

USING A BINARY PROBIT MODEL WITH RANDOM EFFECTS TO EVALUATE THE EFFECTIVENESS OF HIGH-VISIBILITY PERSONAL PROTECTIVE EQUIPMENT ON NIGHTTIME HIGHWAY OPERATIONS

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ABSTRACT

Nighttime construction has become an accepted procedure for roadway maintenance and construction operations although it presents visibility problems for motorists and workers. High-visibility garments are used to improve the visibility of roadway workers. This paper presents a methodology to compare the visibility of different high-visibility safety garments. The high-visibility garments were displayed in a simulated maintenance work zone on an interstate in Midwest USA. Videos were recorded using a camera which was mounted on a passenger car which passed through the work zone at the posted speed limit. These videos were then shown to drivers who compared the visibility of the garments of the construction workers. Statistical analysis was conducted to examine the impact of random effects by considering characteristics of the garments, drivers and site, etc. The study found that variables such as the mean of the retroreflectivity measurements of the garment and the frequency of the drivers encountering nighttime work zones were significant when choosing the most visible garment. The study provides insight regarding practices related to high-visibility garment, and can play a significant role in improving worker visibility on nighttime operations.

Keywords: Nighttime, Safety, Binary Probit, Personal Protective Equipment, High-visibility, Work Zone, Construction, Maintenance.

1. INTRODUCTION

Nighttime construction has become an accepted procedure for roadway maintenance and construction operations although it presents visibility problems for motorists and workers. Visibility is critical to workers and motorists on roadways. The sooner a driver detects a worker, the more likely a struck-by incident can be prevented (ANSI/ISEA 207-2006). High-visibility Personal Protective Equipment (PPE), which is composed of fluorescent background color and retroreflective material, is regularly used to improve the visibility of roadway workers.

In response to the importance of high-visibility garments, the International Safety Equipment Association (ISEA) and the American National Standard Institute (ANSI) published the American National Standard for High Visibility Safety Apparel and Headwear, known as ANSI/ISEA 107-2004. This publication provides recommendations for the use, design and testing of high-visibility apparel. ANSI/ISEA 107-2004 defines three performance classes (Class I, II and III) for high-visibility apparel, depending upon the minimum area of the different materials on the safety garment.

2. PRIOR STUDIES IN EVALUATING EFFECTIVENESS OF HIGH-VISIBILITY PPE

Typically, the effectiveness of high-visibility garments in the nighttime hours has been evaluated by determining the distance between the pedestrian and the point at which the driver recognizes the presence of a pedestrian. Previous research studies have evaluated the characteristics of safety vest luminescence using computer software and by obtaining the perspectives of human evaluators on their visibility. Table 1 summarizes prior studies that evaluated the effectiveness of high-visibility PPE. None of these studies were conducted in Indiana, nor have they incorporated in the assessment the combination of different high-visibility PPE, the perspective of drivers regarding visibility of different PPE and the features in a maintenance work zone. This study considers different types of safety garments (safety pants, safety vest and retroreflective bands) in a simulated maintenance work zone. Drivers compared the visibility of these garments. A statistical model was developed to predict which characteristics make garments more visible to drivers.

3. DATA COLLECTION

This study incorporates the perspective of drivers and the assessment of the visibility of different combinations of high-visibility PPE displayed in a maintenance work zone environment. A Binary Probit Model was developed to predict those characteristics which cause drivers to rate a garment as more visible. The following subsections provide further details.

Selection of Experimental Set-up

A simulated maintenance work zone located on interstate I-74 in southeast Indianapolis between Exits 96 and 99 was used. The cones at the work zone were placed at every other skip of the pavement markings. Figure 1 shows how the work zone was set up. A worker wore high-visibility garments and was videotaped in the active work zone area while performing two different tasks in two positions: position 1 and position 2. These two positions were found to be very common in nighttime work zones. Figure 2 shows workers in these positions on a maintenance project in downtown Indianapolis, Indiana.

