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DEVELOPMENT OF FUNCTIONAL REQUIREMENTS FOR A HIGHLY-MOBILE BARRIER SYSTEM TO PROTECT HIGHWAY WORKERS: INTERIM REPORT

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DRAFT

Prepared By

Texas Transportation Institute
The Texas A&M University System
College Station, Texas 77843-3135

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INTRODUCTION

Many work zone devices, such as truck-mounted attenuators (TMAs), cones, and barrels, are used to separate workers from the traveling public during construction and maintenance activities. However, these devices do not provide lateral impact protection. Conversely, concrete barriers are often used to separate workers and moving traffic at long-term construction projects that remain stationary for long periods of time. Unfortunately, many work activities are of shorter duration or require continuous movement along the roadway, and so cannot be protected through concrete barrier placements. This research project is being conducted to investigate the feasibility of developing a highly-mobile lateral protection system. The specific objectives for the project are to:

- define elements of typical highway maintenance and construction work activities that require workers to be on the roadway with traffic and
- establish functional requirements and performance specifications for a highly-mobile protection system to protect workers under such conditions.

In order to achieve these objectives the following tasks are being completed:

- Task 1 – Categorization of Construction and Maintenance Activities
- Task 2 – Discussion of Historical Research on Mobile Worker Protection Systems
- Task 3 – Assessment of Road Work Environment Constraints
- Task 4 – Characterization of Physical Impact Conditions
- Task 5 – Formulate Functional Requirements
- Task 6 – Analysis, Testing, Simulation, and Field Test Activities
- Task 7 – Preparation of a Final Report

This interim report documents the work completed to date for Tasks 1-4.

CATEGORIZATION OF CONSTRUCTION/MAINTENANCE ACTIVITIES AND INFLUENCE OF ROADWAY CONDITIONS AND CONSTRAINTS

The goal of tasks 1 and 3 was to define and characterize construction and maintenance activities that could be considered to be highly mobile. In the sections that follow, researchers present a summary of common mobile activities; catalog these activities along the key dimensions of mobility, spatial, and access requirements; present available statistics regarding the extent of mobile activity and potential application of a mobile barrier protection system; and discuss various roadway considerations and constraints that influence the design of such a protection system.

Identification of Construction and Maintenance Activities

Motor vehicles from the traffic stream intrude into active work areas fairly infrequently (when measured against the frequency of work activities throughout the U.S.), but do have significant consequences when such intrusions occur. Recent data from New York indicates that worker injuries and fatalities due to vehicle intrusions account for about 7 percent of all serious worker injuries that occur in work zones (*1*). In addition, it does appear that vehicle intrusions may be overrepresented in mobile work activities as compared to more stationary work zones. In New York, vehicle intrusion crashes into mobile work zones accounted for 20 percent of all intrusion crashes that occurred. Although actual work zone exposure data are not available, the researchers believe that mobile work zones make up a much smaller percentage of total work activities that occur on public roadways.

Work activities that last only a short time at any one location or which move slowly or intermittently along the roadway and involve some level of worker exposure (i.e., workers on foot in the roadway) create the most difficulty for worker protection as well as for traffic control. Table 1 contains the construction and maintenance activities, identified by researchers that meet these criteria and thus would benefit most from a highly-mobile worker protection system. These were identified based on knowledge acquired through previous research efforts (*2-4*) and discussions with Texas Department of Transportation (TxDOT) maintenance personnel.

Table 1. Identified Construction and Maintenance Activities.

• Litter pickup	• Raised pavement marker installation/removal
• Bridge clearance measurements	• Crack seal
• Pavement profiling	• Pothole patching
• Pavement core sampling	• Asphalt milling
• Edge/guardrail repair	• Sealcoat
• Short-line striping	• Asphalt overlay
• Signal installation/maintenance	• Level up
• Lighting installation/maintenance	• Traffic control setup/removal
• Rumble strip installation	

Litter pickup operations can either be stationary or continuously progress along a roadway. In one day, the number of sites or the length of roadway cleaned is dependent upon the speed of the operation. In general, a litter pickup operation is comprised of two crews: a ground crew and a bag crew. The ground crew is a group of workers that pick up the litter and place it in trash bags. The bag crew travels in a vehicle and places the full litter bags into a trailer. The number of workers and their location are highly variable; however, most work can be accomplished off the roadway with some minor encroachment.

Bridge clearance measurements are typically completed to verify the bridge height above a recently resurfaced roadway. The crew, comprised of two to four workers, is located under the bridge and takes measurements on foot at multiple points along the structure. Thus, at some measurement points the work crew is exposed to active travel lanes. However, the work duration at each site ranges from 5 to 15 minutes with work in the active travel lanes lasting only one to two minutes; therefore, extensive traffic control (i.e., lane closures) is generally not used.

Pavement profiling is completed to determine the surface smoothness on paving projects. These operations are continuously moving and travel approximately 3 miles per hour (mph) (i.e., walking speed). The length of roadway traveled in one day is dependent upon the speed of the operation but typically range from three to five miles. One to two workers are located directly behind the profilograph and need access to one travel lane.

Pavement core sampling is a stationary operation that typically takes less than one hour at each site. The operation consists of two to three workers and a truck with an auger mounted on the back. The workers are located on the roadway approximately 6 ft behind the auger and need access to one travel lane.

Edge/guardrail repair includes primarily stationary operations that work near the edge of the roadway. The work area is generally 20 to 30-ft long and may include one travel lane with some minor encroachment (depending on whether or not a paved shoulder exists between the guardrail and travel lanes). The work duration at each site is highly variable but is typically longer than one hour. The crew may consist of four to six workers, two to four vehicles, and some heavy equipment. The workers are located between the work vehicles and use some hand operated equipment.

Short-line striping operations include the application of stop bars, crosswalks, gore markings, and in-lane directional markings (e.g., turning movements). These operations are stationary and generally take approximately 15 minutes at each site. The crew consists of four to five workers. These workers need access to hand operated equipment (e.g., blower and thermoplastic applicator) and must transport the thermoplastic pavement marking material from a truck located near the work area to the hand operated equipment. Typically, the length of the work space is approximately 30 ft and can be located adjacent to or within one travel lane. In some cases, an entire approach (i.e., multiple lanes) to an intersection may be closed.

The *installation and maintenance of traffic signals and overhead lighting* are similar stationary operations. The work activity generally takes less than one hour at each site and consists of two to four workers, a bucket truck, and hand operated equipment (i.e., saw) when installing loop detectors into the pavement in advance of the signal. The work space is typically less than 50 ft long and includes one travel lane. However, for loop detector installation two travel lanes may need to be closed at one time to allow saw operators to stand out of the lane to finish a cut.

There are two types of *rumble strip installation*: lateral rumble strips and longitudinal shoulder texture. The installation of lateral rumble strips is a stationary operation that typically takes a couple of hours to complete. The work crew consists of two workers, vehicles, and hand operated equipment. Workers need access to one travel lane and less than 50 ft of roadway. The installation of longitudinal shoulder texture is a continuously moving operation that travels approximately 3 mph. Thus, the length of roadway traveled in one day is dependent upon the speed of the operation. For shoulder rumble strips milled into the pavement, one to two workers are located on foot adjacent to a milling machine (some longitudinal rumble strips are rolled into the final course of hot-mix overlays using a special roller for that purpose). Most of the work activity is completed on the shoulder but can include minor encroachment into a travel lane.

Raised pavement marker (RPM) installation and removal is another moving operation that typically travels approximately 3 mph but can include intermittent stops. There are several ways to install and remove RPMs; however, with respect to this research the focus is on those methods that utilize workers on foot in the roadway. The crew may include two workers, a hand operated melting pot that holds tar to attach the markers to the pavement, and a vehicle that holds materials. Workers are located near the vehicle and hand operated equipment. Typically, one lane is closed for this type of operation; however, since RPMs are located between lanes along with the lane lines or centerlines, workers encroach upon adjacent travel lanes to place or remove markers.

During a *crack seal* operation, workers fill cracks in the pavement with tar. These operations are generally mobile in nature (approximately 3 mph) but can include intermittent stops. Typically, multiple groups of workers and vehicles are used. The first group consists of a truck with an air compressor and at least one worker. This worker walks behind the truck and uses hand-operated equipment attached to the air compressor to blow off the pavement. The second group includes a second truck with a melting pot and two to three workers. These workers walk behind the second truck and apply the tar to roadway using hand held equipment attached to the melting pot Workers need access to at least one travel lane and in some instances an adjacent shoulder or turn bay. The work space between vehicles is approximately 50 ft, while the length of roadway traveled in one day is dependent upon the speed of the operation.

Pothole patching is a stationary operation that takes approximately 5 minutes at each site. A crew of two to four workers needs access to a vehicle that contains materials. Workers are located immediately behind the vehicle and need access to one travel lane.

Asphalt milling is an operation where a layer of asphalt is removed through a milling process. This type of operation progressively moves along the roadway at approximately 3 mph. The work crew consists of two workers on foot. These workers are located on each side of the milling machine. Workers need access to at least one travel lane, but in most situations the work encroaches on adjacent travel lanes.

Sealcoat and *asphalt overlay* operations continuously progress along the roadway at approximately 5 mph and involve the resurfacing of a roadway. In addition, both operations utilize multiple crews: paper/preparation crew, spreader/overlay crew, and tab installation crew. The paper/preparation crew consists of two to three workers that place paper on the roadway to guide the chip spreader or overlay machine. The spreader/overlay crew has one worker on foot. This worker is positioned in front of the heavy equipment and helps direct the operator driving the machinery. The tab installation crew includes two to three workers that walk along the roadway after the resurfacing is complete and install temporary tabs to denote the travel lanes. All crews need access to one travel lane.

Level-up is the application of materials in order to level-up an uneven roadway surface. During this type of operation, the only workers on foot in the roadway are the tab installation crew which consists of two to three workers. Work duration at each site is generally one to two hours and workers need access to one travel lane.

Traffic control setup and removal is highly dependent upon the characteristics of the roadway (e.g., geometry and volume) and work duration. Thus, the traffic control utilized for each of the operations previously discussed varies not only across operations (e.g., asphalt overlay versus litter pickup) but within operations as well. For example, a crack seal operation on a low speed, multi-lane roadway may involve a moving lane closure with a single traffic control person (flagger) responsible for controlling and prohibiting vehicles attempting to turn out of driveways from entering the work area. In contrast, the same crack seal activity on a two-lane, two-way roadway could entail a stationary lane closure and the use of flaggers and a pilot vehicle to direct traffic. In other words, nearly all types of work activities might include one or more workers on foot assigned to traffic control, the specific duties of which are likely to be highly site-dependent.

Categorization of Construction and Maintenance Activities

Researchers defined the characteristics of each activity according to three key roadway and environmental dimensions believed to be most critical for ultimately defining mobile barrier protection functional requirements:

- mobility needs,
- spatial requirements, and
- access requirements.

