

Mobile Barrier Trailer: A Critical Analysis of an Emerging Workzone Protection System

Matthew R. Hallowell¹, J. Brent Protzman², and Keith R. Molenaar³

ABSTRACT

Each year construction is responsible for more fatal injuries than any other single service industry. Within this industry, the highway sector is particularly dangerous. Despite the fact that highway workzone safety has received significant attention from research community, injury rates continue to increase due increasing nighttime work under traffic. This manuscript describes a study of the attributes and potential impacts of the Mobile Barriers trailer (MBT-1), a an innovative safety barrier technology designed for use in highway workzones. The study focuses particular attention on the benefits and limitations of the lighting schemes associated with the MBT-1. The authors conclude that there are some significant advantages to the MBT-1's lighting schemes, programmable message board, crash-tested barrier, and mobility.

INTRODUCTION

The construction industry accounts for a disproportionate injury rate. According to Bureau of Labor Statistics (www.bls.gov), the construction industry consistently employs approximately five percent of the American workforce but accounts for approximately twelve percent of all

¹ Asst. Prof., Civ., Envir., and Arch. Engrg., University of Colorado, Boulder, CO 80309-0428; Tel.: 303-492-7994; E-mail: matthew.hallowell@colorado.edu

² Asst. Prof., Civ., Envir., and Arch. Engrg., University of Colorado, Boulder, CO 80309-0428; Tel.: 303-492-7603; E-mail: brent.protzman@colorado.edu

³ Assoc. Prof., Civ., Envir., and Arch. Engrg., University of Colorado, Boulder, CO 80309-0428; Tel.: 303-735-4276; E-mail: keith.molenaar@colorado.edu

occupational fatalities. These occupational injuries have a significant impact on the economy. In 2004 the industry was responsible 460,000 disabling construction injuries resulting in a total estimated cost of \$15.64 billion (National Safety Council 2006). Within the construction industry, the highway sector accounts for the highest injury and illness rate (BLS 2007). When compared to workers on all other types of construction sites, workers on road construction sites were found more likely to be killed by vehicles and heavy equipment (BLS 2007; CPWR 2008). The estimated direct costs of highway construction zone accidents were as high as \$6.2 billion per year between 1995 and 1997 with an average cost of \$3,687 per accident (Mohan and Gautam 2002).

As highway agencies continue to repair America's progressively failing transportation infrastructure, roadways must be renewed quickly with minimum disruption to the community. Such work requires the use of specific strategies such as nighttime work, continuous work, extended shifts, modularization, and others aimed to compress schedules. Based on the observations made by previous researchers, these emerging construction trends are likely to result in an increase in injuries and illnesses. Such increases have been observed and previously documented. For example, annual construction zone fatalities rose from 872 in 1999 to 1028 in 2003 (FHWA 2004). Since that time, there has been a steady increase in injuries and fatalities despite the fact that the volume of construction work (i.e., worker-hours) has remained relatively constant (BLS 2008).

There are many methods that highway agencies and private contractors use to protect highway work zones such as cones, signage, semi-permanent concrete barriers, and vehicular barriers

created by enclosing the work zone with idle equipment (i.e., “ring of steel”). This study investigates the benefits and limitations of a new method of protecting highway work zones: mobile barrier systems. Specifically, this paper presents the findings from an in-depth analysis of the MBT-1, a new mobile barrier system with unique features targeted at injury prevention and provides a comparison of this system with existing strategies. The study pays specific attention to lighting schemes associated with the MBT-1 as the lighting-related benefits are the most ambiguous.

This paper includes a literature review that outlines the causes of highway workzone injuries, methods of mitigating safety risk, and lighting schemes. This literature review is followed by a discussion and comparison of existing mobile barrier systems, a thorough description of the MBT-1, an analysis of the possible lighting schemes, and concludes with a discussion of the benefits and limitations of utilizing the MBT-1 for highway projects.

CAUSES OF HIGHWAY WORKZONE INJURIES

Highway construction sites can be differentiated from other construction sites because of the additional dangers attributed to high-speed passing vehicles, heavy equipment, and repetitive work tasks. There have been several studies that focus on the causes of highway construction and maintenance injuries. While these studies focus only on fatal injuries, this previous work sheds light on the factors that contribute to the disproportionately high injury rate. In 1999, statistics for fatalities occurring on highway construction and maintenance projects between 1992 and 1998 were published by the BLS. Among the 492 work zone fatalities, the leading occupations affected were construction laborers (42%), truck drivers (9%), construction trades supervisors

(8%), and operating engineers (8%). The most common primary sources of injury were trucks (45%), road grading and surfacing machinery (15%), and cars (15%). According to NIOSH (2001) nighttime work, contact with heavy equipment, and being struck by passing vehicles are the leading root causes of fatalities. Other literature reports that highway workers are also at risk of injury or death from contact with overhead power lines, falls from machinery or structures, gas line explosions, or being struck by falling objects or materials (Bryden and Andrew 1999).

Nighttime Work

Highway construction and maintenance is frequently performed throughout the night due to the pressure from the public to minimize traffic delays during high volume times. Night-time highway construction has been established to be more hazardous for both passing drivers and construction personnel because of decreased visibility. Furthermore, there is a higher probability of drivers impaired by drugs, alcohol, fatigue, or age-related vision impairments during nighttime, all of which contribute to the frequency of accidents (Arditi et al. 2005). According to Arditi et al. (2005), the factors that most contribute the nighttime fatalities on highway construction and maintenance sites include poor lighting conditions (43%), unfavorable weather conditions (8%), poor performance of safety garments (7%), workers not wearing safety garments (14%), fatigue or impairment of vehicle operator (64%), and other causes (32%). One should note that some injuries were deemed to be caused by multiple factors; as a result, the percentages add up to more than 100. The most common accident types at night were caused by the condition of the vehicle operator (64%) and poor lighting conditions (43%). Not surprisingly, the majority of these fatalities occurred when small maintenance crews performed nighttime work without proper visibility or barriers for the work zone. Furthermore, accidents associated

with mobilization, demobilization, and traffic control, increase dramatically when performed at night.

