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16. Abstract

This report describes a recommended set of functional requirements, performance specifications, analysis approaches, and testing procedures needed for the development of a highly-mobile barrier system to protect highway workers. These requirements were developed based on an assessment of the various types of construction and maintenance work activities that are highly mobile and which would potentially benefit from such a system. As defined, a system meeting the stated requirements could accommodate about two-thirds of the types of activities considered (perhaps even more if work crews were to adopt slightly different procedures to accommodate a mobile barrier system into some of the remaining activities).

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

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INTRODUCTION

PROBLEM STATEMENT

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 was conducted to investigate the feasibility of developing a highly-mobile lateral protection system. The specific objectives for the project were 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.

The risk to highway workers from errant vehicles entering the work area is not insignificant. 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. TTI researchers estimate that there are as many as 6,500 work zone activities that occur on the National Highway System (NHS) on a peak work day during the summer which could potentially involve highway workers on foot next to moving traffic (*2*). If even only a small portion of these activities could be protected via a highly-mobile barrier system, a significant reduction in highway worker risk exposure could be realized each year. Furthermore, the NHS itself only represents about 4 percent of the total amount of public roadway mileage in use across the U.S. Hence, the potential exposure reduction that is possible via a mobile barrier protection system is truly significant.

An interim report previously prepared under this contract and submitted to the Federal Highway Administration (FHWA) outlined a detailed assessment and categorization of construction and maintenance activities that are considered to be highly mobile and which could potentially benefit from a mobile barrier protection system, reviewed the historical documentation of previous mobile barrier worker protection systems, assessed the influence of roadway and work environment constraints upon the ability of such a mobile barrier system to protect the various construction and maintenance activities identified, and characterized the typical impact condition that a mobile barrier would need to protect (*3*).

In this final report, researchers relied on the information from that prior report to generate a set of functional requirements for a highly-mobile barrier system and to assess which of the various construction and maintenance activities a system that met the requirements could actually protect. Researchers have also identified and discussed the relevant performance specifications, analysis methods, and testing procedures that will be required in order to develop a successful mobile barrier protection system.

CONSTRUCTION AND MAINTENANCE ACTIVITIES POTENTIALLY PROTECTED BY A HIGHLY-MOBILE BARRIER PROTECTION SYSTEM

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. The specific characteristics of each were identified in the previous interim report (*3*), and are repeated again in Appendix A of this final report.

Table 1. Highly-Mobile 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	

Each construction and maintenance activity can be categorized along 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.

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 as one of three types of operations (following the standard work duration definitions included in the *Manual on Uniform Traffic Control Devices* [MUTCD] [*4*]):

- 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.

Table 2. Mobility Requirements of Mobile Activities.

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

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. 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 (such as loop detector installation or 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 work activities being considered for protection by a mobile barrier protection system.

Table 3. Spatial Requirements of Mobile Activities.

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

[a] Could also include a traffic control crew.
[b] This includes installation of inductive loop detectors in the travel lane.

Finally, 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. As Table 4 implies, 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 for Mobile Activities.

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	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 Pothole patching Longitudinal shoulder texture Asphalt milling Sealcoat/asphalt overlay - spreader/overlay crew - paper/prep crew Traffic control - setup/removal

ROADWAY CHARACTERISTICS INFLUENCING MOBILE BARRIER SYSTEM DESIGN

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 the American Association of State Highway and Transportation Officials (AASHTO) (*5*) 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 – 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 National Cooperative Highway Research Program [NCHRP] 350 do not use truck characteristics as part of the crash test impact conditions [*6*]). 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.

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 (*5*) 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. However, severe vertical alignment changes can create potential "hang-up" problems, depending on the particular design of the mobile barrier system. Vehicles and equipment with overhangs greater than 15 feet <u>and</u> wheelbases 40 feet or longer may be more prone to hang-up problems (*7*). Fortunately, software has been developed to evaluate specific vehicle or equipment configurations for hang-up potential (*8*).

Horizontal Curvature – Horizontal alignment is defined by curve radius and superelevation rate, both of which are selected based on roadway classification and design speed (*5*). The most significant implications of horizontal curvature upon a mobile barrier protection system are in terms of the lateral encroachment over the adjacent lane 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. With regards to the issue of lateral encroachment, Table 5 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 (*5*). As Table 5 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 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.

Table 5. 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

Worse-case oblique-angle side impacts occur on horizontal curves, as the impact angle (Ω) increases slightly from what would likely occur on a tangent, as depicted in Figure 1. 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.