A detailed description of the dimensions for each activity can be found in Appendix A. Texas Transportation Institute (TTI) researchers established formal category definitions for those activities within each dimension in order to assess the impact to the functional requirements of a highly-mobile worker protection system. These categorizations are summarized in Tables 2 through 4. Mobility requirements were assessed following the standard work duration definitions included in the *Manual on Uniform Traffic Control Devices* (MUTCD) (*5*):

- long-term stationary work zones occupy a location for more than three days;
- intermediate-term stationary work zones occupy a location for more than one daylight period but no more than three days, or at night at a location for at least one hour;
- short-term stationary work zones occupy a location for one hour or more during a single daylight period;
- short duration work zones occupy a location for up to one hour; and
- mobile work zones move intermittently or continuously along a roadway segment.

As shown in Table 2, the latter three categories were used to assess the various work activities of interest in this project:

- constantly/ intermittently moving at approximately 3 mph (walking speed),
- short duration stationary (less than one hour at a location), and
- short-term stationary (less than 12 hours at a location).

This categorization illustrates that the majority of mobile work activities that occur move continuously at speeds somewhat less than 3 mph, or intermittently along the roadway. For these types of operations, a key functional requirement of a mobile barrier protection system will be to provide protection to a work crew while still being moved along the roadway.

Table 2. Mobility Needs Categorization.

Constantly/Intermittently Moving	Short Duration Stationary (less than 1 hour)	Short-Term Stationary (less than 12 hours)
Litter pickup	Bridge clearance measurements	Edge/guardrail repair
Pavement profiling	Pavement core sampling	Lateral rumble strips
RPM installation/removal	Short-line striping	Traffic control (flagger)
Crack seal	Signal/lighting install/maintenance	
Longitudinal shoulder texture	Pothole patching	
Asphalt milling		
Sealcoat/asphalt overlay		
Level-up (tab installation)		
Traffic control setup/removal		

Table 3 contains the spatial requirements that the research team categorized by work location and the number of separate work crews likely to be present during the construction or maintenance activity. One of the more interesting considerations shown in Table 3 is that there are two activities that can involve multiple crews on foot outside of a vehicle. This implies that a protection system for these activities will either have to be quite lengthy if they are to protect all on-foot workers, or else multiple protection systems would need to be used to effectively protect these operations.

Researchers estimate that each work crew (not including litter pickup or bridge clearance measurements) typically utilizes a work space 20 to 50 ft long. The upper end of this range reflects situations where the work area is created by two work vehicles following each other, with the crew positioned in between. Consequently, it is possible that the specific actions taken by each crew in those situations could be accomplished in a somewhat smaller distance. Researchers could not determine by simple visual inspection whether all of those types of activities could be accomplished within the lower bound of the range (i.e., 20 ft).

As denoted in Table 3, most of the activities take place in a single travel lane that is moved longitudinally as work progresses. However, if multiple lanes are first closed in a stationary traffic control set-up, a few activities (loop detector installation, short-line striping) are sometimes accomplished by moving laterally across the travel lanes in a sequential manner. For these types of activities, the ability of the protection system to move laterally or to expand laterally to incorporate as much as an additional lane of traffic may be beneficial in some situations. However, such capabilities do not appear to be an absolute necessity for the majority of mobile work activities being considered for protection by a mobile barrier protection system.

Table 3. Spatial Requirements Categorization.

Single or Multiple Crews All Lanes/Roadside	Single Crew[a] One or More Lanes	Multiple Crews[a] One or More Lanes
Litter pickup Bridge clearance measurements	Pavement profiling Pavement core sampling Edge/guardrail repair Short-line striping Signal/lighting install/maintenance Lateral rumble strips RPM installation/removal Pothole patching Longitudinal shoulder texture Asphalt milling Level up (Tab install crew)	Crack seal - Blowout crew - Sealing crew Sealcoat/asphalt overlay - Paper/prep crew - Spreader/overlay crew - Tab install crew

[a] Could also include a traffic control crew

The final assessment dimension considered was that of access requirements. As shown in Table 4, access requirements refer to the need of workers to bring equipment and tools into the active work area, or to access them somehow while working. For some operations, access to additional equipment beyond what the workers typically carry to complete the work is not required. In contrast, other activities require rather large objects or materials, hand-operated equipment, or even heavy equipment to be brought into and out of the work space. For example, pavement profiling is performed with a wheel-mounted device that is several feet long and three to four feet tall (sensors to record the pavement profile are attached to the device) that is rolled along the roadway. This device is carried to a location on a trailer, and then put on the roadway to begin data collection. Similarly, RPM installation requires an adhesive heater to be brought into the work area to roll along the roadway and dispense adhesive where each marker is to be placed. In both of these cases, the equipment is small enough to be lifted (although possibly by more than one person) onto and off of trailers, and so could be lifted into and out of a work area protected by a mobile barrier system (as long as the system was designed to allow such access). As a final example, activities such as crack sealing, pothole patching, core sampling, etc. require workers to access equipment and materials directly from the back of the vehicle carrying the equipment/materials. In general, the ability to bring fairly large pieces of equipment into the actual work area, as well as access materials and equipment contained on the back of a lead vehicle, are is seen as a critical functional requirements for a mobile barrier protection system.

Table 4. Access Requirements Categorization.

None	Hand-Carried or Rolled Equipment	Vehicle/Heavy Equipment
Bridge clearance measurements Litter pickup (Ground crew) Sealcoat/asphalt overlay (Tab installation crew) Level-up (Tab installation crew) Traffic control (flagger crew)	Short-line striping Signal/lighting install/maintenance Lateral rumble strips RPM installation/removal Pavement profiling	Litter pickup (Bag crew) Pavement core sampling Edge/guardrail repair Signal/lighting install/maintenance Lateral rumble strips RPM installation/removal Crack seal (both crews) Pothole patching Longitudinal shoulder texture Asphalt milling Sealcoat/asphalt overlay (Spreader/overlay crew, paper/prep crew) Traffic control (set up and removal crew)

Frequency and Duration of Mobile Construction and Maintenance Activities

In a recently-completed Federal Highway Administration (FHWA) study, TTI researchers explored the availability and quality of data documenting the frequency and type of work zone activity on National Highway System (NHS) roadways in several locations throughout the U.S. (*6*). Generally speaking, records are not kept by type of activity, making it difficult to establish solid estimates of the frequency of the above work activities. However, the data which are available do offer some insights into the magnitude of demand for a mobile barrier protection system.

Table 5 shows the frequency of various types of in-house maintenance activities for two regions examined in the FHWA study. Some of the classifications shown in Table 5 align very well with specific mobile activities identified above (i.e., lighting maintenance, signal maintenance). Other classifications encompass several types of the above-mentioned activities. Pavement repair, for example, is believed to include activities such as crack sealing, pothole patching, and level up. Likewise, the signing and delineation maintenance category likely encompasses the RPM installation and short-line striping activities described above. Unfortunately, these categories also likely some include work activities not of immediate interest to this study. Mobile striping operations that do not involve highway workers on foot may be included in the signing and delineation maintenance category, for example. For purposes of this analysis, the activities without workers on foot are assumed to be a relatively small portion of the total amount of activity that occurs in these categories. Finally, some of the activities of interest could be included under more than one of the various categories noted. For instance, guardrail repair activities may be included under accident repairs, under roadside maintenance, or under the "other" category.

While the variation in values shown in Table 5 imply that a detailed assessment of the frequency of the different types of work activities will not be possible, it is possible to come to some conclusions as to the overall amount of these types of mobile activities in general for which a mobile barrier protection system might prove useful. Table 6 contains the number of maintenance activities performed by state highway agency forces on the national highway system (NHS) in each region per year. Interestingly, the total number of activities was found to be very consistent between regions. If one assumes that only one-half of these activities are those where a highly-mobile barrier worker protection system could be utilized, applying the values in Table 6 (divided by two) to the approximately 161,000 route-miles of the NHS equates to approximately 1.3 million daily work crew activities per year. Stated another way, these values imply that approximately 5,000 mobile barrier worker protection systems could potentially be deployed for work crews on the NHS each and every work day.

Table 5. Frequency of Various Types of In-House Maintenance Activities.

Type of Activity	AZ Region	OH Region
Accident Repairs	25.8%	7.8%
Signing and Delineation Maintenance	14.1%	9.4%
Roadside Maintenance	11.6%	41.7%
Lighting Maintenance	5.0%	5.0%
ITS Maintenance	11.7%	0.4%
Signal Maintenance	7.0%	10.6%
Pavement Repair	8.3%	15.3%
Other	16.5%	9.8%

Table 6. In-House Maintenance Activities on the National Highway System (NHS) in Each Region.

	AZ Region	OH Region
Number of In-House Maintenance Activities per NHS Route-Mile per Year	15.2	15.4

Whereas Tables 5 and 6 provide highway worker exposure estimates pertaining to maintenance activities, Table 7 can be used with other data in the work zone exposure report to develop similar estimates for those construction activities involving workers on foot that could be protected by a mobile barrier worker protection system. Table 7 illustrates the relative distribution of various categories of contract work zone activity in five regions from the FHWA study (*6*). Construction contracts generally involve the addition or complete rebuilding of travel lanes, intersections, interchanges, etc. Many of these types of activities are performed behind portable concrete barriers or with considerable physical separation between the work area and traffic. Except for the occasional traffic switches for phase or sequence changes, workers are not generally out on or near travel lanes in any type of moving operation with these types of projects. Bridgework projects have many of these same characteristics and so also are not of primary interest to this study. The "other" category incorporated all remaining projects that did not fit well in the remaining four categories. These were highly individualized, with no particular overriding characteristics associated with them, and so are also not considered to be of primary concern in this particular study.

On the other hand, resurfacing contracts include both seal-coat and hot-mix asphalt overlay activities, both of which are continuous/intermittently moving activities of interest. Furthermore, some regions were found to contract out certain (but not all) maintenance activities. Common work activities contracted out by the state agencies included mowing, pavement restriping (both vehicle-operated longitudinal striping and worker-on-foot manual short-line striping), RPM replacement, guardrail repairs, and occasional even some pavement repairs such as level up or pothole patching. All but the vehicle-operated striping activities are of interest to this study. For purposes of this report, it is assumed that all of the resurfacing contracts and at least one-half of the maintenance contracts put workers out on foot in or near moving traffic in a mobile work operation of some type. From Table 7, this implies that 36 percent of work zone contracts on the NHS could also have the need for a highly-mobile barrier worker protection system.

Table 7. Summary of Contract Work Zone Characteristics.