There are also specific risk events that increase substantially during nighttime work. For example, TRB (2008) found that the rate of private vehicles entering the work zone at high speed (i.e., incursions), triples after dark while the frequency of injuries resulting from debris and a projectile entering the work zone doubles. A conclusion of this TRB report is that alternatives, other than lane closures, should be used to protect workers in highway work zones.

Heavy Mobile Equipment

The majority of fatal injuries incurred by road construction workers are attributable to vehicle- and mobile heavy equipment-related incidents. When compared to workers on all other types of construction sites, workers of many differing occupations on road construction sites were found more likely to be killed by vehicles and heavy equipment. According to McCann and Cheng (2006) the majority of deaths involving vehicle and heavy equipment in traffic work zones include construction laborers (29%), heavy equipment operators (23%), and construction managers (14%). An analysis of 240 incidents involving serious injuries to workers on highway and bridge construction projects in New York State confirms that highway workers are at risk of severe nonfatal injuries from being struck by traffic vehicles or construction equipment (Bryden and Andrew 1999). This analysis revealed that passing traffic contributed to 22% of highway construction worker injuries and 43% of deaths in New York between 1993 and 1997.

Poor Signage

According to Maze (2000), many accidents result from poor signage. In this study, Maze found that among all the techniques used (e.g., police, radar detectors, automatic signs, and flagging devices) flagging and the use of police enforcement strategies had the most positive impact (Maze 2000). Unfortunately, utilizing law enforcement vehicles is much more expensive than other devices and work zone flagging has been found to be the highest risk construction work task.

Benekohal and Shu (1992) investigated the impact of work zone speed limit signs on the speed of passing traffic. This study found that about 63% of drivers reduced their speeds shortly after the first work zone speed limit sign, while 11% of drivers reduced their speeds when they were close to the actual work zone activity, 11% of drivers remained at a constant speed, and 15% increased their speed after passing speed limit signs. Benekohal and Shu (1992) also found that programmable signage is much more effective than standard signage or cones because of the visibility and size.

Incursions

Incursions could likely become a larger problem as more highway construction work is performed on active roadways. Incursions include cars hitting cones to actual interaction with workers and are usually the result of drivers under the influence, fatigue, poor visibility, or poor signage. Despite all the practices and efforts performed by the workers and management to protect work zones, injuries are still frequent in highway work zones resulting from falls, workers being struck by mobile equipment, and incursions from vehicles operated by the traveling public (NIOSH 2009). Many studies have been performed on work zone related

crashes. For example, Hall and Lorenz (1989) found that crashes are 26% more likely in work zones than in non-work zones; Harb (2008) also found that, between 1999 and 2008, work zone related crashes have increased 334%; and the Indiana Department of Transportation (2008) found that the U.S. has over 40,000 work zone crash injuries each year.

Daniel et al. (2000) found that straight, level work-zone roadways are much more accident-prone than ones with horizontal or vertical curves. This is because drivers are much more comfortable on straight, level roads as opposed to curved ones and so less rubbernecking occurs on more dangerous roadways (Harb 2008). Workers who are working adjacent to active traffic are often distracted by passing traffic, as well as when no visible barrier between the work zone and active lanes is present.

METHODS OF IMPROVING HIGHWAY WORKZONE SAFETY

To respond to the relatively high incident rate, several studies have been conducted to determine measures to improve site safety on highway construction and maintenance projects. For example, the National Institute for Occupational Safety and Health (NIOSH) conducted a study that involved the aggregation of relevant literature and a three-day workshop that brought together sixty stakeholders from government agencies, labor unions, and private employers to discuss measures to reduce highway construction site worker injuries from vehicles and equipment. The resulting document includes preventative measures to help protect highway workers from hazards posed by construction and traffic vehicles and is considered the most definitive guide to highway work zone safety (NIOSH 2001).

This NIOSH document outlines the roles and responsibilities of the contracting agency (e.g., highway agency), the contractor, and policy-makers at the federal, state, and local levels. The measure most highlighted is proper work zone layout and construction management on the part of the contractor. NIOSH suggests that road builders and maintainers adopt the following strategies:

- Assign a traffic control supervisor who is knowledgeable in traffic control principles and who will assume overall responsibility for the safety of the work zone setup;
- Set up temporary traffic control devices, such as signage, warning devices, paddles, and concrete barriers in a consistent manner throughout the work zone to provide passing motorists with advanced warning of upcoming work zones;
- Educate flaggers in topics such as traffic flow, work zone setup, and proper placement of channelizing devices; and
- Require all workers on foot to wear high-visibility safety apparel;

Regardless of these efforts, highway construction zone safety remains unsatisfactory. There remains a need for additional innovative safety management strategies and tools that are specifically designed for highway construction and maintenance. Recently, contractors and state highway agencies have begun to utilize physical barrier systems and lighting schemes to reduce safety risk in work zones. The subsequent sections of this paper discuss the salient aspects of physical barrier systems and lighting schemes.

HIGHWAY WORKZONE BARRIER SYSTEMS

Mobile barrier systems are emerging as a method for protecting workzones by providing a moveable, rigid barrier between the workzone and passing traffic. Traditional systems provide

varying degrees of protection ranging from negligible protection to crash-tested protection systems (MBS 2009). While this paper describes recent advances in mobile barrier systems, the concept of a mobile barrier is not new. In fact, according to the Texas Transportation Institute (TTI 2004), iterations of mobile barrier systems have been produced since the 1950's. Several images of first-generation mobile barriers are provided as Figures 1 and 2.



Figure 1 - First TTI mobile barrier (Texas Transportation Institute 2004)



Figure 2 - Second TTI mobile barrier (Texas Transportation Institute 2004)

Loshe et al. (2007) describes the various barrier systems implemented in the construction industry. Table 1 describes each of the major barrier systems and the advantages and disadvantages of each. The MBT-1 system is discussed in detail in the following section.