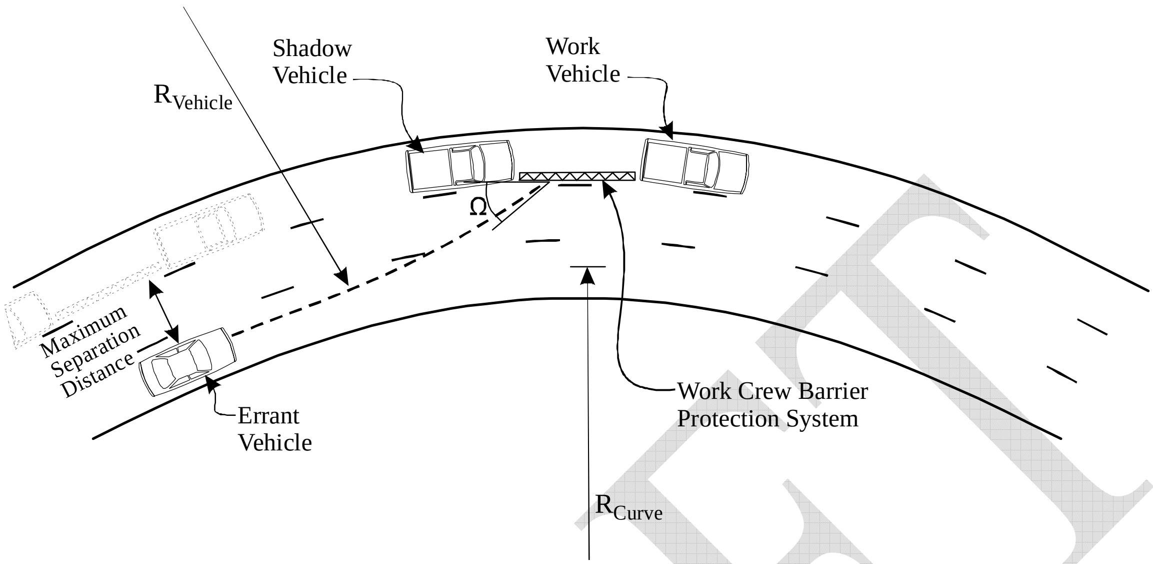
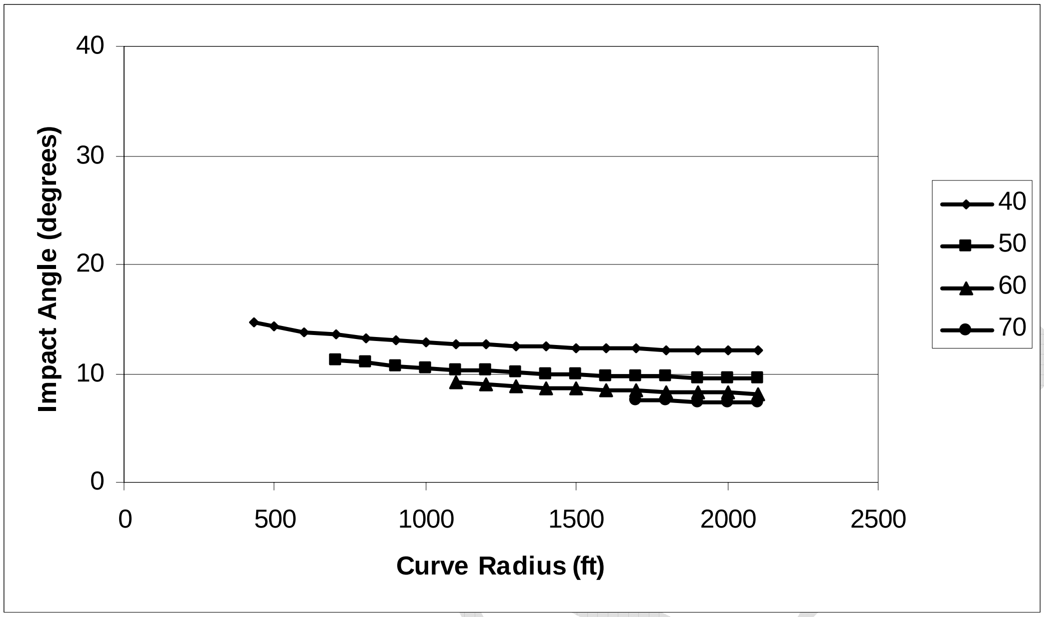


Figure 1. Illustration of Impact Condition on a Horizontal Curve.