Types of Contracts:	TX Region	AZ Region	WA Region	OH Region	VA Region	5-Region Average
% Construction	7	54	12	32	55	30
% Resurfacing	56	24	33	40	0	31
% Bridgework	7	3	22	18	36	17
% Maintenance	18	15	15	0	0	11
% Other	12	4	18	10	9	11

The results of the previous FHWA study also indicated that during the peak contract time (summer), work zone activity occurs on over 6,400 route-miles of the NHS each day (*6*). The average length of work activity (all types of work zone contracts combined) each day was found to be approximately 1.5 miles. Thus, one could hypothesize that nearly 4,300 contract work zones were active each day during the peak contracting time (note that contract numbers do decrease by 20 to 40 percent in the non peak times of the year). If one then multiplies this value by the estimated 36 percent of contract work zones that could involve highway workers on foot near moving traffic, another 1,500 work zones could make potential use of a highly mobile barrier worker protection system on a peak work day. Added to the previous estimate of in-house work zones, this means that such a protection system could potentially be applied to over 6,500 work zones during a peak work day on the NHS alone. As a final degree of extrapolation, the NHS itself only represents about 4 percent of all the federal-aid roads open to travel in the U.S. Even if one assumes that construction and maintenance activity levels on NHS roadways are considerably higher (because of higher agency priority and traffic volumes), these numbers imply that the number of work zones where a mobile barrier protection system might be applied could easily approach or even exceed 50,000 activity locations across the nation each work day.

Data regarding crash rates or history for these types of work zone activities are even more difficult to obtain and assess properly. Nationally, existing police reports of crashes do not typically include enough detail to allow separation by type of work being performed at the time of the crash. New York and possibly a few other state DOTs have themselves begun collecting data regarding work zone crashes in their jurisdiction, but have not reported any significant trends with regards to highly-mobile work activities.

Roadway Considerations That Can Influence Protection System Design

Roadway Geometrics and Operating Conditions

Generally speaking, the highly-mobile construction and maintenance activities described above can be required to occur on essentially all types of public roadways nationally. Roadway design standards are established by AASHTO (*7*) and by state DOTs, and vary by functional classification of roadway and other factors. The specific roadway design features believed to have the most significant impact upon the functional requirements of a highly-mobile barrier worker protection system are listed below.

Lane and Shoulder Width – Current design standards establish 12-foot lanes as the norm for most roadways. Slightly smaller widths (typically down to 11 feet) are sometimes used even on high-speed freeways in urban areas, if space availability was a concern at the time of roadway design or if the roadway segment was re-striped to increase the number of slightly-narrowed travel lanes available to traffic. Furthermore, some low-speed facilities in urban areas may have lanes as narrow as 10 feet. A mobile barrier system must be designed so as to allow full access to an entire lane cross section, as many of the operations involve repairs right up to the lane or edge lines. A bigger potential concern, however, is the amount of encroachment that may be required of the barrier system into an adjacent lane to accommodate the work area. The smaller the width of the travel lanes, the greater the effect of an adjacent-lane encroachment by the barrier system upon the ability of approaching traffic to safely pass by the work area.

Traffic Speeds – Generally speaking, both traffic volumes and speeds on a given roadway segment can vary substantially over the course of a day. Similarly, volumes and speed vary by roadway as well. Although most mobile construction and maintenance work occurs during normal work hours, more and more activity is being shifted to nighttime hours in order to avoid generating long traffic delays and queues. Operating speeds on roadways where a mobile barrier system might be employed could vary from as low as 30 mph on urban collectors to 70 mph or more on rural facilities (with higher speeds obviously representing the more sever constraint from a mobile barrier design perspective).

Vehicle Type – With regards to vehicle types, most roadway facilities are used by both automobiles and by large trucks. Whereas the protection against an intrusion by a truck would represent the most severe barrier design condition, it is possible that truck intrusions do not represent enough of a potential safety concern to mobile work zone activities to justify using them as a design vehicle (especially given that test requirements in NCHRP 350 do not use truck characteristics as part of the crash test impact conditions). Unfortunately, researchers were unable to uncover any crash data as to the relative risk of truck intrusions into mobile work zones.

Number of Travel Lanes – The number of travel lanes on a given roadway segment influences the mobile barrier worker protection system design not only in terms of requiring protection on either side of the work area (i.e., a work crew in the left lane of a multi-lane facility will require protection on the right side, whereas a crew in the right lane requires protection on the left side), but also in defining whether protection on both sides of the work area will be required at the same time (for any middle lane work activities). It should be noted that although long-term middle lane traffic-splitting techniques have been used by some agencies on multi-lane facilities, such techniques are currently not used very extensively for mobile work activities because of safety concerns. Therefore, the need for simultaneous protection from both sides of the work area is likely to be quite small.

The number of travel lanes on a roadway segment is also a factor in defining the potential side impact condition of an errant vehicle into the work area; the greater the number of travel lanes present, the greater the potential initial offset or lateral separation between the vehicle and the work area and the greater the possible impact angle into the mobile barrier. The relationship between separation distance and potential impact conditions are discussed in more detail later in this report.

Vertical Curvature – Vertical alignment is defined by the algebraic difference in grades on a roadway segment and the length of the curve used to bridge that difference in grade. These curves are designed to provide adequate stopping sight distance by a passenger automobile to a 0.5-foot object in the travel lane. These vertical curves require that a mobile barrier protection system be designed to accommodate small changes in elevation through appropriate hinged connections to anchor vehicles, minimum clearance heights to the bottom of the barrier, etc. A review of the AASHTO design standards (*7*) suggests that a mobile barrier 50 feet long will need to accommodate only about 6 inches of elevation change (i.e., will need at least 6 inches of ground clearance) over a vertical curve, regardless of the operating speed of the roadway.

In addition to simple vertical curves, issues can possibly arise during barrier transport with respect to other more severe vertical alignment changes. For example, recent research on "hang-up" problems of certain types of vehicles was studied for both railroad crossings and driveways where significant differences in grade exist (*8, 9*). Researchers in that study identified vehicles and equipment with overhangs greater than 15 feet and wheelbases 40 feet or longer, as being more prone to hang-up problems. In addition, software has been developed to evaluate specific vehicle or equipment configurations for hang-up potential, such as the new mobile barrier system being discussed in this report.

Horizontal Curvature – Horizontal alignment is defined by curve radius and superelevation rate, both of which are selected based on roadway classification and design speed (*7*). The most significant implications of horizontal curvature upon a mobile barrier protection system are in terms of the lateral encroachment that will occur as the work convoy traverses a curve, and in the possible worse-case impact conditions that can develop between by an errant vehicle approaching the work convoy positioned on a curve. These potential impact conditions are analyzed and discussed in detail later in this report. With regards to the issue of lateral encroachment, Table 8 provides estimates of extent of encroachment of a barrier system into an adjacent lane as a function of curve radii and corresponding maximum design speed for which a curve of that radius would be allowed) (*7*). As Table 8 illustrates, encroachment values would be minimal at all but only the very sharpest of horizontal curves if the barrier system length is kept to about 50 feet. Such minor encroachments would still allow for traffic to continue to operate in the adjacent lane. However, if the barrier length requirements approach 100 feet in length, significantly larger encroachments can be expected. In fact, for curve radii less than 1000 feet, it is likely that a work convoy would need to require traffic in the adjacent lane to vacate that lane into the next lane over or possibly onto the shoulder. It is believed that this requirement would significantly reduce the applicability of the barrier system.

Table 8. Possible Mobile Barrier Lateral Encroachment Into Adjacent Lanes on Horizontal Curves.

Curve Radius (ft)	Maximum Design Speed (mph)	Lateral Encroachment into Adjacent Lane for 50-ft Barrier Length (in)	Lateral Encroachment into Adjacent Lane for 100-ft Barrier Length (in)
300	30	12.5	50.0
400	30	9.4	37.5
500	40	7.5	30.0
750	50	5.0	20.0
1000	50	3.8	15.0
1250	60	3.0	12.0
1500	60	2.5	10.0
1750	70	2.1	8.6
2000	70	1.9	7.5
2500	70	1.5	6.0

MUTCD Requirements

The Manual on Uniform Traffic Control Devices (MUTCD) sets forth the basic principles and standards for traffic control on all public roadways in the U.S. (*5*). Part VI of the manual provides standards for temporary traffic control, including construction and maintenance work zones. The manual is fairly explicit with regards to advance signing requirements, channelizing device design and placement, and pavement delineation for temporary traffic control situations. Requirements for vehicle and equipment delineation are less defined. Generally speaking, vehicles and equipment on or next to travel lanes for the purposes of construction, maintenance, or service are simply required to have at least one flashing or rotating beacon as delineation. Research is currently underway by AASHTO (*10*) to provide better guidelines regarding warning lights to be used on work vehicles and equipment.

A considerable amount of engineering judgment is to be exercised when applying the principles of the MUTCD to field situations, particularly those as site-specific and with as many safety concerns as exist at highway work zones. For this reason, the typical applications and guidelines presented in the manual are minimums, which may need to be enhanced depending on conditions. In many cases, the engineer-in-charge may choose to raise the level of traffic control used for a mobile work zone operation in order to ensure adequate levels of safety for traffic and workers. This may mean that a mobile operation, which typically has minimal advance signing and no channelization, may be performed within the limits a long section of a formal lane closure that remains stationary over the course of a work period. One of the key concerns regarding mobile operations is maintaining adequate sight distances to the work convoy so as to allow motorists time to safely vacate the lane in which work is occurring. Horizontal and vertical curves, highway structures, and large trucks can all obscure sight distance of the approaching driver. Work convoys include chevrons and arrow panels on the back of the shadow vehicle that is commonly used to protect work crews in a mobile environment. Most agencies have moved towards increased use of truck-mounted attenuators on their shadow vehicles (as discussed later in this report as well).

HISTORICAL RESEARCH ON MOBILE WORKER PROTECTION SYSTEMS

TTI Initiatives

A summary of past research efforts of truly mobile worker protection systems as well as closely related quasi-portable worker protection systems has been conducted. In the early 1980s, Texas Transportation Institute crash tested a box beam barrier suspended between two dump trucks, *Development of Truck-Mounted Portable Maintenance Barrier* (*11*). They also crash tested a "centipede" barrier made of a train of old cars, titled *A Portable Traffic Barrier for Work Zones* (*12)*. However, while there was some field testing of the units, these efforts did not result in fully operational devices. In 1993, TTI completed NCHRP Project 17-8, *Traffic Barrier and Control Treatments for Restricted Work Zones* (*13)*, which resulted in a User's manual for guidelines of barrier treatments in work zones but does not directly address the protection of workers in short duration work zones.

Plymouth station wagons were used in the first portable construction barrier developed at TTI. Five station wagons were connected together by tow bars and strut assemblies. Thrie-beams were attached to the side of the station wagons and lapped in anticipation of an impact with the side of the system from rear to front. The "centipede" was 100 ft long and was driven to experimental sites. That system is shown in Figure 1. Connection details are shown in Figure 2. Since the system occupied at least a vehicle width, it wouldn't provide adequate work space on single lane closures. Therefore, unless multiple lanes were to be closed, this system would have limited applications.