Table 1 – Advantages and Disadvantages of Existing Mobile Barrier Systems

Safeguard Link System	The Safeguard Link system is a towable steel barrier system. The barrier is constructed with wheels at the base and can be towed longitudinally with a pneumatic attachment or a hand crank. The barrier can be installed at a rate of 200-300 feet every 30 minutes. Unfortunately, this barrier system results in relatively large deflections when struck by a vehicle and is not appropriate for high speed workzones.
BarrierGuard 800	This system is a semi-mobile steel barrier that is typically used as a replacement for concrete barriers. The system is more mobile than concrete barriers because of its relatively low weight. The most useful feature of the BarrierGuard system is that 1000 feet of barrier can be set up in around one hour and curved sections can be added to accommodate curvature within the perimeter of the workzone. A disadvantage is that the system must be anchored when used, making the system difficult to move in short time periods.
VulcanBarrier	The Vulcan Barrier System is a portable steel barrier with steel sections in effective lengths of four, eight, and twelve meters. The system meets NCHRP 350 TL-3 test requirements and uses an interlocking steel pivot which allows each module to follow

	curves of up to six degrees. Disadvantages of this system are that it must be anchored, it is difficult to move in short time periods, and it requires separate equipment to move the sections.
Concrete Reaction Tension System (CRTS)	This concrete barrier system relies on a barrier transfer machine that can move barriers up to two lanes at a speed of 10 mph. The CRTS system can move across lanes allowing for versatility of lane closures. However, the system is relatively expensive as special equipment is required to move the barriers.
Steel Reactive Tension System (SRTS)	Like the CRTS, the SRTS requires a barrier transfer machine. In fact, the applications of the SRTS are the same with the CRTS. While the steel system offers less protection to the workers, it is lighter and smaller allowing the system to be moved more quickly and used in situations where there is minimal lane width.
K Rail	The K Rail system is a concrete barrier that provides low deflection and very high containment. This system allows for pin connections (1.1m deflection) and bolted connections (1m deflection). The weight of this system makes it difficult to move as heavy equipment is required. Further, the K Rail is limited in its applications due to cost and most suited for bridge work.
Balsi Beam	The Balsi Beam is a steel barrier system that provides 30 feet of protected work space. The system is composed of two hydraulically-controlled box beams attached to the sides of a flat bed trailer. The system is towed by a semi-tractor making it highly mobile. While the system is light and agile, it has yet to pass the most rigorous FHWA crash test standards.

OVER VIEW OF THE MBT-1 SYSTEM

The Mobile Barrier Trailer (MBT-1) is a rigid-wall trailer that serves as a structural and visual barrier between a highway construction work site and active roadways. The trailer is specifically designed to provide fore, aft, and side protection from passing traffic. The rigid trailer is towed into place by a standard semi-tractor at the front and includes an integrated crash attenuator at the rear. The attenuator and tractor trailer provide approximately 40 feet of protection. The MBT-1 also includes three removable twenty-foot panels. This versatile design allows the users to select 60, 80, or 100 feet of protection based upon the area and accessibility of the worksite and the comfort and competence of the driver. Each structural panel is five feet in height and includes four additional feet of visual (non-structural) barrier. In its maximum height configuration, the barrier includes five feet of structural protection and a total of nine feet of visual barrier between workers and passing traffic. In addition to providing a physical and visual barrier, the MBT-1 includes other unique features that help to mitigate safety risk within the enclosed work zone

such as an integrated three-line message board, vertical lift, usable power, portable air, welder, storage and supply areas, radar, safety lighting, and work lighting.

Perhaps the most notable aspect of the MBT-1 is the fact that it is the only barrier system that has been crash tested and approved for use on the National Highway System by FHWA under the National Cooperative Highway Research Program (NCHRP) 350 and (Test 311) MASH-08 Guidelines (MBS 2009). The test utilized a 5,135 lb 2002 Dodge Ram 1500 Quad Cab pickup truck at a speed of 100 km/hr at an angle of 25-degrees. No structural damage occurred and a maximum dynamic deflection of two feet was observed (Gomez-Leon 2008).

While the impacts of most of the above items are fairly obvious, the potential safety associated with the work zone lighting warranted additional investigation. In order to measure the quality of the work zone lighting, various scenarios were modeled using the illuminance, glare, and shadowing relationships discussed. This analysis was performed to aid future users of the MBT-1 system with the selection of appropriate lighting schemes for highway construction and maintenance work tasks. Before presenting the results of the analysis, an overview of lighting metrics and relationships will be provided. The reader should note that the fully extended MBT-1 system includes three 1000W halogen light source that provides 32,000 lumens each; one source for each barrier section. Each light pole can be adjusted between 9 and 12ft in mounting height.



INTRODUCTION TO PROPERTIES OF LIGHTING SCHEMES

Lighting of a worksite can have a considerable affect on motorist and worker safety, quality of work, productivity, and worker morale (Ullman 2007). Although lighting requirements for nighttime construction have been established, there are many variables that affect the quality of work zone lighting. The intensity, orientation, direction, and location of lighting sources considerably affect lighting quality, and specifically illumination, glare, and shadowing. If visibility is poor, workers are more likely to be struck by heavy equipment, passing motorists, or materials. The following discussion covers the three salient aspects of lighting that affect safety on highway work zones: (1) illuminance, (2) glare, and (3) shadowing. To provide context, these terms are defined below.

Illuminance: amount of light arriving at a surface measured in Lux ($1 \text{ lux} = 1 \text{ lumen/m}^2 = 0.093$ footcandle).

Glare: uncomfortable or disabling light in the field of view caused by excess luminance and luminance contrast.

Shadowing: a part of a surface that appears dark and unperceivable due to excess contrast caused when a physical object blocks light.