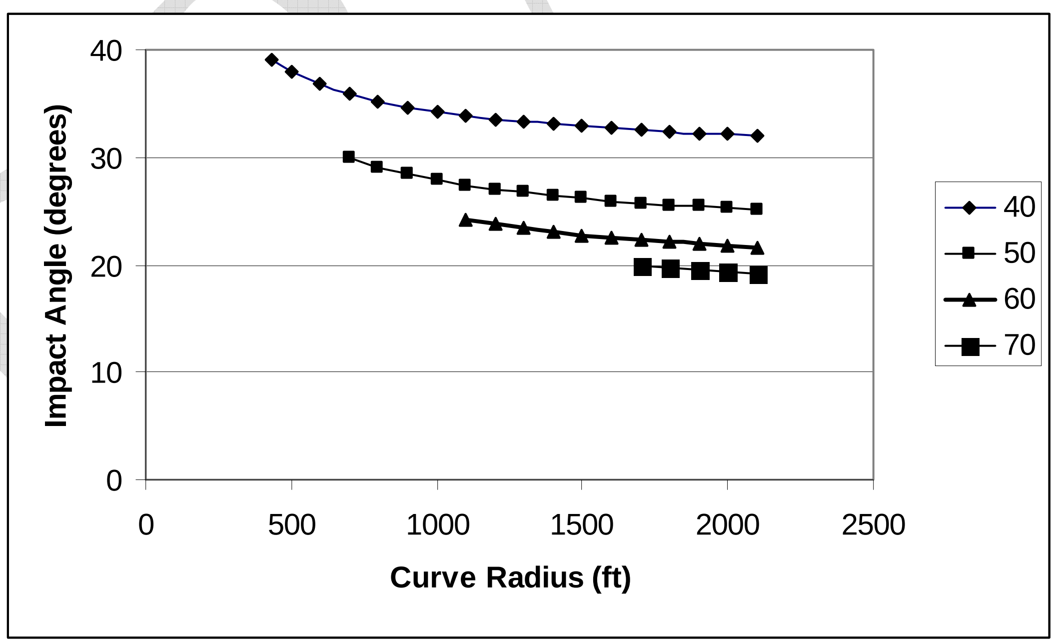
Characteristics of the horizontal curve that influence the calculated impact angle include its radius (R_{curve}), the number of lanes of the roadway (which defines the maximum separation distance between the errant vehicle and the work activity), and the superelevation rate used (e). Superelevation 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 (*5*). 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. Figure 2 illustrates 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. 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. At higher (60 and 70 mph) errant vehicle speeds, however, impact angles of 20 to 25 degrees are calculated to be possible.

MARKING AND TRAFFIC CONTROL REQUIREMENTS

The MUTCD sets forth the basic principles and standards for traffic control on all public roadways in the U.S. (*4*). 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 (*9*) to provide better guidelines regarding warning lights to be used on work vehicles and equipment.



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



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

Figure 2. Effect of Errant Vehicle Speed Upon Possible Impact Angles.

FUNCTIONAL REQUIREMENTS OF A HIGHLY-MOBILE BARRIER SYSTEM

Table 6 contains the minimum and desirable functional requirements for a highly-mobile barrier system that researchers have prepared based on the results of the assessments of work activities and impact conditions developed for the interim report and summarized in the previous chapter. These requirements were developed based on the three dimensions previously identified, as well as two ancillary dimensions:

- spatial requirements,
- access requirements,
- mobility needs,
- transportability, and
- traffic control and illumination

Minimum requirements were defined by the researchers as those which were essential for a highly-mobile barrier system to meet in order to have any type of applicability to the types of work activities being considered. Failure to meet the minimums would negate the ability of a work crew from using the system in most of its potential applications. Desirable requirements, on the other hand, were defined as those which could further increase the applications and conditions under which the system could be deployed or which could reduce the difficulties associated with deploying the system under constrained conditions.

Table 7 cross-references the identified construction and maintenance activities to the functional requirements and thus shows which activities do and do not meet the functional requirements. A discussion on the development of the functional requirements follows.

As Table 7 illustrates, a majority of the construction and maintenance activities being considered for protection by a mobile barrier protection system take place in a single travel lane and can typically utilize a work space 20 to 50 ft long (and is why the minimum length and width requirements were developed around these values). However, a few activities (bridge height measurements, loop detector installation, and some short line striping) are sometimes accomplished by moving laterally across the travel lanes in a sequential manner. In addition, activities such as milling and overlay tend to encroach into the adjacent travel lanes and typically need a longer space, since the equipment works right next to the edge of the travel lane and the operation includes trucks delivering materials, large equipment, and several crews of workers in the immediate vicinity of the equipment. In most cases, litter pickup would also not be accommodated by the minimum spatial requirements since multiple workers are typically spread out over long distances along the roadside. These exceptions are noted where appropriate in Table 7.

In addition to the minimum width and length requirements, the system must be capable of protecting either side (left or right, depending on the lane where work is occurring) of a work area. However, in order to make the system more versatile and applicable to more constrained width situations, it is desirable for the system to be capable of being configured so as to protect both sides of the work area. Such a need would exist when activities occur in the middle lane of multi-lane roadways, for example. However, a system that protected only one side of a work area at a time could still be used in this type of situation (presumably to protect the side considered to be at most risk to workers), and thus why this type of requirement is considered only desirable. Finally, another desirable requirement of a system would be for it to accommodate varying travel lane widths from 10 to 12 feet in order to minimize the encroachment of the system into adjacent travel lanes.