Selection of PPE used in the Analysis

Fourteen different types of high-visibility PPE were considered in this study, including the high-visibility garment (Class II PPE) currently used by the Indiana Department of Transportation (INDOT). All of the garments were yellow-green in color with white retroreflective material. The PPE evaluated in this study included weather-related garments (coats, raincoats and sweatshirts); however these garments were not included in the statistical analysis. Table 2 provides a listing of the key features of the garments considered in the Binary Probit model. Multiple coefficients of retroreflection (RA) measurements were taken for each high-visibility PPE using a retroreflectometer. Clothing assemblies were created by combining two or more high visibility items. The high-visibility PPE assemblies all meet the minimum requirements for Performance Classes 2 or 3 of the ANSI/ISEA 107-2004. Table 3 shows the assemblies that were evaluated in this study.

Table 1: Prior studies that evaluated the effectiveness of high-visibility PPE

Authors /Year	Key features of the Data Collection	Data collected and analysis performed	Key Findings
Luoma (1995)	<ul style="list-style-type: none"> • Studied the effects of retroreflector positioning on the recognition of pedestrians. • Considered four retroreflector positions at different locations and conditions. 	<p>Analysis of variance considering recognition distances, retroreflector positions and walking direction.</p> <p>Pair wise comparison and Thurstonian scaling</p>	<p>Pedestrians with retroreflectors at the major joints of their bodies had the greatest mean recognition distance (249m), followed by pedestrians with the material at the wrists and ankles (241m), torso (136), and no retroreflectors (35m).</p> <ul style="list-style-type: none"> • Combinations of color contrasts, within the vest and in contrast relative to the surroundings, affect the noticeability of the vest. • Stimuli having orange and yellow color were found to be more noticeable. • For nighttime, safety vests with higher luminance trim material were found to be more noticeable.
Sayer and Mefford (2000)	<ul style="list-style-type: none"> • Examined the effect of color contrast in visibility during both the daytime and nighttime operations. • Experiment was conducted in a simulated work zone. 		
Sayer et al. (2002)	<ul style="list-style-type: none"> • Normal and color deficient drivers assessed the effects of color on the detection of pedestrians who were wearing different colors of retroreflective markings on the legs. • Drivers sitting in the driver's seat of a stationary automobile observed the pedestrian walking along the road. 	<p>Modeling of detection distances as a function of specific intensity of unit area and analysis of variance</p>	<p>The effect of the participants' ages was not significant; and for persons with normal color vision, the color of the retroreflective marking affected the distance at which the pedestrian was detected.</p>

Arditi et al. (2003)	<ul style="list-style-type: none"> Evaluated six safety vests in highway work zones by measuring their luminescence when they were displayed in a work zone. Involved the videotaping of the vests and considered the lighting intensities in the work zone, weather conditions, etc. Factors evaluated by a group of subjects included the 360° visibility of these vests, their conspicuity against the background, etc. 	<p>A system was developed to perform a field test and calculate the luminance of the safety vests.</p>	<p>Two of the vests which were very similar and did not have the largest amount of retroreflective material were superior to the other vests.</p>
Sayer and Mefford (2004a)	<ul style="list-style-type: none"> Assessed the attributes of 18 retroreflective personal safety garments on pedestrian conspicuity at night by having drivers passing through a simulated work zone attempting to detect pedestrians. The detection distances were found using the coordinates of the vehicle and the pedestrian, obtained using a differential global positioning system. 	<p>Analysis of variance considering detection distances, garment configuration, trim color, trim intensity, driver's age, etc.</p>	<ul style="list-style-type: none"> Class 3 jackets were significantly more conspicuous than both the Class 3 or Class 2 vests Younger drivers detected a pedestrian at significantly greater distances than older drivers. Gender and retroreflectivity were not significant. The blaze orange color was found to be the most conspicuous of the retroreflective trim colors.
Sayer and Mefford (2004b)	<ul style="list-style-type: none"> Assessed the effects of retroreflective arm treatments, pedestrian arm motion, scene complexity, and pedestrian orientation on the detection distances of older drivers. Twenty-four drivers with a mean age of 68.8 years drove through a route and indicated to a researcher when they were confident of seeing a pedestrian 	<p>Analysis of variance considering detection distance, scene complexity, garment, orientation, etc.</p>	<ul style="list-style-type: none"> The garment and pedestrian orientation were not significant factors. Both the scene complexity and arm motion had a significant effect on the results.
Hirasawa et al. (2006)	<ul style="list-style-type: none"> Conducted an experiment in a simulated work zone to determine the most recognizable uniform colors (dark blue, red, yellow, and orange) as perceived by users during the winter and autumn seasons in the daytime and nighttime hours and at dusk. Two lighting conditions were evaluated at nighttime: 	<p>Comparisons of the color recognition distance and worker</p>	<p>The most recognizable colors were yellow during daytime and orange at dusk and nighttime.</p>

spotlighting and balloon lighting.

recognition
distance.

