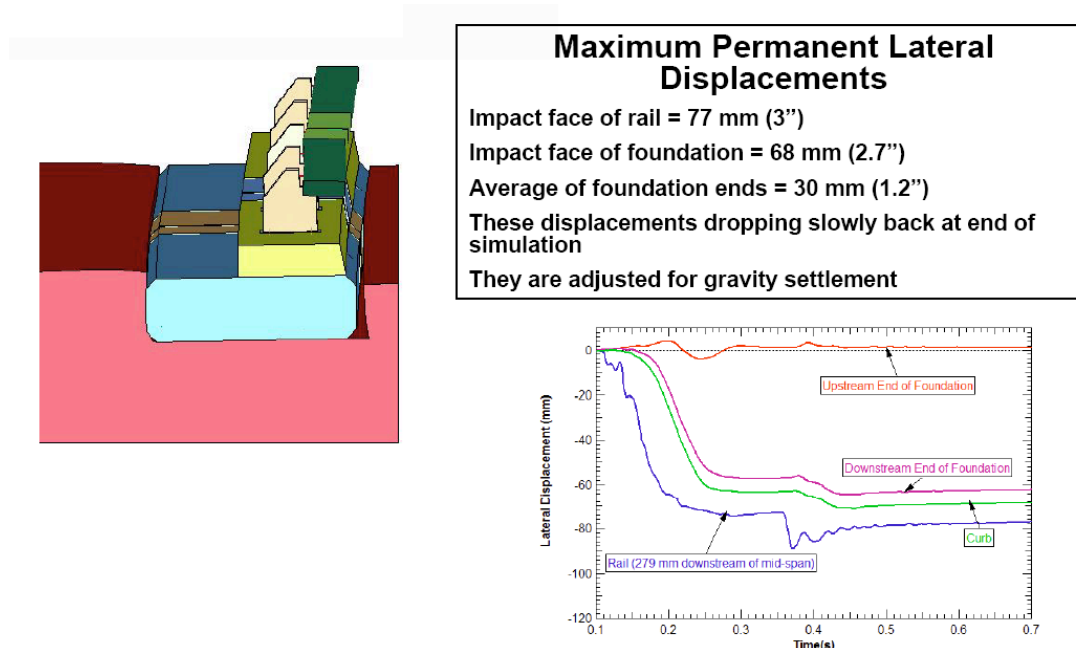


Figure 15. Maximum Permanent Lateral Displacements

Conclusion

The development of the barrier through computer simulations has produced an optimum barrier structure and foundation design that has a low-profile. The purpose of the rigid soil case was to test the strength of the barrier. The weak soil case tested the permanent deflections of the barrier and the vehicle's response from the impact. The barrier was designed according to the federal requirements of redirecting the vehicle safely without serious injuries to the occupants. The next phase of the project is to validate the weak soil simulation run with full scale crash testing. Crash testing of the low-profile barrier will be conducted by Caltrans.

References

1. *ARA Caltrans Barrier Report, April 21, 2008*
2. *ARA Caltrans Barrier Report, July 24, 2008*
3. *ARA Caltrans Barrier Report, October 16, 2008*
4. *Caltrans Bridge Design Specifications, April 2000*
5. *National Cooperative Highway Research Program (NCHRP) Report 35*