The two minimum functional requirements pertaining to accessibility were included in Table 6 in order to meet the needs of the workers to bring equipment and tools into the work area, and continue to access them while working. In general, the few activities (signal/lighting installation/maintenance, longitudinal shoulder texture, asphalt milling, and overlay) that cannot be accommodated by these minimum accessibility requirements typically require large amounts of heavy equipment and multiple vehicles to complete the work, such that it was not possible to identify any type of desirable functional requirement that could accommodate one or more of these activities in any reasonable fashion.

The minimum mobility requirement was included since a majority of the identified mobile activities move continuously or intermittently along the roadway at speeds somewhat less than 3 mph. In order to better accommodate the remaining activities, which can take less than one hour to complete, it is desirable to be able to deploy the system into a travel lane in less than 30 minutes, and for the system to be capable of being picked up and ready for transport to another location for deployment within 30 minutes. Such a requirement ensures that the sum of the deployment and pick-up time does not take more than expected activity time at a particular location.

The transportability minimum requirement ensures that the system could be transported on typical roadways without special permits. In addition, minimum and desirable requirements for traffic control and illumination were included to address the need for delineation, rear-end crash protection, and night work.

Table 6. Functional Requirements of a Highly-Mobile Barrier System.

Dimension	Minimum Requirement	Desirable Requirement
Spatial	▪ The system must be capable of allowing workers to access the entire width of a single travel lane. ▪ The system must adequately protect the typical work area lengths required for mobile and short-duration construction and maintenance activities. Limited observations indicate that these activities are currently accomplished within 20 to 50 foot lengths. ▪ The system must be capable of protecting either side (left or right, depending on the lane where work is occurring) of a work area.	▪ The system should be capable of accommodating varying travel lane widths from 10 to 12 feet in order to minimize the encroachment of the system into adjacent travel lanes. ▪ The system should be capable of being configured so as to protect both sides of the work area when activities occur in the middle lane of multi-lane roadways.
Accessibility	▪ While deployed, the system must allow rolling equipment such as thermoplastic and bitumen heaters and hand equipment to be brought into the work area. ▪ Once deployed, the system must continue to allow workers to access truck-mounted equipment and materials (i.e., air compressor hoses, pothole patching material, etc.) normally used in mobile maintenance operations.	
Mobility	▪ Once deployed, the system must have the ability to protect a work area that progresses continuously or intermittently along the roadway at speeds less than 3 mph.	▪ The system should be deployable into a travel lane in less than 30 minutes. ▪ The system should be capable of being picked up and ready for transport to another location for deployment within 30 minutes.

Table 6. Functional Requirements of a Highly-Mobile Barrier System, continued.

Dimension	Minimum Requirement	Desirable Requirement
Transportability	▪ When configured in its "transport" mode, the system must operate within the design template of a WB-50 (semi-tractor trailer) design vehicle with regards to horizontal and vertical clearances, turning path radii, vehicle hang-up potential, etc.	
Traffic Control and Illumination	▪ The system, when deployed, must comply with the *Manual of Uniform Traffic Control Devices (MUTCD)* with regards to delineation and warning light requirements for on-roadway work equipment. ▪ The deployed system must have rear-end crash protection.	▪ The system should be flexible enough to accommodate special flashing warning light and delineation requirements for work equipment as defined by each state's motor vehicle code, Department of Transportation special vehicle warning light and delineation policies, or similar local requirements. ▪ The system should be capable of accommodating artificial lighting that may be needed in the work area at levels defined by recent AASHTO guidelines (*9*, *10*, *11*).

Shaded area indicates no requirements.

Table 7. Assessment of Functional Requirements Per Work Activity.

Dimension	Meets Minimum Requirements	Meets Desirable Requirements	Does Not Meet Requirements
Spatial	Pavement profiling Pavement core sampling Edge/guardrail repair Short-line striping [a] Signal/lighting install/maintenance [b] Lateral rumble strips RPM installation/removal Crack seal Pothole patching Longitudinal shoulder texture Sealcoat/asphalt overlay - tab installation crew Level up - tab installation crew Traffic control		Litter pickup Bridge clearance measurements Short-line striping [s] Signal/lighting install/maintenance [b] Asphalt milling Sealcoat/asphalt overlay - paper/prep crew - spreader/overlay crew
Accessibility	Litter pickup Bridge clearance measurements Pavement profiling Pavement core sampling Edge/guardrail repair Short-line striping Lateral rumble strips RPM installation/removal Crack seal Pothole patching Sealcoat/asphalt overlay - tab installation crew Level-up - tab installation crew Traffic control		Signal/lighting install/maintenance Longitudinal shoulder texture Asphalt milling Sealcoat/asphalt overlay - paper/prep crew - spreader/overlay crew

Table 7. Assessment of Functional Requirements Per Work Activity, continued.