Illuminance

Ellis et al. (2003) discusses different lighting layouts, including light plant and machine mounted lighting methods and provides illumination guidelines for different construction tasks. These guidelines are based on human, environmental, task-related, and lighting factors. The result of this study showed that the Illuminating Society of North America's (IESNA) and Occupational Safety and Health Administration (OSHA) have recommended minimum light levels for three categories of construction. These findings are summarized in Table 2

Table 2: Recommended minimum illuminance levels and categories for nighttime highway construction and maintenance. After (Ellis et al. 2003).

Category	Min. Illuminance Level lx (fc)	Area of Illumination	Type of Activity	Example of Areas and Activities to be Illuminated
I	54 (5 fc)	general illumination throughout spaces	performance of visual task of large size; or medium contrast; or low desired accuracy; or for general safety requirements	<ul style="list-style-type: none"> • Excavation • Sweeping and cleanup • Movement area in the work zone • Movement between two tasks
II	108 (10 fc)	general illumination of tasks and around equipment	performance of visual task of medium sizes; or low to medium contrast; or medium desired accuracy; or for safety on and around	<ul style="list-style-type: none"> • Paving • Milling • Concrete work • Around paver, miller, and other construction equipment
III	216 (20 fc)	illumination on task	performance of visual task of small sizes; or low contrast; or desired high accuracy and fine finish	<ul style="list-style-type: none"> • Crack filling • Pot filling • Signalization or similar work requiring extreme caution and attention

Glare

Ellis (2003) identifies the following major sources of glare on construction work sites:

- Glare from passing vehicles,
- Glare from temporary work area lighting, and
- Glare from lighting on construction equipment.

Figure 3 is provided to illustrate a typical lighting configuration. According to the report, the beam angle (B) should not be more than 60 degrees, and the light tower should not exceed 30

feet in height. Furthermore, it warns that decreasing the beam angle too drastically can have adverse effects on the beam spread and area of illumination. The MBT1 lighting scheme meets these two requirements.

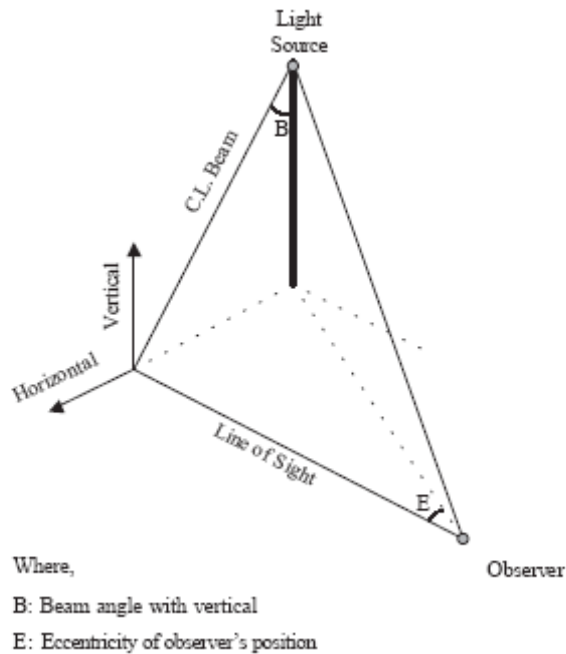


Figure 3: Effect of beam angle and eccentricity in reducing glare. After Ellis (2003)

In addition to limiting construction workers' vision, glare can also cause discomfort and pain when severe. Bullough (2008) described glare on the comparative De Boer scale that includes descriptors of glare that range from 'just noticeable' (1) to just permissible (5) to 'unbearable' (9). Bullough (2008) models discomfort glare (DG) using Equation 1. The variables in Equation 1 can be measured using an illuminance meter or by simulating the illuminance through lighting software.

$$\text{Discomfort Glare (DG)} = \log(E_L + E_S) + 0.6 \log(E_L / E_S) - 0.5 \log(E_A) \quad [1]$$

Where,

Light source illuminance (E_L) in fc or lux,

Light source luminance (L_L) in cd/ft^2 or cd/m^2 ,

Surround illuminance (E_S) in fc or lux, and

Ambient illuminance (E_A) in fc or lux.

The light source illuminance (E_L) is the vertical illuminance at a point with the ambient illuminance is completely blocked so only light directly from the source contributes. The light source luminance (L_L) is a measure of the brightness of the source in the direction of the point. The ambient illuminance (E_A) is the vertical illuminance with the light source switched off. The surround illuminance (E_S) is a measure of the light from the light source that reaches the point through reflection and dispersion and is the ambient illuminance (E_A) and the light source illuminance (E_S) subtracted from total vertical illuminance with the source switched on.

$$\text{De Boer Rating (DB)} = 6.6 - 6.4 \log(\text{DG}) \quad [2]$$

Shadowing

The third visual performance metric, shadowing, is measured using the Vector-Scalar Ratio (VSR). This ratio is intended to classify the directionality of light, which quantifies the potential for shadowing and object recognition capabilities of a given lighting setup. While there is little published on this topic, Cuttle (1974) developed a guideline for calculating and analyzing the VSR using the six (6) Cartesian directions. In this relationship the illumination vector is defined as the asymmetrical, directional component of light while the scalar illuminance is symmetrical,

diffuse component of light. The vector quantity divided by the scalar quantity provides the VSR and has a maximum value of 4.0 (no diffuse component) and a minimum value of 0 (completely diffuse).

$$VSR = \text{Vector} / \text{Scalar} \quad [3]$$

Once the Vector Scalar Ratio is calculated the values can be compared against Table 3 to determine the directionality of the light.

Table 3 - VSR Interpretation (After Cuttle 1974)

VSR	Strength of the Flow of Light	Typical Appraisal
3	Very Strong	Strong contrasts: detail in shadow is not discernible.
2.5	Strong	Noticeably strong directional effect: suitable for display but generally too harsh for human features.
2	Moderately Strong	Pleasant appearance of human features for formal or distant communication.
1.5	Moderately Weak	Pleasant appearance of human features for informal or close communication.
1	Weak	Soft lighting effect for subdued contrasts.
0.5	Very Weak	Flat shadow-free lighting: directional effect is not discernible.