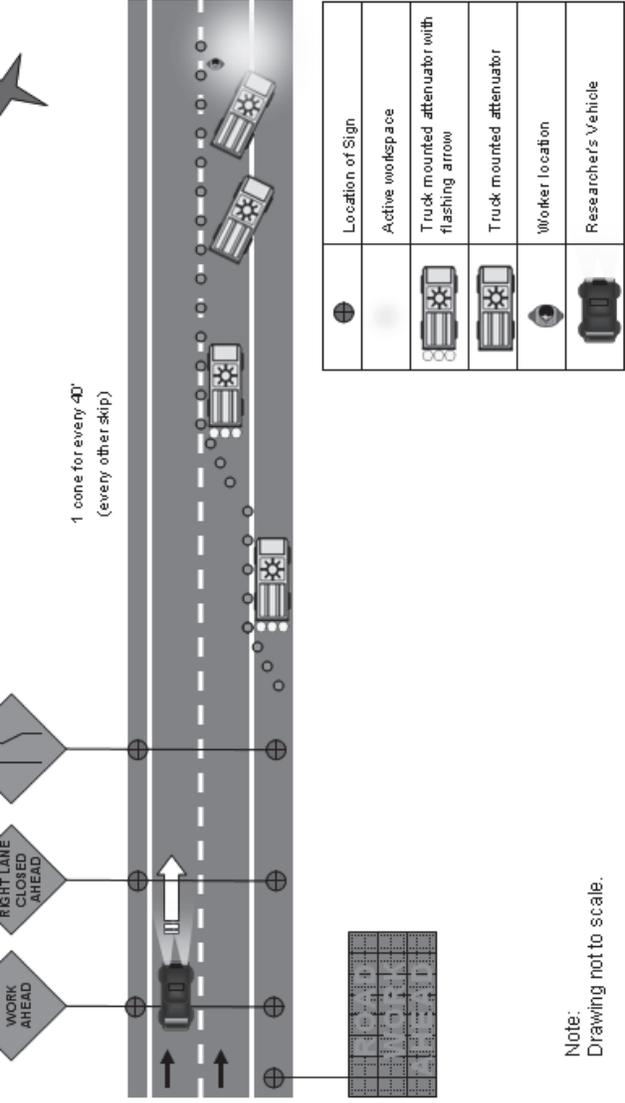


Figure 1: Test layout for data collection

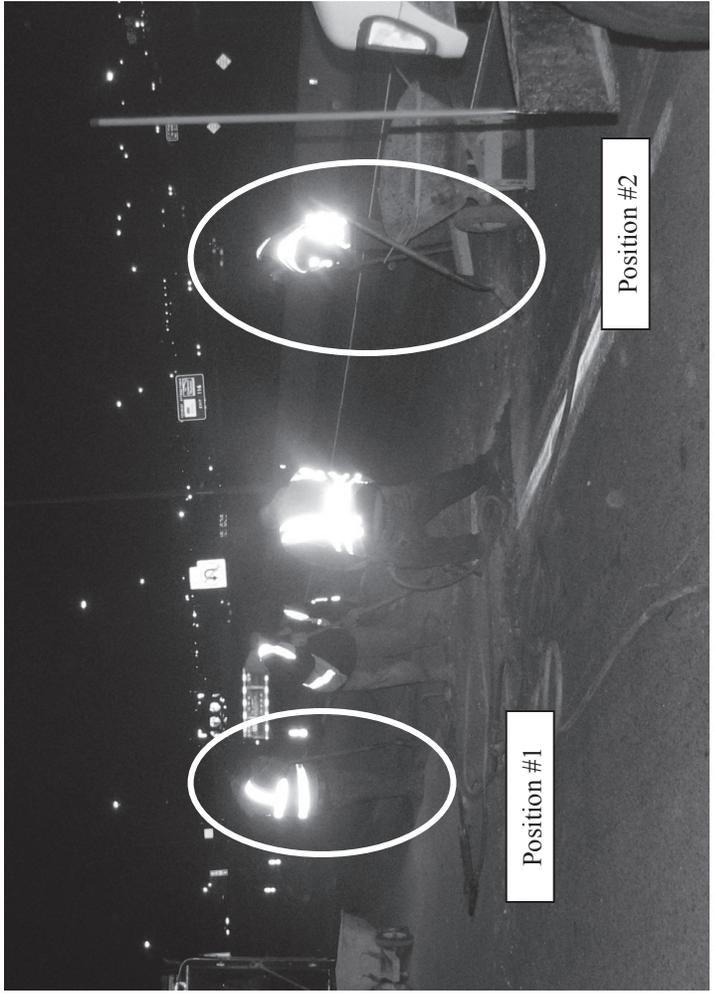


Figure 2: Photograph of positions used in testing (photo taken during site visit to a maintenance project, I-65 Downtown Indianapolis, on November 14, 2006)

C	✓	✓	✓	✓
D		✓	✓	✓
E	✓			
F	✓	✓	✓	✓
G	✓			✓
H	✓		✓	
I	✓			✓

Special considerations in data collection

A video camera was mounted on the dashboard inside a passenger automobile. The research team passed multiple times through the open lane of the work zone and recorded the approach view of the worker. A total of 30 videos were developed – each video depicted each assembly in each worker position. The videos were recorded at 45 mph, which is the posted work zone speed limit on Indiana’s interstates. The purpose of this set-up was to obtain an image similar to that seen by drivers while passing through the work zone. The position and angle of the camera were determined through initial trials in a controlled environment. The video camera was centered behind the automobile steering wheel and its shooting angle was parallel to the work zone.

Since lighting can be a significant factor in the conspicuity of high-visibility apparel, the amount of light in the active work zone was measured in candelas and lux using an electronic light meter. During the test, the worker modeling the assemblies was told to take a light reading locating the light meter at the middle of the garment that was facing the traffic. The measures were taken to obtain a range of representative lighting levels in the work zone when the test automobile was passing at an average of approximately 1,000 feet and 180 feet before the testing assembly. The automobile driver, using a short wave radio, then informed the model worker when the automobile had reached the measurement point so the worker would know when to record the light intensity.

Use of surveys to compare the visibility of the garments