Dimension	Meets Minimum Requirements	Meets Desirable Requirements	Does Not Meet Requirements
Mobility	Litter pickup Pavement profiling RPM installation/removal Crack seal Longitudinal shoulder texture Asphalt milling Sealcoat/asphalt overlay Level-up - tab installation crew Traffic control - setup/removal	Bridge clearance measurements Pavement core sampling Edge/guardrail repair Short-line striping Signal/lighting install/maintenance Lateral rumble strips Pothole patching Traffic control - flagger	

[a] Short-line striping such as in-lane markings can be accomplished by closing one travel lane; however, other activities such as crosswalk markings and stop bars may require that more than one travel lane be closed.
[b] Most signal/lighting installation and maintenance activities can be accomplished by closing one travel lane; however, loop detector installation generally requires more than one lane to be closed.
Shaded area indicates no requirements.

MOBILE-BARRIER PERFORMANCE SPECIFICATIONS, ANALYSES, AND TESTING REQUIREMENTS

Traditional analysis of beams with various end conditions, simply supported to semi-rigid frame connections, has been done on beams with lengths varied from 20 to 50 ft. Test Level 3 (TL-3) loadings from the *AASHTO LRFD Bridge Design Specifications*, Chapter 13 (*12*), design loads for parapet impacts from errant vehicles are used. TL-3 impact conditions, from NCHRP Report 350 (*5*), are a ¾ ton pickup impacting the barrier at approximately 60 mph and 25 degrees. The equivalent static design load for TL-3 test conditions is 54 kips distributed over a 4 foot span. The most critical loading condition is when the span is loaded at the midpoint. Additional evaluations have been made at TL-2 conditions (¾ ton pickup, 45 mph and 25 degrees), the equivalent static load for this impact condition is 27 kips with load application length being the same.

The test load conditions outlined in the *AASHTO LRFD Bridge Design Specifications*, Chapter 13 (*12*), Design Loads for Parapet Impacts from Errant Vehicles, references NCHRP Report 350 (*5*). Impact criteria outlined in that document assumes a worst case impact scenario, consequently, the associated load conditions may yield designs that are conservative in nature. Additionally, the computed section properties assume there is no movement on the impacted structure. Since the structure will be mounted on a rolling sub-assembly, movement in both the longitudinal and lateral directions is likely under severe impact conditions. The elastic section properties dictated by the above impact conditions will produce members that are excessively large, therefore, both elastic and plastic section properties have been computed for the various spans. Furthermore, the analysis has been computed with both simply supported end conditions and then again with some restraint against rotation. There will likely be a rigid frame connection at the end of the beam span, this serves to reduce the maximum moment at mid-span and generates some moments at the end frame connections. However, since the mid-span moment has been reduced, member sizes can be reduced. It is desirable that no damage be experienced by the mobile barrier system, but weight and cost constraints may dictate upper design limits of the barrier system.

The preliminary analysis described above yielded the results shown in Table 8. When the system is designed under TL-3 test conditions (the beams simply supported at the ends), the section modulus ranges from 70 in^3 for 42 ksi yield material and 20 ft spans to 230 in^3 for 35 ksi yield material and 50 ft spans. Using the same parameters and using some larger diameter and more economical pipe sections, the associated computed deflections range from 1.5 inches up to 3.5 inches when the beams are designed elastically. If the beams are designed in the plastic range, deflections increase to approximately 2.5 inches on the shorter spans and approximately 9 inches on the long span since smaller beam elements are used. When evaluated under TL-2 test conditions, with the beams simply supported at the ends, the section modulus ranges from 35 in^3 for 42 ksi yield material and 20 ft spans to 120 in^3 for 35 ksi yield material and 50 ft spans. Using the same parameters and using some economical pipe sections, the associated computed deflections again range from 1.5 inches up to 3.5 inches when the beams are designed elastically. If the beams are designed in the plastic range, deflections increase to 3.5 inches on the shorter spans and approximately 5.5 inches on the long span since smaller beam elements can be used.

For a system designed under TL-3 test conditions, with the beams having framed connections at the ends, the required section modulus ranges from 40 in^3 for 42 ksi yield material and 20 ft spans, to 135 in^3 for 35 ksi yield material and 50 ft spans. Approximately 30% additional capacity is available when the plastic section modulus is used rather than the elastic section modulus.