Figure 1. First TTI Mobile Work Zone Barrier.

The system successfully redirected a 2000 kg (4400 lb) passenger vehicle traveling 77.7 km/h (48 mph) and an impact angle of 15 degrees. The measured barrier deflection was 210 mm. Computer simulations predicted 660 mm (26 inches) of deflection if the system was impacted with the same vehicle traveling 97 km/h (60 mph) at an angle of 25 degrees. This test was never conducted.

Figure 2. Connection Details for first TTI Mobile Work Zone Barrier.

The original truck-mounted portable maintenance barrier developed at TTI was fabricated from rectangular structural tubes welded together and supported on two (2) standard 5 cubic yard Texas Department of Transportation (TxDOT) dump trucks as shown in Figure 3. Additional modifications were made to mate the barrier to the trucks. This system is shown in Figures 4 and 5. Mobilization of the system involved the use of a separate transport dolly and the unit towed behind one of the support trucks as shown in Figure 6. Some deployment of the system was required upon reaching the destination. A 2000 kg (4400 lb) passenger sedan traveling 80 km/h (50 mph) impacted the system at 15 degrees and was successfully redirected.

Figure 3. Truck Mounted Portable Barrier

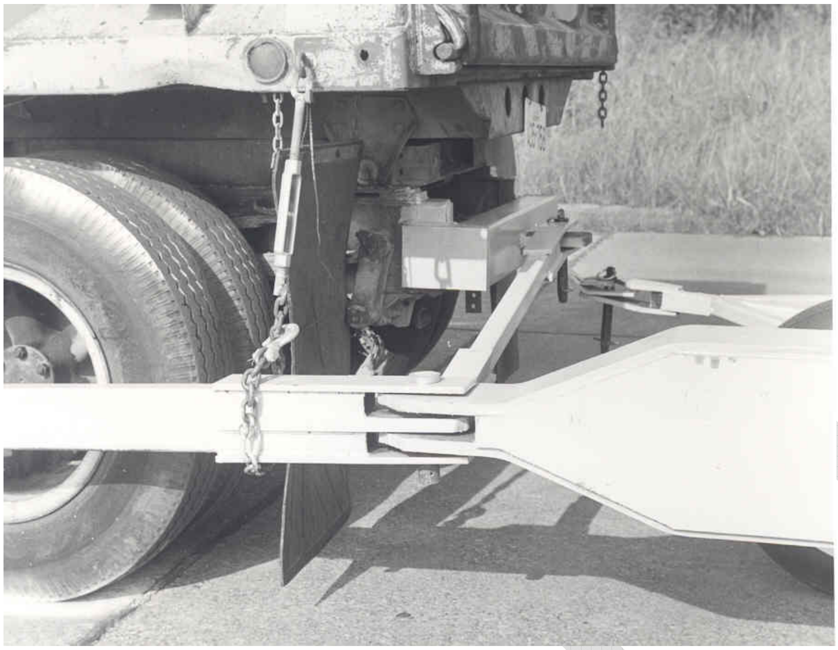

Figure 4. .Modifications to Lead Truck

Figure 5. Modifications to Trailing Truck

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Figure 6. Transport Dolly for Portable Barrier.

Caltrans Balsi Beam

More recently, the California Department of Transportation (Caltrans) has developed the Balsi beam, mobile work zone protective device. It was named after Mark Balsi who lost a leg when a vehicle penetrated the work zone. Limited information has been provided by Caltrans, however, a brief article, *Shields of Steel: California Introduces New Mobile Work Zone Protection*, was carried by the January/ February 2004 issue of *Focus* (*14*), U.S. Department of Transportation's Federal Highway Administration (FHWA) Turner-Fairbank Highway Research Center's internal publication. As noted in the article:

"The system, which is carried on a tractor-trailer, is specifically intended to enhance worker safety when carrying out shoulder repair in work zones adjacent to guardrails, bridge rails, and soundwalls. Each side of the trailer consists of high-strength steel box section beams that are capable of extending an additional 4.6 m (15 ft). Using hydraulic power, each beam can rotate to either side (left or right), depending on which side of the road a protective barrier is needed. The trailer then extends to provide a 9.1-m (30-ft) secure work zone. The trailer beams act as a rigid obstacle to deflect traffic away from maintenance workers, in essence forming what Caltrans calls "shields of steel" to protect workers. The system reverses the procedure for transport. Whereas in a typical work zone, trucks are in the front and back of the work zone but there is no protection from vehicles in adjacent traffic lanes for workers, use of the system "lengthens out the area where workers are protected," says Iwasaki." Caltrans has indicated successful testing of the device. However, TTI researchers are unable to comment on the types or test levels of the full-scale crash tests.

Photos from the website of the device being deployed are shown in Figures 7 and 8.

Figure 7a. Balsi Beam being Deployed.

Figure 7b. Balsi Beam being Deployed.

Figure 8. Deployed Balsi Beam.

Other Related Systems

Each of these three previously discussed portable systems are intended to prevent side intrusion into a work zone. Obviously, these devices themselves could constitute a hazard to the motoring public and would require shielding from rear-end impacts. A number of manufacturers have developed and tested Truck Mounted Attenuators (TMA's) for attachment to the rear of work zone vehicles. TMAs are used quite extensively on shadow vehicles used to support many of the construction and maintenance mobile activities described previously.

A number of quasi-portable barriers have been developed and are currently used in the highway safety industry. Water filled barriers with some type of structural skeleton have been tested to redirect a 2000 lb vehicle as per NCHRP Report 350 requirements (*15*). While the time to deploy these units is somewhat less when compared to portable concrete barriers, the number of units required to provide adequate mass for anchorage, yields systems that are approximately 160 to 200 ft (50 to 60 m) long. Furthermore, additional distance is required for a crashworthy end treatment. Therefore, these types of devices will have limited appeal for truly short duration work zones and moving operations will not use them.

Barrier Systems of Rio Vista, CA has developed a portable steel barrier (SafeGuard Link System) that is equipped with wheels for ease of movement within work zones. Figure 9 illustrates the operational concept of the system. Appendix B contains a product information sheet supplied on the Barrier Systems Website listed below.
http://www.barriersystemsinc.com/dynamic/docs/filename_275.pdf

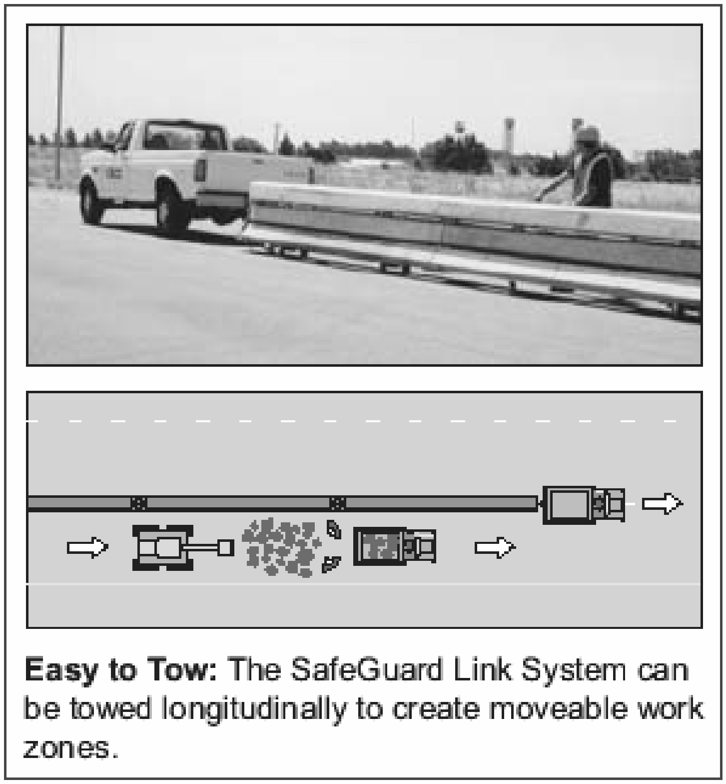


Figure 9. SafeGuard Link System.

This system is transported to the work site and deployed. The minimum length of the system is 223 ft (68 m). Short duration work zones will have limited application for this system and ends of the system will again need to be shielded.

Since advance warning will need to be provided in work zones, Truck Mounted Attenuators (TMAs) should be readily available to protect workers from rear-end collisions and to protect occupants of errant vehicles. Some consideration will need to be given to the redirection of errant vehicles at locations other than the protected work zone. The sides of the support vehicles/structures must also provide a continuous, smooth surface for potential re-directive type impacts.

CHARACTERIZATION OF PROTECTION SYSTEM PHYSICAL IMPACT CONDITIONS

Current Guidance

Guidelines for testing roadside appurtenances originated in 1962 with a one-page document – *Highway Research Circular 482* entitled “Proposed Full-Scale Testing Procedures for

Guardrails." This document included four specifications on test article installation, one test vehicle, six test conditions, and three evaluation criteria.

NCHRP Report 350, "Recommended Procedures for the Safety Performance Evaluation of Highway Features," which was published in 1993, is the latest in a series of documents aimed at providing guidance on testing and evaluating roadside safety features (*15*). This 132-page document represented a comprehensive update to crash test and evaluation procedures. It incorporated significant changes and additions to procedures for safety-performance evaluation, and updates reflecting the changing character of the highway network and the vehicles using it.

NCHRP Report 350 uses a 2000-kg pickup truck as the standard test vehicle to reflect the fact that over one half of new passenger vehicles sales in the U.S. are in the "light truck" category. This change was made recognizing the differences in wheelbases, bumper heights, body stiffness and structure, front overhang, and other vehicular design factors associated with light trucks. *NCHRP Report 350* further defines other supplemental test vehicles including an 8000-kg single-unit cargo trucks and 36000-kg tractor-trailer vehicles to provide the basis for optional testing to meet higher performance levels.

The mobile worker protection system that is the subject of this study would be characterized as a longitudinal barrier. Six test levels are defined for longitudinal barriers in *NCHRP Report 350*, each of which place an increasing level of demand on the structural capacity of a barrier system. The basic test level is Test Level 3 (TL-3). At a minimum, all barriers on high-speed roadways on the National Highway System (NHS) are required to meet TL-3 requirements.

While testing is classified by vehicle speed and mix, most work zone devices are not tested beyond Test Level 3 (TL-3). The matrix for evaluating a longitudinal barrier system at TL-3 consists of two tests: test designations 3-10 and 3-11. Test 3-10 is considered a severity test whose primary purpose is to evaluate occupant risk associated with impacting the mobile protection barrier system. The test involves an 820-kg passenger car impacting the barrier at a nominal impact speed 100 km/h and impact angle of 20 degrees, with initial vehicle contact occurring at the critical impact point (CIP) along the system. The CIP is the point that maximizes risk to the occupant due to the probability of adverse interaction (e.g., snagging) between the vehicle and barrier.