Surveys for drivers were developed to evaluate the videos. These surveys included questions about the characteristics of the driver, such as age and whether they wore contact lenses/glasses. In addition, pair-wise comparisons between the safety vest currently used by INDOT and a new assembly (*Assembly X*) to find which of the assemblies shown in two videos was more visible or if there was no difference in their visibilities. If the driver found a difference between the visibility of the garments, he/she would rate how large the difference was on a scale from one to five (1-small, 3-medium, and 5-large).

University, West Lafayette, Indiana. These students represented drivers who were likely to encounter work zones. Each video was approximately seven seconds long and showed the last portion of the work zone. Immediately after watching a pair of videos, the subjects were asked to compare the visibility of the high-visibility safety garments they had seen in the videos. The first video displayed on each comparison was the one showing the garment currently used by the Indiana Department of Transportation while the second video contained an *Assembly x*. Characteristics of the room in which the video screening was conducted and the location of the respondent in the room was recorded in order to determine if these factors had significant effects on the responses.

4. DATA ANALYSIS

A Binary Probit model with random effects was developed which considered the effects of the variables: (a) the drivers, (b) the assemblies, (c) the work site, and (e) the display room, on the selection of the more visible safety garment. The Binary Probit model considered two discrete outcomes: (1) “INDOT safety garment is more visible” and (2) “*Assembly X* is more visible”. The basic principles of the Binary Probit model, the type of outcomes and the random effect component of the model are discussed in the following sections.