The data presented thus far is based on using sections that are economical. Smaller diameter sections which are heavier in weight could be used, however, there will be a significant increase in weight (approximately 50 percent) and deflection (approximately 75 percent). Results using the smaller sections are summarized in Table 9.

Samples of the design methodology are available in Appendix B of this report. Further investigation into member types such as rectangular box beams, wide flanges and other “built-up” members should be investigated for the most economical design. Clearly the largest members, indicated in the simply supported elastic analysis, are unacceptable from space limitation standpoint. Another area that will require additional investigation is the potential movement of the portable barrier when impacted. The inertia of a heavier portable barrier will limit its movement when impacted but the upper weight bound without permitting is 80,000 lb total vehicle weight. Perhaps a secondary vehicle for anchorage could be investigated rather than single heavy unit.

A preliminary structural design of a 50 foot long system was performed using the engineering structural program RISA-3D. In this design, impact forces from TL-3 impact conditions (54 kips distributed over 4.0 feet) were used at mid-span of the truss system. The preliminary design incorporates a 3 foot deep by 50 foot long truss system constructed from standard steel shapes (see Figure 3). The truss was designed using 16 equally spaced panels with each panel measuring 3 feet 1.5 inches in length. Hollow steel tube shapes (HSS16x4x3/8) were used for the top and bottom chords of the truss. The vertical members in the truss were W6x9 steel shapes. All diagonals members used in the design were single angle L3x3x3/8 steel shape. The truss was supported on the ends by a single hollow steel tube (HSS12x12x3/8). These steel tubes were cantilevered away from rigid supports which were used to simulate the support from a large mobile vehicle similar to a large truck. For additional information, please refer to the design information presented in Appendix B.

Table 8. Evaluation Results, Larger Sections.

No.	Pipe Designation (Note: All Pipe A500 Grade B)	Outside Dia. (inches)	Wall Thickness (inches)	Section Modulus (S, in^3)	Usage
Test Level 2 (Elastic Design Conditions)					
1	14-inch Standard Weight Pipe	14.00	0.375	53.25	Spans Up to 25 feet
2	16-inch Standard Weight Pipe	16.00	0.375	70.26	Spans 25 to 35 feet
3	18-Inch Standard Weight Pipe	18.00	0.375	89.63	Spans 35 to 45 feet
4	20-inch Standard Weight Pipe	20.00	0.375	111.35	Spans 45 to 50 feet
Test Level 3 (Elastic Design Conditions)					
1	18-inch Standard Weight Pipe	14.00	0.375	89.63	Spans Up to 25 feet
2	20-inch Standard Weight Pipe	16.00	0.375	111.35	Spans 25 to 30 feet
3	22-Inch Standard Weight Pipe	18.00	0.375	135.42	Spans 30 to 35 feet
4	24-Inch Standard Weight Pipe	24.00	0.375	161.86	Spans 35 to 42 feet
5	24-inch Extra Strong Pipe	24.00	0.500	212.45	Spans 42 to 50 feet
Test Level 3 (Elastic Design Conditions w/ Partially Fixed Ends)					
1	16-inch Standard Weight Pipe	16.00	0.375	70.26	Spans 20 to 30 feet
2	18-inch Standard Weight Pipe	18.00	0.375	89.63	Spans 30 to 40 feet
3	20-Inch Standard Weight Pipe	20.00	0.375	111.35	Spans 40 to 50 feet

No.	Pipe Designation (Note: All Pipe A500 Grade B)	Outside Dia. (inches)	Wall Thickness (inches)	Section Modulus (Z, in^3)	Usage
Test Level 2 (Plastic Design Conditions)					
1	12-inch Standard Weight Pipe	12.75	0.375	57.45	Spans Up to 30 feet
2	14-inch Standard Weight Pipe	14.00	0.375	69.63	Spans 30 to 35 feet
3	16-Inch Standard Weight Pipe	16.00	0.375	91.57	Spans 35 to 45 feet
4	18-inch Standard Weight Pipe	18.00	0.375	116.51	Spans 45 to 50 feet
Test Level 3 (Plastic Design Conditions)					
1	18-inch Standard Weight Pipe	18.00	0.375	116.51	Spans Up to 28 feet
2	20-inch Standard Weight Pipe	20.00	0.375	144.45	Spans 28 to 35 feet
3	22-Inch Standard Weight Pipe	22.00	0.375	175.38	Spans 35 to 42 feet
4	24-inch Standard Weight Pipe	24.00	0.375	209.32	Spans 42 to 50 feet
Test Level 3 (Plastic Design Conditions w/ Partially Fixed Ends)					
1	14-inch Standard Weight Pipe	14.00	0.375	69.63	Spans 20 to 30 feet
2	16-inch Standard Weight Pipe	16.00	0.375	91.57	Spans 30 to 40 feet
3	18-Inch Standard Weight Pipe	18.00	0.375	116.61	Spans 40 to 50 feet

Table 9. Evaluation Results, Smaller Sections.