Test 3-11 is considered a structural adequacy test for the barrier system. The impact conditions consist of a 2000-kg pickup truck impacting a barrier at 100 km/h (62 mph) and 25 degrees, with initial contact occurring at the critical impact point (CIP). The objective of this test is containment and redirection of the vehicle in a stable manner (i.e., without overturning). The CIP is selected such that the impact loads in the barrier members are maximized, thus maximizing the structural failure of the rail. This test controls the size and strength of the barrier members, and dictates the dynamic design deflection of the barrier system.

It will likely be desirable for the mobile protection system to provide rear as well as longitudinal protection. The accommodation of rear-end impacts is generally accomplished through some form of crash cushion. For mobile operations, the crash cushion typically takes the form of a truck-mounted attenuator (TMA). This can be accomplished by having a shadow vehicle (commonly a dump truck) equipped with a TMA follow the longitudinal mobile protection barrier system. In this configuration, an approved (i.e., NCHRP Report 350 compliant) TMA would be used on a vehicle of appropriate size and mass, and no further testing would be required.

If it is decided the mobile protection device requires independent capability to attenuate rear-end crashes, the test matrix for truck mounted attenuators (TMAs) recommended in *NCHRP Report 350* would be appropriate for evaluating this aspect of the mobile protection system. The two tests required for evaluation of a TMA under TL-3 are test designations 3-50 and 3-51. Test 3-50 involves an 820-kg passenger car impacting the crash cushion head on at a nominal impact speed of 100 km/h and an angle of 0 degrees. This test evaluates occupant risk and helps ensure that the crash cushion is not too stiff for small passenger vehicles. Test 3-51 involves a 2000-kg pickup truck impacting the crash cushion head on at a nominal impact speed of 100 km/h and an impact angle of 0 degrees. This test helps ensure adequate length and staging of the stiffness of the cushion to provide for the safe attenuation of heavy vehicle.

Although the characteristics and specifications of the mobile protection system will be defined in more detail in the next phase of the project, the idea of separating the function of the protection system into two independent systems (e.g., barrier and crash cushion) appears desirable. The addition of a TMA to the rear of the mobile protection unit would increase the cost and complexity of the system and the increased length and weight would further restrict its functionality on the highway. Shadow vehicles with approved TMAs are already in widespread use among state DOTs for a variety of mobile work zone applications, and can be deployed at reasonable cost.

Higher containment barriers are sometimes used when conditions such as a high percentage of truck traffic warrant. Such barriers are necessarily taller, stronger, and more expensive to construct. Many state transportation departments require some of their longitudinal barriers (most notably bridge railings and median barriers) meet Test Level 4 (TL-4) of NCHRP Report 350. The TL-4 test matrix is inclusive of the TL-3 matrix described above, and adds accommodation of single-unit trucks. More specifically, test 4-12 involves an 8000-kg single unit truck impacting the barrier at 80 km/h (50 mph) and 15 degrees.

The impact energy for the single-unit truck test (i.e., 4-12) is nearly identical to that for the pickup truck test (e.g., 3-11 or 4-11). Thus, a barrier designed for TL-3 impact conditions will generally have sufficient size and strength to accommodate TL-4 impact conditions. However, whereas a 711 mm (28 in.) barrier height will redirect a pickup truck, the height of a TL-4 barrier should be at least 762 mm (30 in.) and preferably 813 mm (32 in.) However, when raising the rail height, consideration should be given to the underride potential of small passenger cars, which will be a function of the depth and number of longitudinal rail elements.

Future Guidance

The forward of *NCHRP Report 350* states the following: "The evolution of the knowledge of roadside safety and performance evaluations is reflected in this document. Inevitably, parts of this document will need to be revised in the future…" NCHRP Project 22-14(2), "Improvement of Procedures for the Safety-Performance Evaluation of Roadside Features," was initiated to take the next step in the continued advancement and evolution of roadside safety testing and evaluation. Since publication of *Report 350*, changes have occurred in vehicle fleet characteristics and testing technology. The result of Project 22-14(2), which is scheduled for completion in January 2005, will be a new document that will govern full-scale vehicular crash testing. Unlike its predecessors that were published through NCHRP, this new document will be published by AASHTO.

Since the development of a highly mobile barrier system will include full-scale vehicle crash testing, it is important to stay abreast of the proposed changes being considered in the update to *NCHRP Report 350* being developed under NCHRP Project 22-14(2). After a clinical review of impact speed obtained from the reconstruction of over 500 real-world run-off-road crashes, it was recommended that the basic impact speed (100 km/h) for TL-3 remain unchanged. A similar analysis of impact angles indicated an increasing percentage of higher angle (>20 degree) impacts. Consequently, it was recommended that the impact angle associated with the TL-3 structural adequacy pickup truck test remain 25 degrees. For consistency with the structural adequacy test, and in recognition of the increasing probability of higher angle impacts observed from the reconstructed crashes, it has been recommended that the impact angle for the small car severity test be increased from 20 degrees to 25 degrees.

Due to the prohibitive cost of crash testing, the philosophy adopted in recent testing guidelines has been to run tests with vehicles that bracket the vehicle fleet in terms of size and weight. Given that a roadside safety devices passes the severity test with the smaller, lighter vehicle (e.g., 820-kg passenger car) and the structural adequacy test with the larger, heavier vehicle (e.g., 2000-kg pickup truck), it is assumed that the device will also perform satisfactorily for the vehicles falling between the design test vehicles.

At this time, it appears that both design test vehicles will need to increase in weight to reflect the general upsizing trend that continues to dominate new vehicle design. While the large design test vehicle will continue to be a ¾-ton, standard cab, 2-wheel drive pickup truck, the current recommendation is to increase the test inertia weight from 2000 kg (4,400 lb) to 2268 kg (5,000 lb).

The kinetic energy that the barrier has to withstand is referred to as the impact severity. It is a function of the vehicle mass, impact speed, and impact angle. The proposed increase in weight of the pickup truck represents an increase in impact severity of approximately 15%. Such an increase will undoubtedly affect the design impact loads for longitudinal barriers such as those currently specified in the AASHTO *LRFD Bridge Design Specifications* for various test levels.

The 820-kg passenger car currently serving as the small design test vehicle has become virtually non-existent in terms of new vehicle sales. Consequently, in order to test with a vehicle that is reasonably represented in terms of vehicle sales, it is being proposed to increase the weight of the small passenger car from 820-kg (1,800 lb) to 1100 kg (2,425 lb). One of the vehicle makes and models in this weight range likely to be considered as a test vehicle is the Kia Rio. The significant increase in vehicle weight will effectively make the occupant risk criteria used to evaluate the severity test easier to pass. That is, when subjected to a given impact load, a vehicle with greater mass will experience lower decelerations then a smaller vehicle. However, the proposed increase in impact angle (from 20 to 25 degrees) will increase occupant risk and offset the benefit derived from the increase vehicle mass.

Application-Specific Considerations

The discussion of impact conditions has, to this point, focused on the standardized test conditions that currently exist and those that are being proposed in the ongoing update of *NCHRP Report 350*. To help ensure that crash tested devices will perform satisfactorily in the field, the impact conditions are selected to be practical worst case conditions derived from crash data, and are intended to be broadly applicable to a range of different highway types.

Exceptions to these basic impact conditions may be justifiable depending on characteristics of the safety device and the nature of the environment in which it is implemented. An example of such an instance is a longitudinal barrier deployed in a restricted work zone. Due to narrow lane widths and lack of shoulder, barriers (when needed) are typically placed at the edge of the travelway, bringing them in much closer proximity to vehicles than a permanent barrier installation. Under such circumstances, the minimal offset that exists between vehicles limits the impact angle that can be achieved and makes an impact angle of 25 degrees extremely unlikely.

However, from a practical standpoint, state DOTs develop their portable concrete barrier standards to accommodate a wide range of work zones with different characteristics. Rather than develop a separate (and potentially more economical) design for use exclusively in restricted work zones, a single barrier is typically tested following the basic impact conditions of *NCHRP Report 35*0 to enable its deployment on any high-speed facility without the need to consider other site characteristics.

Another example that can justify revision of the basic design impact conditions is a bridge rail on a narrow through truss bridge. Due to their historical significance, it is often desired and sometimes required that older truss bridges remain in service. When upgrading the safety features of such bridges, a reduced impact angle can be justified for the evaluation of retrofit bridge rails due to the narrow width of the structure.

These examples are cited in lieu of the fact that a mobile protection system deployed in a travel lane may warrant similar consideration due to its proximity to adjacent or opposing traffic. The maximum attainable angle for a given speed and lateral offset can be determined theoretically using a point-mass model with the assumption of maximum steering such as that depicted in Figure 10.