Use of Binary Probit Models

Following Washington et. al. (2003), the formulation for the Binary Probit model is derived from a simple linear function Z_{in} that determines discrete outcome i for observation n ,

$$Z_{in} = \beta_i X_{in} + \varepsilon_{in} \quad (1)$$

where β_i is a vector of estimable parameters for discrete outcome i , and X_{in} is a vector of observable characteristics that determine discrete outcomes for observation n . These parameters determine the discrete response for the observation and in this case are related to the characteristics of the assembly, the driver, the video and the display room. The addition of the disturbance term ε_{in} emerges because of the possibility that for instance: (1) variables have been omitted, (2) the form of Eq. 1 may not be linear, or (3) variations in β_i are not accounted for (Washington et al. 2003).

If the probability of observation n to have a discrete outcome I is denoted by $P_n(i)$, with I being all possible outcomes for observation n , and ($i \in I$) then,

$$P_n(i) = P(Z_{in} \geq Z_{in}) \forall I \neq i. \quad (2)$$

Combining Eq. 1 and Eq. 2,

Eq. 3 is assumed to be normally distributed, resulting in Equation 4, which estimates the probability of outcome 1 occurring for observation n :

$$P_n(1) = P(\beta_1 X_{1n} - \beta_2 X_{2n} \geq \varepsilon_{2n} - \varepsilon_{1n}) \quad (4)$$

In this equation, ε_{1n} and ε_{2n} are normally distributed with mean = 0, variances σ^2_{1} and σ^2_{2} respectively, and the covariance is σ_{12} . When there are normally distributed variates, the addition or subtraction of two normal variates also produces a normally distributed variate (Washington et al. 2003). The parameter vector (β) is estimated using standard maximum likelihood methods. In the binary case with $i = 1$ or 2, the log-likelihood is,

$$LL = \sum_{n=1}^N \left(\delta_{1n} LN\Phi \left(\frac{\beta_1 X_{1n} - \beta_2 X_{2n}}{\sigma} \right) + (1 - \delta_{1n}) LN\Phi \left(\frac{\beta_1 X_{1n} - \beta_2 X_{2n}}{\sigma} \right) \right) \quad (5)$$

Types of Outcomes and Random Effects Components

The two discrete outcomes considered in the analysis of the data were: (1) the INDOT safety garment is more visible and (2), *Assembly X* is more visible. However, each one of the drivers made multiple comparisons that will likely share unobserved effects and can result in the underestimation of the standard errors of the model's parameters. This can result in inflated t statistics, potentially misleading levels of significance, and potential biases in parameter estimates. These problems can be addressed with a random effects model which includes a normally distributed individual-specific error term (φ_i) to account for random error within each individual (Shafizadeh and Mannering 2006) in addition to the traditional disturbance term of each observation. In this case, Equation 1 becomes,

$$Z_{in} | \varphi_i = \beta_1 X_{in} + \varepsilon_{in} + \sigma_\varphi \varphi_i \quad (6)$$

where φ_i is normally distributed with the mean zero and the variance one, and the term σ_φ is an estimable parameter. The development of an estimable model from this equation follows that from Equations 2 to 5 above. Please note that if σ_φ is not significantly different from zero, the random effects are not significant in the model; and if it is significantly different from zero, then the random effects are significant.

5. RESULTS OF THE STUDY AND IMPLICATIONS

The model developed predicts which assembly the driver would choose as the more visible (INDOT safety vest or *Assembly X*), given *Assembly X*-related characteristics, the characteristics of the drivers, and site-related characteristics. The observations of the drivers who did not find a difference in the visibility of the INDOT safety vest and *Assembly X* were not taken into account. Each driver made multiple comparisons and after eliminating the answers where the drivers believed there was no difference between the garments, the sample contained 325 observations. 46 of the respondents believed that

Assembly X was more visible.

Characteristics such as whether the driver wears glasses/contact lenses and how long they had been driving were not found to be significant. The descriptive statistics for the variables found to be significant in the Binary Probit model are presented in Table 4, and the estimation results for the model are presented in Table 5. The model provides information on how the characteristics of the assembly, driver, and site are associated with the perceived visibility of the garments. A positive sign in the coefficient means that an increase in the value of the variable or a value of 1 for the indicator variables will make *Assembly X* more likely to be chosen as the more visible PPE.

Table 4. Description of variables found to be significant in random effects Binary Probit.