No.	Pipe Designation (Note: All Pipe A500 Grade B)	Outside Dia. (inches)	Wall Thickness (inches)	Section Modulus (S, in^3)	Usage
Test Level 2 (Elastic Design Conditions)					
1	12-inch Standard Weight Pipe	12.75	0.375	43.80	Spans Up to 25 feet
2	12-inch Sch. 60 Pipe	12.75	0.625	68.80	Spans 25 to 35 feet
3	12-Inch Sch.100 Pipe	12.75	0.843	88.10	Spans 35 to 45 feet
4	12-inch Sch. 120 Pipe	12.75	1.000	100.70	Spans 40 to 50 feet
Test Level 3 (Elastic Design Conditions)					
1	12-inch Sch. 120 Pipe	12.75	1.000	100.70	Spans Up to 25 feet
2	14-inch Sch. 100 Pipe	14.00	0.937	117.90	Spans 25 to 30 feet
3	14-inch Sch. 120 Pipe	14.00	1.093	132.80	Spans 30 to 35 feet
4	16-inch Sch. 100 Pipe	16.00	1.031	170.60	Spans 35 to 42 feet
5	16-inch Sch. 120 Pipe	16.00	1.218	194.50	Spans 42 to 50 feet
Test Level 3 (Elastic Design Conditions w/ Partially Fixed Ends)					
1	12-inch Sch. 80 Pipe	12.75	0.687	74.50	Spans 20 to 30 feet
2	12-inch Sch. 120 Pipe	12.75	1.000	100.70	Spans 30 to 40 feet
3	12-inch Sch. 160 Pipe	12.75	1.312	122.60	Spans 40 to 50 feet

No.	Pipe Designation (Note: All Pipe A500 Grade B)	Outside Dia. (inches)	Wall Thickness (inches)	Section Modulus (Z, in^3)	Usage
Test Level 2 (Plastic Design Conditions)					
1	10-inch Sch. 40 Pipe	10.75	0.365	39.38	Spans Up to 20 feet
2	12-inch Sch. 40 Pipe	12.75	0.375	57.45	Spans 20 to 30 feet
3	12-inch Sch. 60 Pipe	12.75	0.562	83.54	Spans 30 to 40 feet
4	12-inch Sch. 80 Pipe	12.75	0.687	100.08	Spans 45 to 50 feet
Test Level 3 (Plastic Design Conditions)					
1	12-inch Sch. 80 Pipe	12.75	0.687	100.08	Spans Up to 28 feet
2	14-inch Sch. 80 Pipe	14.00	0.750	131.8	Spans 28 to 35 feet
3	14-inch Sch. 100 Pipe	14.00	0.937	160.24	Spans 35 to 42 feet
4	14-inch Sch. 120 Pipe	14.00	1.093	182.52	Spans 42 to 50 feet
Test Level 3 (Plastic Design Conditions w/ Partially Fixed Ends)					
1	10-inch Sch. 100 Pipe	10.75	0.718	72.38	Spans 20 to 30 feet
2	12-inch Sch. 80 Pipe	12.75	0.687	100.08	Spans 30 to 40 feet
3	12-inch Sch. 100 Pipe	12.75	0.843	119.72	Spans 40 to 50 feet

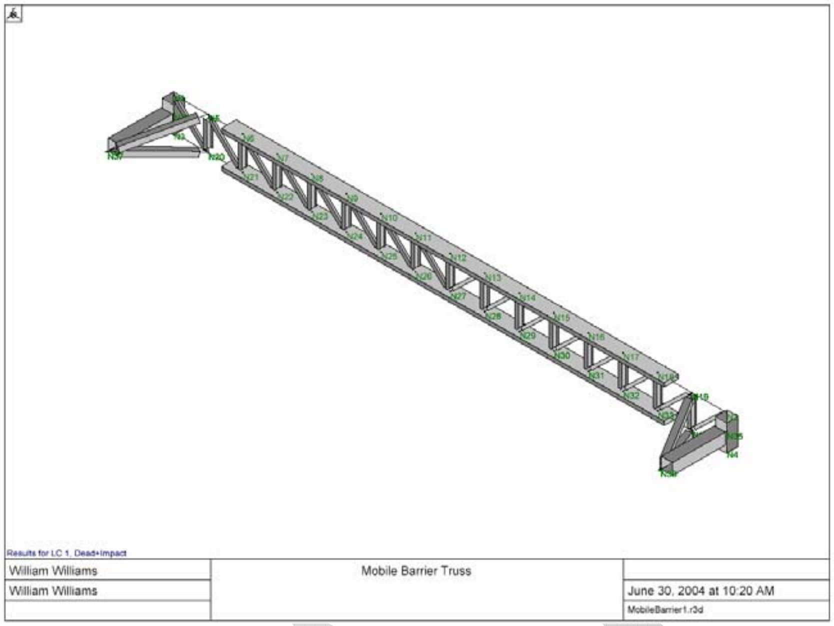


Figure 3. Illustration of Example Truss Used in Analysis.