FINDINGS FROM MBT-1 LIGHT MODELING

The evaluation metrics for the MBT-1 lighting follow standard design guidelines in the measurement of the Vector-Scalar Ratio and the De Boer glare metric. The guidelines presented by *Report 498* were used to evaluate the extent to which the MBT-1 lighting is adequate based on the quantitative measure of illuminance and the qualitative measure of glare. In addition, the VSR was used to evaluate the intensity of shadows in the work zone and the De Boer glare metric was used to quantitatively evaluate glare.

The computations required the measurement of quantitative metrics and the creation of a computer model that simulates the exterior lighting condition based on the 1, 2, and 3 pole configurations of the MBT1. The program used for this was *AGI32* which takes three dimensional model inputs and the light source intensity distribution file and computes the illuminance at specified calculation points in the 3-D environment. The calculation point boundary was defined as a rectangular grid that is the complete length of the MBT1 setup (2, or 3 sections and 9 or 12ft mounting) by 40ft perpendicular to the barrier. Only 2 and 3 sections of the MBT1 were analyzed as the single light pole no longer has any advantage over a standard generator light cart. The large calculation grid allows an evaluation of the usable work space at night based on lighting conditions alone. Within this boundary a 5ft x 5ft spacing between points was used to get a reasonable understanding of the lighting quality across the work area.

Quantity of Light

The evaluation of quantity of light is based on the horizontal illuminance at the ground plane computed in the model. This is a critical aspect which determines the general visibility of the unobstructed workplane. This is a verification of the task visibility ignoring issues relating to shadows on the specific task and glare in the field of view. Without adequate light levels workers are likely to underperform, but more critically, are more likely to be involved in accidents that were initiated inside the workzone. In general, the MBT1 has adequate illuminance for all task categories as long as within 20ft of the barrier with all configurations. In terms of illuminance alone, there appears to be very little difference in usable area by changing from a 9ft mounting to a 12ft mounting, although the 9ft mounting has a much lower uniformity. Therefore, based on illuminance alone, it appears that the 12ft mounting has a slight advantage

over the 9ft mounting, unless a specific activity requires greater illuminance than Category III according to Ellis et al (2007). Figures 4, 5, 6, and 7 indicate the recommended work zones by task type and MBT1 setup. These figures highlight the areas of the work zone where specific task categories (1-3) that are most appropriate given the quantity and quality of light. As shown in these figures, the all of the lighting schemes for the MBT1 provide a large illuminated area for each task type. Just as important is the increased level of uniformity that a multiple source system, such as the MBT1, creates as opposed to a single source.

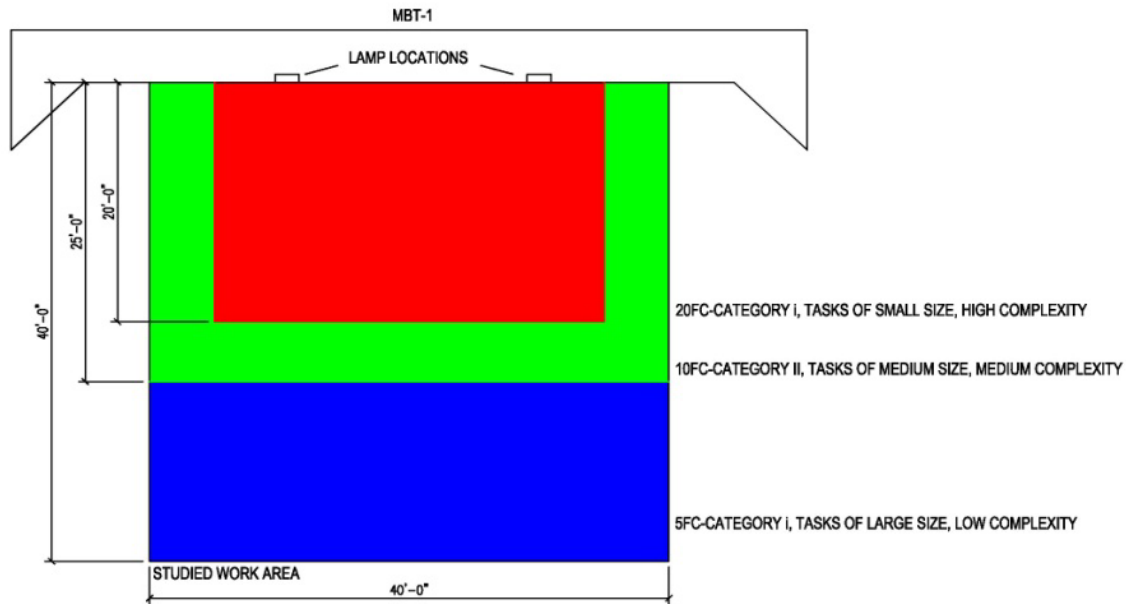


Figure 4: Illuminance categories and corresponding task capabilities for studied work area for 2 sections of MBT1 at 12ft mounting height.