Independent Variable	Model Estimations			Minimum /Maximum
	Symbol	Mean	Standard Deviation	
Characteristics Related to Drivers				
Frequency driving at night (1 if daily or weekly, 0 otherwise)	<i>freqn</i>	0.92	.26	0/1
Characteristics Related to Assembly X				
Mean of retroreflectivity ($cd/lx \cdot m^2$) of the main garment	<i>mmean</i>	448.75	38.77	410.3/554.4
Variance of retroreflectivity ($cd/lx \cdot m^2$) of the main garment	<i>mvar</i>	119.60	198.71	31.50/679.40
Variance of retroreflectivity ($cd/lx \cdot m^2$) of the secondary garment	<i>svar</i>	262.27	225.72	0/530
Characteristic Related to Site				

Table 5. Random effects Binary Probit model of perceived visibility of high-visibility Garments

Independent Variable	Symbol	Estimated Coefficient	t statistic
Constant		-8.910	-2.620
Characteristics Related to Drivers			
Frequency driving at night (1 if daily or weekly, 0 otherwise)	<i>frequ</i>	2.190	1.248
Characteristics Related to Assembly X			
Mean of retroreflectivity (cd/lx*m ²) of the main garment	<i>mmean</i>	0.012	2.142
Variance of retroreflectivity (cd/lx*m ²) of the main garment	<i>mvar</i>	0.001	1.439
Variance of the retroreflectivity (cd/lx*m ²) of the secondary garment	<i>svar</i>	-0.003	-1.401
Characteristics related to site			
Amount of light at 180 feet	<i>light</i>	1.170	3.179
Model Parameters			
Random effect (Hausman test) parameter σ	ϕ_i	0.651	3.955
Number of observations			
Initial log-likelihood		-132.518	
Log likelihood at convergence		-67.540	
ρ^2		0.49	
Adjusted ρ^2		0.45	

*Dependent variable are zeros (INDOT safety vest) and ones (Assembly X).

The drivers made multiple comparisons that are likely to share unobserved effects. The significance of the random effects parameter (σ), with a t statistic of 3.955 indicates that the random effects element of the model is warranted.

INDOT safety vest as the most visible. This finding may indicate that a frequent driver may get used to seeing the INDOT safety garment in a work zone. A different garment may capture their attention more effectively, suggesting that high-visibility garments should be changed periodically.

The garment-related characteristics were also found to be significant. Higher values in the mean and variance of *Assembly X*'s retroreflectivity indicate that it is less likely for a driver to choose the INDOT safety vest as the more visible PPE. These findings suggest that garments with lower intensities and a lower variance of retroreflectivity cause the workers to blend into the work zone with inanimate objects, making them less visible to drivers.

However, lower values in the mean of the retroreflectivity of the secondary garment indicate that it is more likely that respondents will choose the INDOT safety vest as the more visible PPE. This finding may reflect that the combination of high retroreflectivity values in the primary and secondary garment is not effective, and differences in the retroreflective values are needed to make the worker more visible and detectable.

As expected, the lighting at the site was a very significant variable. The higher the intensity of light, the more likely it was that the driver did not choose the INDOT safety vest as the more visible garment. Changes in lighting can be produced by the headlights of passing vehicles and by changes in weather conditions. Greater amounts of lighting could mean that more vehicles are passing through the work zone at that time. This finding suggests that the *Assembly X* garment is more likely to be found more visible in nighttime work zones with higher light intensities and/or in work zones with higher traffic congestion.

6. CONCLUSIONS

The visibility of a roadwork worker during nighttime operations is crucial to ensure the safety of the worker and passing motorists. This paper describes a testing procedure to compare the visibility of different types of high-visibility PPE. The procedure begins with an assessment of different types of safety garments, and includes retroreflectivity values in the analysis and considers the characteristics of the work environment.

The paper describes the feasibility of using the Binary Probit model with random effects for determining the characteristics that influence, in a pair-wise comparison, the selection of a PPE garment as the more visible garment. Application of this statistical method can be used to further model an evaluation of the garments used by other DOTs. The statistical analysis identified the characteristics of the garments that could improve worker visibility. For example, a garment with higher retroreflectivity and higher variance in the retroreflectivity would be more likely to be seen than the currently used INDOT garment. In addition, if a secondary item (such as safety pants or retroreflective bands) is used, its retroreflectivity variance should be low. The results of this study also

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