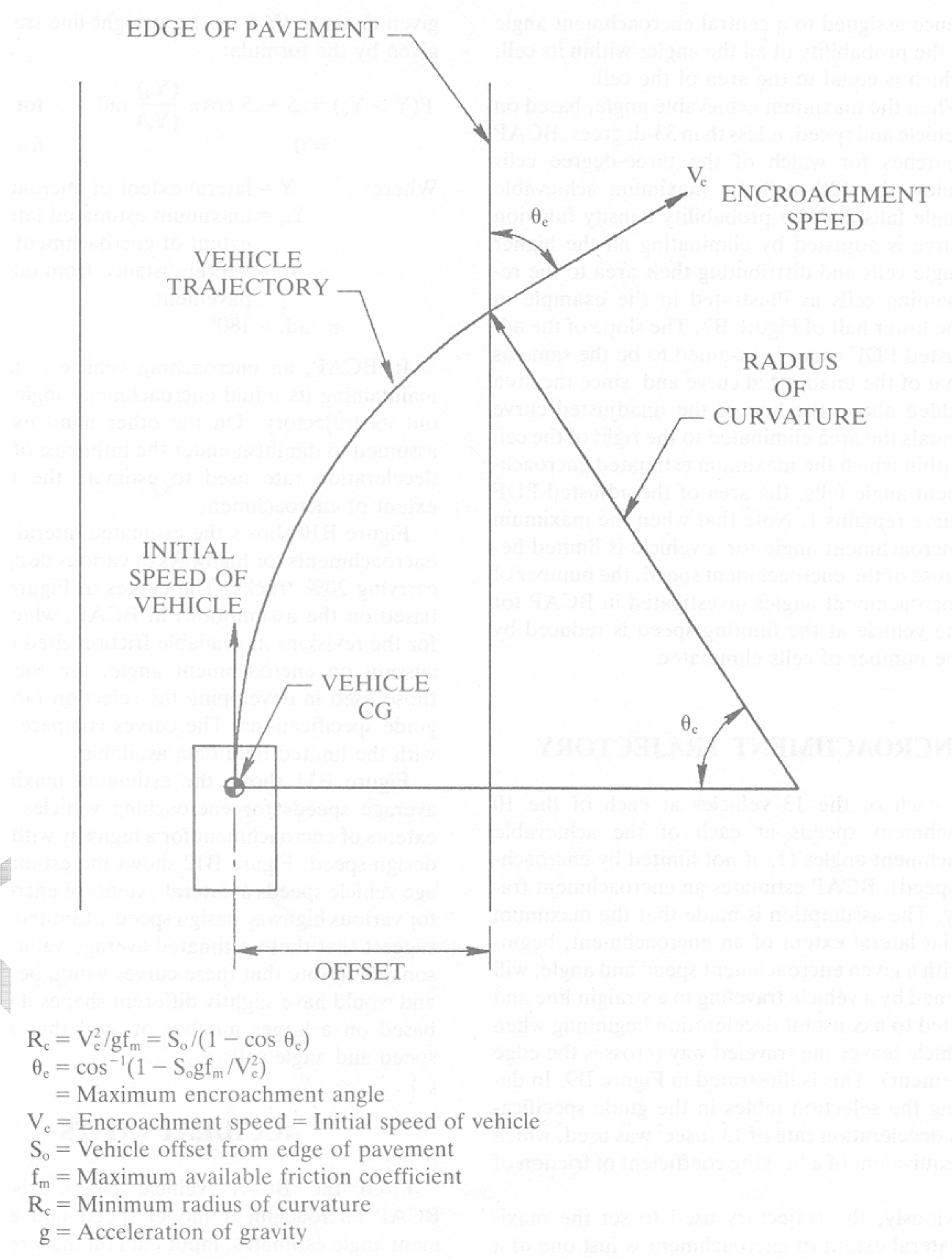


Figure 10. Encroachment Angle Model *(16)*.

Next, Figure 11 shows the maximum attainable angle for a given speed and lateral barrier offset using the point-mass model shown in Figure 10, and assuming a coefficient of friction of 0.7, which is typical of a dry pavement in good condition. In order to reach an impact angle of 25 degrees at a speed of 100 km/h (62.2 mph), the lateral offset has to be approximately 10.5 m (34.5 ft) under the conservative conditions assumed in the analysis. For the same speed of 100 km/h (62.2 mph), the lateral offset distance required to attain an impact angle of 20 degrees is 6.8 m (22.2 ft). Of course, as one would expect, the angle decreases as the speed increases. At a speed of 110 km/h (68.4 mph), the corresponding lateral offset to reach impact angles of 25 degrees and 20 degrees are 12.7 m (41.8 ft) and 8.2 m (26.9 ft), respectively.

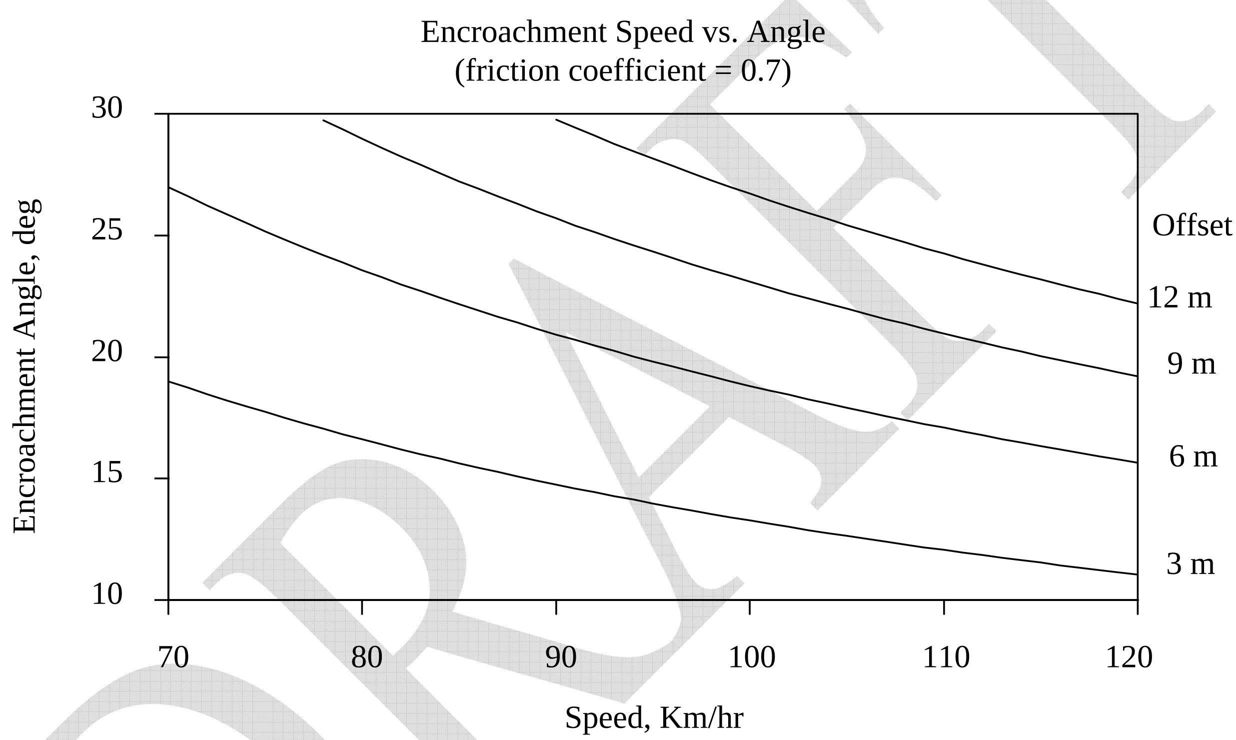


Figure 11. Encroachment Speed and Angle as a Function of Lateral Offset

To put these lateral offsets into perspective of a highway setting relative to a mobile barrier system traveling in an adjacent lane of traffic, consider the following three scenarios: an approaching vehicle in the first, second, or third lane adjacent to the mobile barrier. The assumptions are: lane width 3.7 m (12 ft), longitudinal barrier located at the inside edge of the outside lane, maximum steering, and 0.7 coefficient of tire-pavement friction. Such a situation could exist if the mobile barrier was deployed in the outside lane of a 4-lane undivided highway. Note that, assuming the center of gravity of the approaching vehicle is positioned in the middle of the lane of travel, the three lane scenarios provide lateral vehicle offsets of 1.8, 5.5, and 9.1 m (6, 18, and 30 ft). Table 9 summarizes the maximum attainable angles for selected speeds under these three scenarios.

Table 9. Maximum Attainable Angle by Speed and Offset

Speed, km/h (mph)	Maximum Attainable Angle (deg)		
	1 Lane	2 Lanes	3 Lanes
80 (49.7)	13.0	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

Notes: Barrier assumed to be at inside edge of lane
Tire-pavement friction = 0.7
Lane Width = 3.7 m (12 ft)
Offset Distance = (No. of lanes – ½) x lane width

For a typical two-lane undivided highway or a four-lane divided highway, vehicles traveling at 100 km/h (62.2 mph) would not be able to attain an impact angle of 25 degrees with respect to a mobile barrier when departing from the adjacent lane (10.4 degrees for 1 lane offset). For a four-lane undivided highway, the maximum angle that could be attained with the vehicle and mobile barrier in opposite outside lanes is 23.4 degrees (for 3 lanes), which begins to approach the 25 degree impact angle incorporated into the crash test guidelines, and is essentially within the 1.5 degree impact angle tolerance of *NCHRP Report 350*. If the vehicle speed is reduced from 100 km/h (62.2 mph) to 90 km/h (56 mph), the maximum attainable angle is 26.1 degrees, which is slightly above (but within tolerance of) the basic impact angle recommended in *NCHRP Report 350*.

This is not to say that it is impossible to have a higher impact angle. One scenario is for a vehicle to first depart off the travelway to one side, the driver over corrects and then crosses the centerline at a higher angle than could be attained from the original lane of travel. However, this analysis does serve to illustrate that the proximity of longitudinal barriers to traffic can effectively limit the attainable impact angle.

This analysis can be extended to account for variations in roadway curvature. Depending on the direction of travel, degree of curvature, and super elevation, a horizontal curve can increase the maximum attainable impact angle.

Influence of Horizontal Curve Effects Upon Estimated Impact Conditions

Current practices for those construction and maintenance activities of interest typically include a shadow vehicle as part of the operation in order to shield workers from rear-end impacts. Similarly, most roadwork activities include a lead vehicle in the lane that hold materials and equipment and thus influences the conditions of a head-on impact from opposing traffic. Vehicle impacts from head on or directly from the rear would thus be with those vehicles rather than with the mobile barrier itself. Functionally, such impacts will influence mobile barrier requirements only in terms of accounting for potential roll-ahead and roll-back distances of those vehicles. These distances are a function of vehicle size and traffic speed on the facility. Obviously, rural facilities with 70 mph operating speeds and some non-zero percentage of large trucks represent the worse-case situation.

In considering the right-angle impact condition, these are likely to occur on lower-speed urban roadways due to the prevalence of intersections and driveways. The possibility does exist for a right-angle impact at the intersection of two high-speed rural facilities (where one facility is required to come to a complete stop, for example), but the exposure to such conditions is believed to be fairly remote.

Excluding right-angle impacts, it is the oblique angle impacts originating from behind or in front of the proposed mobile barrier protection system as discussed in the previous section that are the ones most influenced by roadway geometric configurations. Freeways and other divided multi-lane highways will generally limit exposure to vehicles approaching from behind. Conversely, undivided multi-lane and two-lane highways have possible impact angles originating both from behind and in front of the work area. Impacts on either the left or the right side of the work area are a possibility on multi-lane facilities, such that a mobile barrier protection system must be installable from either side. Although temporary middle-lane closures have been attempted in the past on some multi-lane facilities, TTI researchers believe that this practice is not widely used at this time (such middle-lane closures nowadays are more commonly installed for several weeks at a time at a location and protected by portable concrete barriers).

For these oblique-angle side impacts, the key variables of interest are the angle of impact (labeled Ω in the following figures) and the speed of the impact vehicle (from the task 1 analysis, the speed of the mobile barrier protection system is likely to be negligible). Intuitively, impact angles would be expected to be increased slightly from the tangent analyses discussed in the previous section if the impact occurs within a horizontal curve where the mobile barrier is slightly skewed relative to the direction of travel of an approaching vehicle, as depicted in Figure 12. As shown, an approaching vehicle begins to lose control prior to reaching the work area, and its travel path carries it into the work area. Meanwhile, the location of the work activity in the horizontal curve has oriented the side of the proposed barrier system slightly towards the approaching errant vehicle.