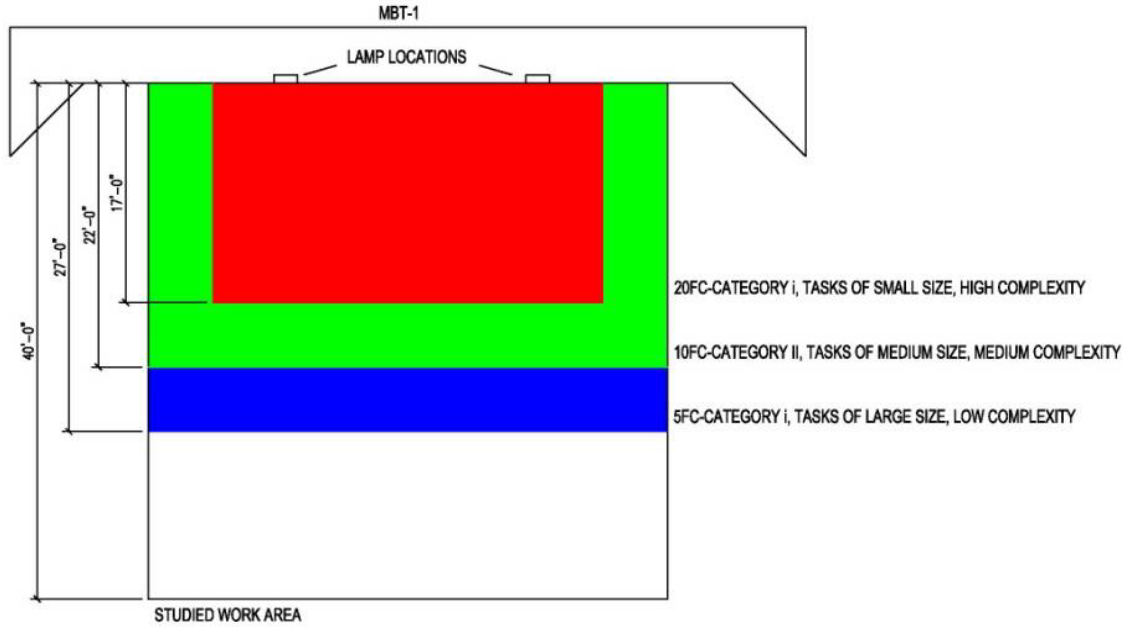


Figure 4: Illuminance categories and corresponding task capabilities for studied work area for 2 sections of MBT1 at 9 ft mounting height.

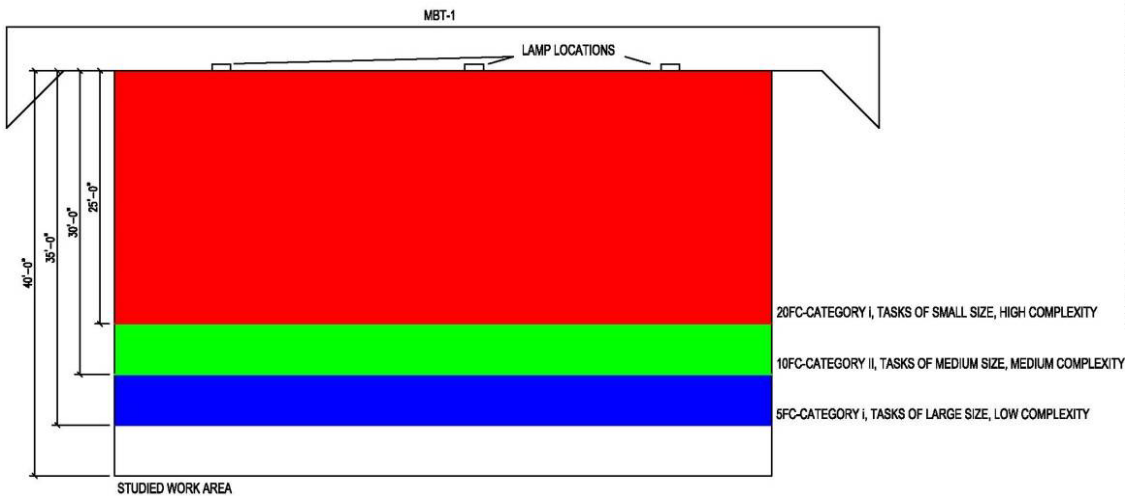


Figure 5: Illuminance categories and corresponding task capabilities for studied work area for 3 sections of MBT1 at 12ft mounting height.

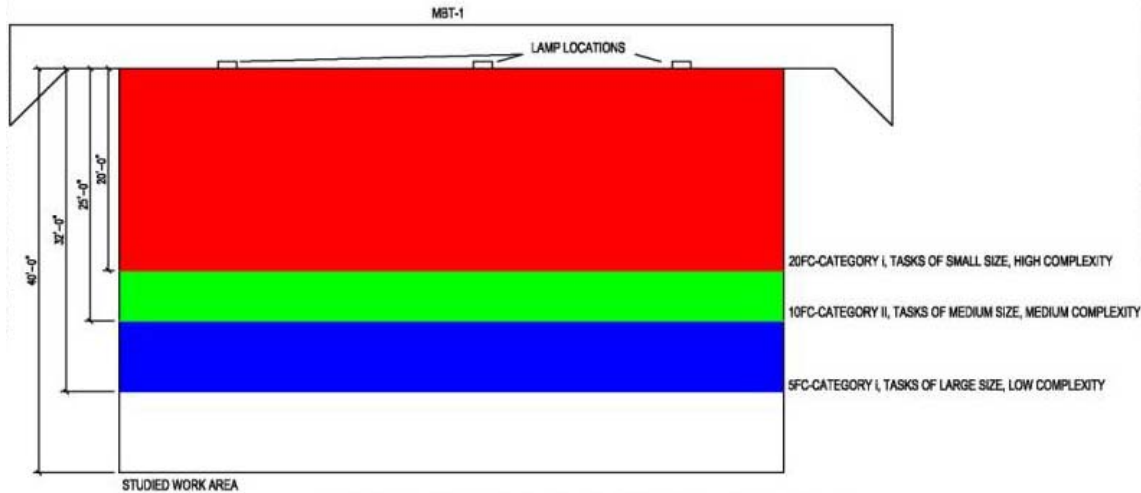


Figure 6: Illuminance categories and corresponding task capabilities for studied work area for 3 sections of MBT1 at 9ft mounting height.