Simulation of the barrier performance under impact conditions may be analyzed with a non-linear finite element code such as LS-DYNA. LS-DYNA is a general purpose nonlinear finite element program capable of simulating complex real world problems and was developed by Livermore Software Technology Corporation - LSTC. LS-DYNA is well suited to evaluate similar designs in a comparative fashion. When attempting to use LS-DYNA in a predictive manner, at least one full-scale crash test will be required for validation and confirmation of overall performance as well as some boundary conditions. Often contact issues require considerable time in the simulation process and some simplification of connections, contact interfaces may be needed. Especially when the barrier will have multiple contact interfaces (i.e., tire-road, king pin-tractor, impacting vehicle-barrier, etc.).

Actual testing of the highly-mobile work zone barrier shall be in compliance with NCHRP Report 350 (*5*), or the current equivalent of that document. As discussed in the interim report, 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. While Test 3-10, 820 kg passenger car impacting at 20 degrees and 100 km/h, would typically be required, it may be waived if good anticipated performance can be predicted by other means. This would include previous crash tests on similar member types and geometries. The main concern with this test is snagging potential that would cause vehicle instabilities or the possibility of high occupant risk values. The outcome of the tests should be evaluated per the compliance standard values for longitudinal barrier (i.e., vehicle stability, occupant risk values, occupant compartment deformation, etc.). In addition, damage to the barrier and level of intrusion are critical to the good performance of the highly-mobile 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 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 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. Occupant risk values are computed and compared against the limits for theoretical occupant contact velocity of 12 m/s and ridedown accelerations of 20 g's. occupant compartment deformation and barrier movement should also be evaluated.

Upon successful completion of full-scale crash testing, some field performance evaluation should be undertaken. First and foremost, the system must be functional. In the transport of the highly-mobile barrier, is maneuverability commensurate with vehicles of similar size and weight? Is deployment on vertical or horizontal curves problematic? Is the setup time reasonable? Is there good accessibility to the protected zone? Do workers within the protected zone have good visibility to their environment? Is stowage of the barrier smooth and timely? If and when field impacts occur, detailed documentation should be undertaken.

SUMMARY AND CONCLUSIONS

According to information cited on the Work Zone Safety Information Clearinghouse (http://wzsafety.tamu.edu), the Laborer's Health and Safety Fund officials indicate that 120 to 130 highway workers are killed each year in work zones. In another Clearinghouse citation, a recent ARTBA review of Bureau of Labor statistics indicates the fatality rate for roadway construction workers is 32 people for every 100,000 workers. By comparison, the rate for all construction is about 13 people per 100,000 workers and the general industry rate is about 4 people per 100,000 workers. These statistics, coupled with the absence of highly mobile protective devices, indicates the need for such devices. It is recognized that all injuries and deaths cannot be prevented but any mitigation (including a highly-mobile barrier system) is likely a worthwhile pursuit.

While it is desirable to have a protective device that covers a wide possibility of work zone conditions, this preliminary study shows there are some practical limits to activities that can be accommodated by a highly mobile work zone protective device. The system must be highly mobile, highly maneuverable, easily deployed, should be adjustable for various lane widths, and capable of redirecting ¾ ton pickups at angles and speeds up to 25 degrees and 60 mph if TL-3 is the selected performance level. A large number of highly mobile work zone operations were reviewed and categorized for functional requirements of the respective operations. Based on the analyses performed, a properly-designed barrier system could accommodate more than two-thirds of the identified mobile construction and maintenance activities. Furthermore, it is possible that some of those activities assessed as not being accommodated by a mobile barrier with these functional requirements might become accommodated with slight modifications in how work crews currently perform those activities.

Preliminary functional requirements, crash performance analysis, and physical size limitations indicate a maximum trailer length of 48-50 feet. Maximum overall width of the system in transport mode will be limited to 102 inches. Full-scale crash testing to NCHRP Report 350 or its subsequent equivalent standard should be required of any developed system. While testing to TL-3 conditions is desirable, structural member size, overall system mass, and likely impact conditions my dictate a lesser test level. A TL-2 device need only manage approximately half the impact energy of a similar vehicle under TL-3 test conditions.

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APPENDIX A

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.

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 - full access to one travel lane
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; sometimes take 1.5 lanes
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

APPENDIX B

EXAMPLE OF DESIGN CALCULATIONS