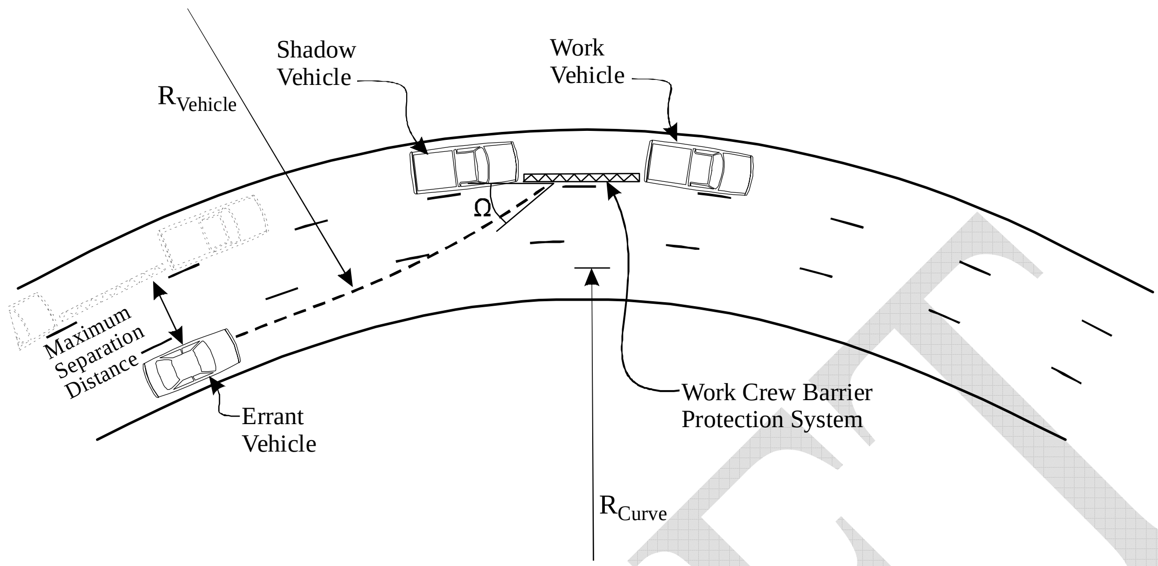


Figure 12. Illustration of Impact Condition on a Horizontal Curve.

The impact angle Ω can be computed by estimating the intersection of the errant vehicle travel path with that of the work activity located along the horizontal curve. Characteristics of the horizontal curve of interest include its radius (R_{curve}), the number of lanes of the roadway (which defines the maximum separation distance between the errant vehicle and the work activity), and the superelevation rate used (e). Superelevation is included on most horizontal curves on high-speed roadways to counter the effects of centripetal force on the vehicle traversing the curve, and can range from 0.04 up to 0.10, depending on the design speed of the roadway (*7*).

To compute the trajectory of the errant vehicle into the work area, it is assumed that the maximum speed and impact angle condition would occur if the vehicle traverses a circular curve at the sharpest curve radius ($R_{Vehicle}$) possible without losing horizontal side friction between the tires and the pavement. This minimum curve radius is a function of the speed of the vehicle (V), the maximum horizontal side friction (f), and the superelevation rate (e) (*7*):

$$R_{Vehicle} = \frac{V^2}{15(e+f)}$$

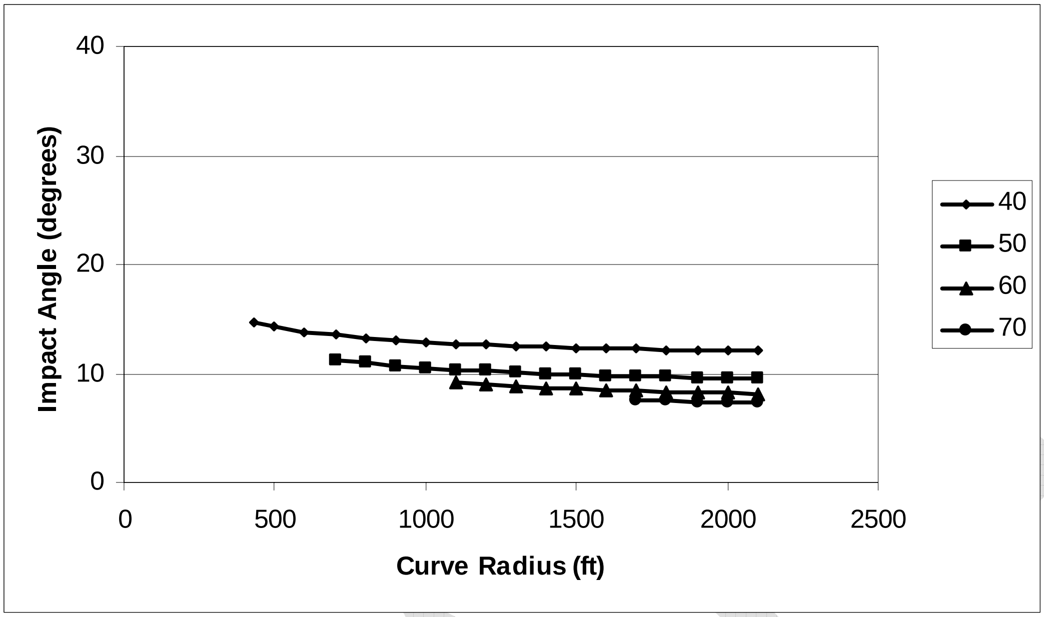
In the above situation, the superelevation rate is actually working against the vehicle and so will be a negative number. Furthermore, as the vehicle traverses its errant path, this effective superelevation influence will diminish:

$$R_{Vehicle} = \frac{V^2}{15f}$$

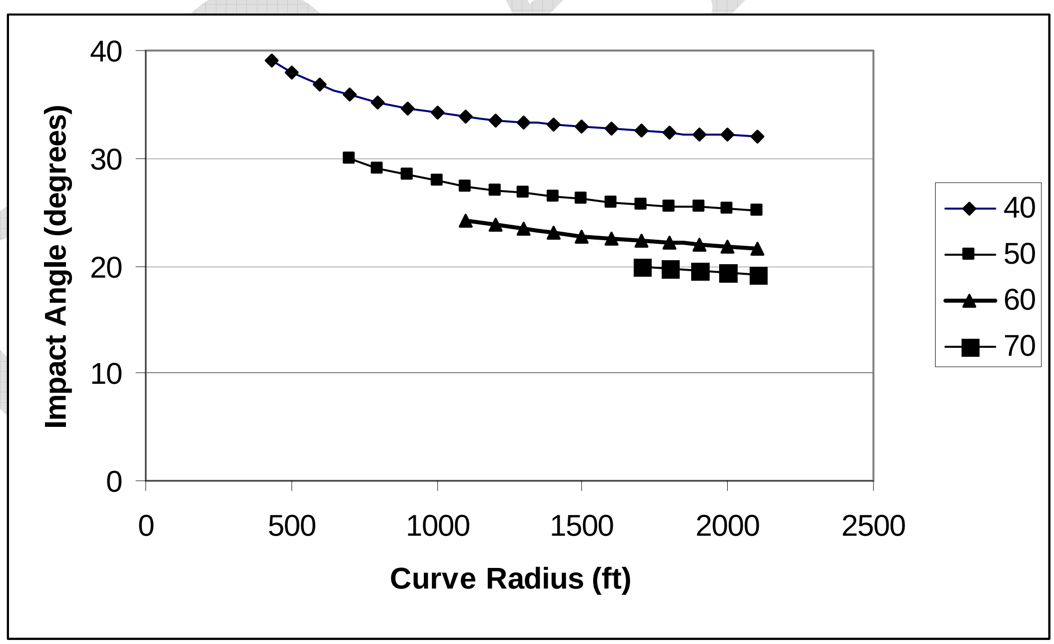
The side friction value used was not that typically considered in horizontal curve design (which is actually an indicator of driver comfort), but rather the friction values used in design for stopping sight distance. In this way, the minimum curve radius possible would be computed (which would in turn result in the maximum possible impact angle between the errant vehicle and the mobile barrier protection system). Friction values of 0.28 to 0.34, depending on the assumed speed of the errant vehicle, were selected (*7*). These values are substantially lower than that used in the previous discussion about impact angles on a tangent section. However, given the fact that superelevation rates on a curve are working against this friction value, a smaller number was deemed appropriate. These calculations can simply be redone at a later date if different friction values are believed to be more appropriate.

The impact angle Ω is actually the sum of the angle of rotation of both R_{Curve} and $R_{Vehicle}$ between the location where the errant vehicle begins its circular path towards the outside of the curve and the point where it meets the mobile barrier protecting the work crew. These angles can be solved through basic trigonometry. Figures 13 and 14 illustrate the resulting impact angles computed as a function of the assumed speed of the errant vehicle, the radius of the curve (R_{Curve}), and lateral separation between where the errant vehicle began and the lane where work activity is occurring. The calculation results are shown only for those conditions that could legally occur. That is, errant vehicle speeds that exceed the design speed of the horizontal curve are not shown. As Figure 13 illustrates, the effect of errant vehicle speed upon possible impact angles is much more pronounced when the maximum lateral separation between the vehicle and the travel lane that the work activity occurs is higher. At a lateral separation of 6 feet (i.e., the errant vehicle begins in the lane immediately adjacent to the lane that work activity is occurring), computed impact angles are all less than 15 degrees regardless of the errant vehicle speed assumed. For a 42-foot separation distance (i.e., the errant vehicle is four travel lanes over from the work activity travel lane), impact angles as high as 40 degrees could potentially occur at lower errant vehicle speeds. Even for 60 and 70 mph errant vehicle speeds, impact angles of 20 to 25 degrees are possible at this separation distance.

Figure 14 resents similar analysis results, segregated by errant vehicle speed in order to illustrate the effect of maximum lateral separation distance upon impact angle. For an errant vehicle speed of 40 mph, impact angles range from 12 to 40 degrees, depending on the assumed curve radius and lateral separation distance. Meanwhile, impact angles only range between 8 and 20 degrees for similar radius and lateral separation distances when the errant vehicle speed is assumed to be 70 mph.