Shadowing

The evaluation of shadow strength is based on the VSR also computed at the ground plane. As *AGI32* does not compute VSR directly, six separate calculation planes (one for each positive and negative Cartesian direction) were created. The VSR was computed at each location on this grid. If the VSR is too high and an object or piece of equipment is introduced in the work zone, objects or tasks within the shadowed area will be very hard to see and potentially avoidable accidents can occur. Even with the multiple lamp scheme, there remains a very strong directionality of light and potential for dangerous shadows. This can be seen in the best case scenario of VSR (which uses 3 separate sources at a mounting height of 12ft) shown in the contour plot of Figure 7. The regions with the highest values (3.5-4) have the highest shadowing and the regions with the lowest values (0-0.5) have the least shadowing. Therefore, tasks that will require extensive detail or complex tasks should be done as close to the MBT1 as possible or during the day. Again, it is important to note that, theoretically, the shadows caused by a single

source system are completely debilitating and requires repositioning to be able to see objects or obstacles within the shadowed region. While shadowing is still high with the MBT1 lighting system, the addition of multiple light sources decrease the shadowing which allows for an increase in visibility within shadowed regions.

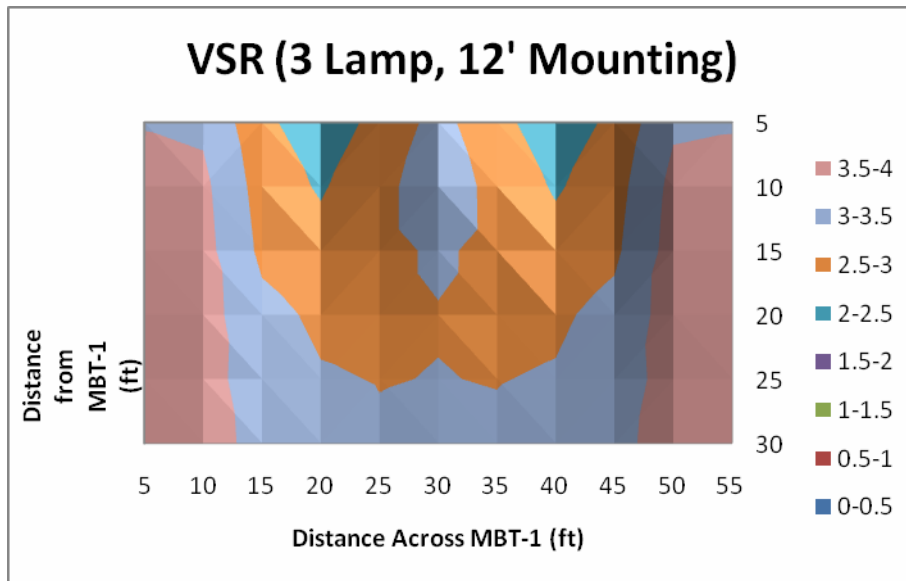


Figure 7: Vector Scalar Ratio over Construction Area.

Glare

Ellis et al. (2007) provides a guideline to avoid glare. As shown in Figure 8, the light source should be aimed no higher than 60 degrees. MBT-1's lighting complies with this guideline under all lighting schemes. It should be noted that, in some locations, workers will be subject to the bright light sources that cause significant glare. A closer examination of the glare produced by MBT-1's lights was examined using the relationships and strategies discussed in the literature review of this paper.

According to Figure 8, which has the least De Boer rating, created from the results of the glare metric calculations, the MBT-1 fixtures will create uncomfortable glare regardless of where in the construction area the lamps are viewed from. Glare will be strongest from 20 to 30 feet from the MBT-1. According to the DeBoer scale the glare in this region is disturbing, while less than 20 feet from the MBT1 the glare is just permissible. The fixture will have the highest intensity values in this area and the lamp will be in full view of the workers. Therefore, head up tasks, tasks that do not require you to look primarily at the ground plan, should be completed as close to the MBT1 as possible and preferably less than 20 feet away. As much as glare is a problem with the MBT1 lighting configuration, a much brighter single light source, as done in the traditional roadway construction lighting setup, would likely be much greater.

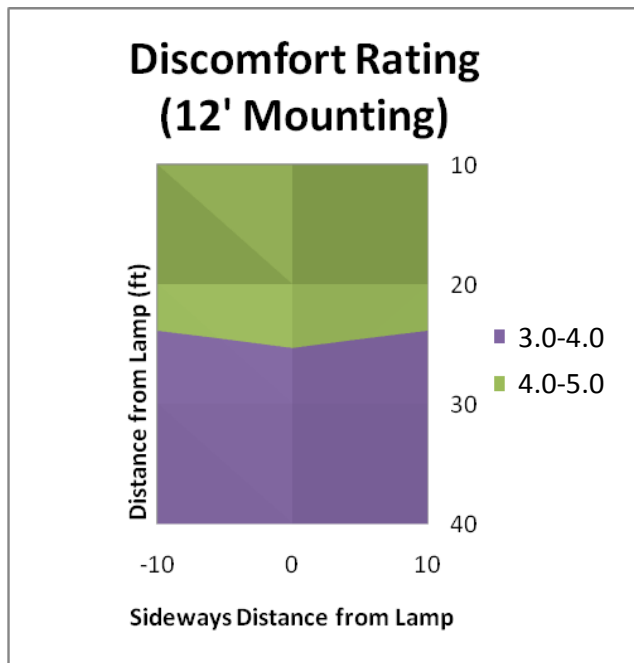


Figure 8: DeBoer Glare Ratings for 12' Mounting from a single source.

PERCEIVED BENEFITS OF THE MBT-1

The MBT-1 system provides an innovative solution to the increasing safety issues related to construction and maintenance on highway work zones. As previously indicated, the major causes of highway work zone injuries include poor illumination, poor signage, incursions, and workers on foot being struck by heavy mobile equipment. The MBT-1 addresses all of these causal factors by providing up to 100 feet of crash-tested barrier with adjustable lighting, a customizable three-line message board, and a visual barrier between workers and active roadways. The MBT-1 also provides a less cluttered work zone due to a decrease in the collateral vehicles associated with the “ring of steel” (MBS 2009).

Based on previous research conducted by Hinze (2006), work sites with visual barriers to prevent distractions increase both safety and productivity. No other barrier system provides such a visual barrier that is also crash-tested to prevent injuries associated with incursions. The visual barrier improves safety by reducing the frequency of rubbernecking from the traveling public and distractions to workers from passing traffic. According to Hinze (2006), reduction in distractions from outside the work zone increase productivity and safety because attention can be redirected on hazards within the work zone and task achievement.