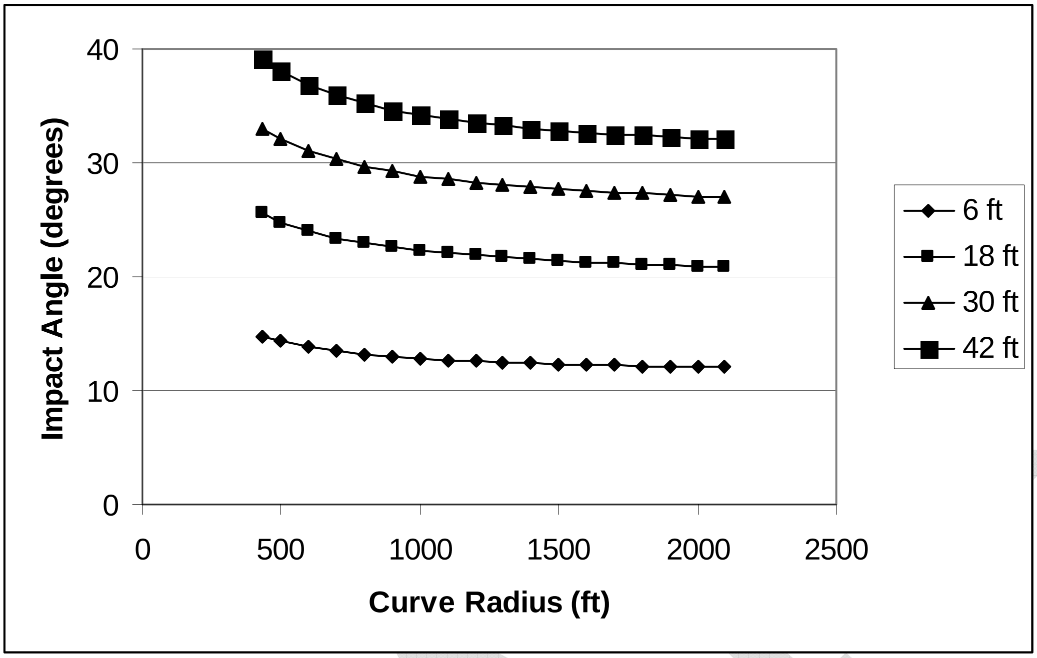


(a) Impact Angles for Maximum Separation Distance of 6 ft.

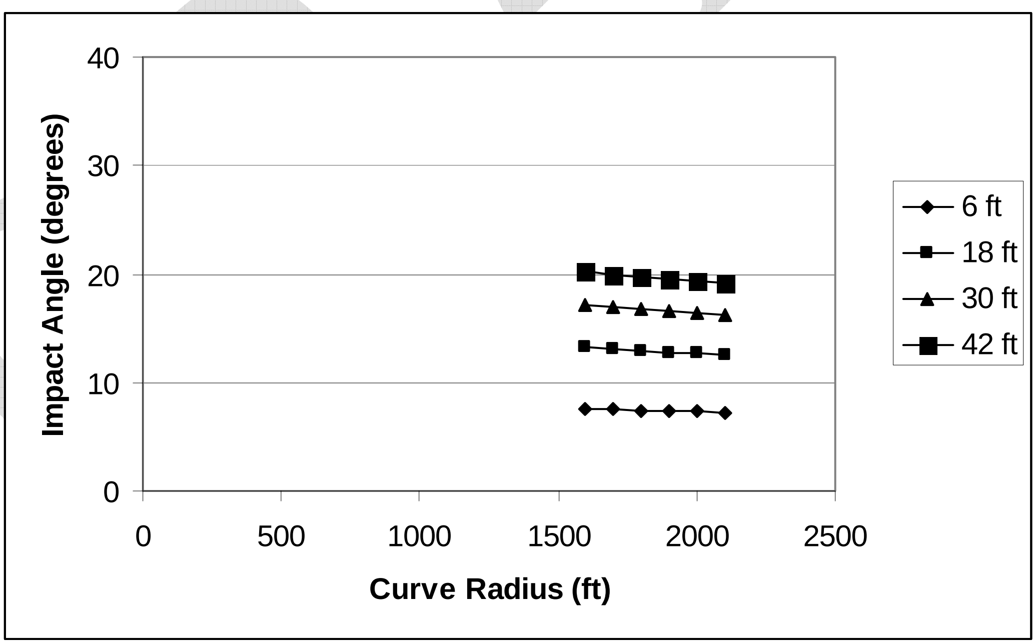


(b) Impact Angles for Maximum Separation Distance of 42 ft.

Figure 13. Effect of Errant Vehicle Speed Upon Possible Impact Angles.



(a) Errant Vehicle Speed 40 mph



(b) Errant Vehicle Speed 70 mph

Figure 14. Effect of Maximum Separation Distance Between Errant Vehicle and Work Area Upon Possible Impact Angles.

SUMMARY

Although the characteristics and specifications for a highly mobile barrier protection system will be more fully investigated in the next phase of the project, it appears that *NCHRP Report 350* TL-3 impact conditions for longitudinal barriers are appropriate for the testing and evaluation of such a system. Since deployment on high-speed roadways is considered a necessary requirement for a useful mobile protection system, an impact speed of 100 km/h is recommended.

While site conditions may justify modification of the impact angle based on the proximity of the mobile barrier to traffic, the basic impact angle of 25 degrees appears appropriate in order to give the system more widespread applicability. For example, deployment in the outside lane of a 4-lane undivided highway would provide a maximum attainable angle for opposing traffic traveling in the outside lane at a speed of 100 km/h of 23.4 degrees.

Although the structural adequacy requirements for TL-4 are essentially the same as those for TL-3, it is recommended that the mobile protection system be designed for TL-3 impacts. TL-3 is the basic test level for high-speed roadways, and most guardrails and transitions are designed and tested for this level.

Although the NCHRP Report 350 update document has yet to be finalized, the current proposal to increase the weight of the pickup truck design vehicle to 2268 kg (5000 lb) will represent a 15% increase in impact energy. The proposed changes to this document should continue to be monitored and considered in the design process.

While considered feasible, the design of a mobile barrier protection system for TL-3 conditions will require relatively large, stiff rail elements in order to provide the desired vehicle containment within reasonable deflection limits. The desired span length will dictate size and weight of rail members. The researchers will provide an estimate of the size and weight of rail members required to meet TL-3 conditions during the next phase of the project, to further assess the feasibility of such a system.

Some form of crash cushion or attenuation device will be needed to protect both workers and vehicle occupants from rear-end impacts. It is recommended that the rear-end protection be provided by an independent shadow vehicle with an approved TMA. This would reduce the development and construction costs of the mobile protection barrier system and permit it to have greater functionality on the highway.

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APPENDIX A

Operation	Mobility	Access	Spatial
Litter Pickup	- constantly moving OR stationary - work duration is typically one day (can be multiple locations) - length traveled is dependent upon speed of operation OR travel to next location at roadway speeds	- 1 to 2 litter vehicles w/ trailers (bag pickup group)	- number and location of workers is highly variable (estimate 10-15) - either working around litter truck placing litter into trailer OR picking up trash - mostly off roadway work (minor encroachment)
Bridge Clearance Measurements	- moves across travel lanes at work site - work duration at each site ranges from 5 to 15 minutes (work in active travel lanes ~1-2 minutes) - travel to next work site at roadway speeds		- 2 to 4 workers - use a long measuring stick to measure vertically - workers move across active travel lanes so dependent upon cross-section of roadway and width of bridge
Pavement Profiling	- constantly moving at ~ 3 mph - work at a single location for a whole day - length traveled is dependent upon speed of operation	- profilograph	- 1 to 2 workers right behind profilograph to operate it - full access to one travel lane
Pavement Core Sampling	- stationary - work duration at each site is less than 1 hr - travel to next location at roadway speeds	- pickup with auger on back	- 2 to 3 workers ~ 6 ft behind auger truck where the auger is working - full access to one travel lane

Operation	Mobility	Access	Spatial
Edge/Guardrail Repair	- primarily stationary - work duration at each site is highly variable (typically longer than 1 hr) - travel to next location at roadway speeds	- 2 to 4 vehicles (pickups and dump trucks) for materials - possibly some heavy equipment	- 4 to 6 workers between vehicles - use hand equipment - length of work space is 20 to 30 ft [a] - up to one travel lane (minor encroachment)
Short-line Striping	- stationary - work duration at each site is generally under 15 min -travel to next location at roadway speeds	- hand operated machinery - must transport thermo from truck to machinery	- 4 to 5 workers - use hand operated equipment (blower and thermo applicator) - length of work space is 20 to 30 ft - adjacent to travel lane to one travel lane dependent on application (e.g., gore area markings, in-lane markings); sometimes block off entire approach to an intersection (e.g., stop bar, crosswalks)
Signal/Lighting Installation/Maintenance	- stationary - work duration at each site is less than 1 hr - travel to next location at roadway speeds	- bucket truck	- 2 to 4 workers - use hand operated equipment (saw) when installing loops - length of work space less than 50 ft (i.e., one vehicle length) - generally up to 1 travel lane but can be up to 2 travel lanes for loop installation

Operation	Mobility	Access	Spatial
Lateral Rumble Strips	- stationary - work duration at each site is generally a couple of hours - travel to next location at roadway speeds	- 1 to 2 vehicles and hand operated equipment	- 2 workers - length of work space less than 50 ft - full access to one travel lane
RPM Installation/Removal	- constantly moving at ~ 3 mph - work at a single location for a whole day - length traveled is dependent upon speed of operation	- "Push" pot (hand operated melting pot) - pickup for materials	- 1 to 2 workers - when installing, workers near hand operated melting pot - when removing, workers in front of vehicle removing RPMs by hand
Crack Seal	- constantly moving at ~ 3 mph - work at a single location for a whole day - length traveled is dependent upon speed of operation	- air compressor (hooked to a truck) - melting pots (hooked to a truck)	- 5 workers; 1 between air truck and work truck blowing off pavement with hand held equipment coming from air compressor, 3 between work truck and shadow vehicle applying crack seal with hand held equipment coming from melting pots, and 1 flagger adjacent to 3 workers between work truck and shadow vehicle - length of work space is ~ 50 ft between each set of vehicles [a] - full access to one travel lane and possibly the shoulder; in urban areas access to adjacent lanes (turn bays)
Pothole Patching	- stationary - work duration at each site is generally 5 minutes - travel to next location at roadway speeds	- pickup for materials	- 2 to 4 workers right behind pickup - full access to one travel lane

Operation	Mobility	Access	Spatial
Longitudinal Shoulder Texture	- constantly moving at ~ 3 mph - work at a single location for a whole day - length traveled is dependent upon speed of operation	- milling machine	- 1 to 2 workers adjacent to milling machine - mostly shoulder work (minor encroachment)
Asphalt Milling	- constantly moving at ~ 3 mph - work at a single location for a whole day - length traveled is dependent upon speed of operation	- milling machine - traffic control devices	- 2 to 6 workers; 1 stationed on each side of the milling machine to control depth (work occurs right up next to adjacent travel lanes) and the others doing traffic control as needed - full access to one travel lane; sometimes take 1.5 lanes
Sealcoat/Asphalt Overlay	- constantly moving at ~ 3 mph - work at a single location for a whole day - length traveled is dependent upon speed of operation	- chip spreader	- 5 to 7 workers; 1 in front of chip spreader, 2 to 3 to place temp tabs, and 2 to 3 to put out paper in front of operation - full access to one travel lane
Level Up	- constantly moving - work duration at each site is generally a couple of hours - length traveled is dependent upon speed of operation OR travel to next location at roadway speeds		- 2 to 3 workers to place temp tabs - full access to one travel lane