The primary lighting benefits of the MBT1 versus traditional roadway construction lighting are due to the multiple source layout, therefore is really only an improvement when multiple sections are used. Utilizing multiple light sources has multiple potential benefits. First, a distributed lighting scheme creates more uniform brightness across the work zone. The optics from a single source can only do so much to spread the light across the work zone. Also, multiple source locations reduces shadowing. The overlap of the light from each source allows light to strike the

work plane even when one source is being blocked by an object or worker. In addition, to get the same brightness on the work zone from only one source, the source must be much brighter, which creates additional glare and potential effectiveness and safety issues.

CONCLUSIONS AND RECOMMENDATIONS

The MBT-1 is a system that could have a significant impact on the safety of highway construction and maintenance work zones. Unlike other systems, the MBT-1 offers a completely mobile barrier that requires minimal equipment to operate and includes high quality lighting schemes that are preferred to traditional workzone lighting methods, a programmable message board, and an attenuator. The system is also crash tested to the most rigorous FHWA standards. This research shows that, when used properly, the MBT-1 offers excellent workzone lighting in addition to the mobile steel barrier.

Specifically, the MBT1 offers the advantage of increased lighting uniformity, decreased shadowing in the workzone, and decreased glare when performing heads up tasks. For those DOTs or private contractors who consider using the MBT-1 system, the writers offer the following recommendations for optimizing the lighting system:

- Use the maximum number of light poles that is available for the specific MBT1 setup;
- The most difficult tasks should be performed as close the MBT1 as possible to take advantage of the maximum brightness and minimum glare; and
- Always use the 12 ft poles in lieu of the 9 ft poles to achieve the greatest shadow reduction and least possible glare.

Finally, the authors recommend future research of the followign topics: (1) the lifecycle safety impact of varios work zone protection systems; (2) cost-benefit analysis of the MBT-1 and other barrier systems; (3) comparison of lighting models with actual measurements; (4) a longitudinal study that investigates the impact of mobile barriers over time; and (5) a study that investigates the most applicable construction and maintenance tasks for MBT-1 deploymnet.

REFERENCES

Arditi, D., Ayrancioglu, M., and Shi, J. (2005). "Worker safety issues in night-time highway construction". *Engineering Construction and Architectural Management*. 12(5): 487-501.

Benekohal, R. F. and Shu, Jie (1992). "Evaluation of work zone speed limit signs with strobe lights." Illinois Cooperative Highway Research Program, Report IHR-014, June, 1992.

Bryden, J. E., & Andrew, L. (1999). "Serious and fatal injuries to workers on highway construction projects". *Transportation Research Record*, 1657: 42– 47.

Bullough, J.D., Brons, J.A., Qi, R., & Rea, M.S. (2008). "Predicting discomfort glare from outdoor lighting installations." *Lighting Research and Technology*, 40: 225-242.

Bureau of Labor Statistics (2008). Occupational Injuries/Illnesses and Fatal Injuries Profiles. <<http://data.bls.gov/GQT/servlet/InitialPage>>. November 2008.

Center for Construction Research and Training. (2008). "Construction chartbook" Silver Spring, MD.

Cuttle, C. (1974). The flow of light in lighting design. Environmental Advisory Service, St. Helens, Merseyside.

Daniel J., Dixon, K., Jared, D., (2000). Analysis of fatal crashes in Georgia work zones. Transportation Research Record 1715. Transportation Research Board, Washington, DC.

Ellis, R., Amos, S., & Kumar, A. (2003). Illumination guidelines for nighttime highway work. Transportation Research Board, National Research Council, Washington, DC.

FHWA, 2004. "Work zone safety facts and statistics." Federal Highway Administration (FHWA). <http://safety.fhwa.dot.gov/wz/wz_facts.htm>, updated on December 24, 2004.

Gomez-Leon, S. (2008) "NCHRP Report 350 update: Test 3-11 full-scale crash evaluation of a mobile barrier trailer." *Southwest Research Institute Project No. 18.13922*.

Harb, Rami. "Freeway Work-Zone Crash Analysis and Risk Identification Using Multiple and Conditional Logistic Regression." ASCE Journal of Transportation Engineering. 134.5 (May 2008): 203-214.

Hinze, J. (2006). *Construction safety, 2nd Ed.* New Jersey: Prentice-Hall.

Loshe, C. Bennet, D, and Velinsky (2007). "Temporary Barrier Usage in Work Zones."

California Dept. of Transportation. June 30, 2007.

http://www.ahmct.ucdavis.edu/images/FinalReportTempBarriers_080821.pdf

McCann, Michael and Mei-Tai Cheng. (2006). "Dump truck-related deaths in construction, 1999-2002". Poster Presentation at the NORA Symposium, Washington, D.C. April 18-19.

Mobile Barriers LLC. (2009). "Mobile Barriers Specs.". IWAPI, Inc. 2 Mar. 2009

<<http://www.mobilebarriers.com/>>.

Mohan, S.B., and Gautam, P.(2002). *Cost of highway work zone injuries. Practical Periodical on Structural Design and Construction*, vol. 7. ASCE (2), 68–73

National Institute for Occupational Safety and Health. (2001). "Building safer highway work zones: Measures to prevent worker injuries from vehicles and equipment." Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention. April.

National Institute for Occupational Safety and Health. "General Information." 2009.

< <http://www.cdc.gov/niosh/topics/constructionsafety/>>

National Safety Council (2006). *Accident facts*, Itasca, Ill.

Texas Transportation Institute. (2004). "Development of Functional Requirements for a Highly-

Mobile Barrier System to Protect Highway Workers: Final Report.” Working paper. June 2004.

Transportation Research Board. (2008). NCHRP Report 627. “Traffic Safety Evaluation of Nighttime and Daytime Work Zones.”

<http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_627.pdf>