Evaluation of the Visibility of Workers' Safety Garments during Nighttime Highway-Maintenance Operations

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Abstract: To reduce traffic congestion in the United States, roadway maintenance and construction operations are widely performed during nighttime hours. This makes visibility a critical issue as workers need to be visible to oncoming traffic and heavy equipment operators in order to ensure their safety. A variety of high-visibility safety garments are available to increase the visibility of workers at night. The study presented in this paper assesses some of these garments from the perspective of drivers. The approach adopted includes the design of a field test setup in which eight safety garment assemblies were displayed in a replicated maintenance work zone. A video was created for each safety garment assembly being worn by workers to capture the approaching view of a driver entering the work zone. The videos were shown to drivers, who evaluated the visibility of the garments in pairwise comparisons. Two random effects binary probit models were estimated. One model was used to understand the characteristics that would make it more likely that the subject could detect a difference between a high-visibility vest used by the Indiana Department of Transportation workers and a competing assembly. The amount of background and retroreflective material, the driver's age, and the speed at they which they traveled through the work zone were found to be significant in this model. A second model was a conditional one: given that a difference in garments could be detected, was the competing garment assembly more or less visible than the current safety garment used by the Indiana Department of Transportation? In this case, the mean and variance of the retroreflective material of the garment and the lighting in the work environment were found to be significant.

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Introduction

A primary reason for nighttime highway construction and maintenance operations is to reduce the traffic congestion caused by daytime road work due to lane closures (Arditi et al. 2005; Rebholz et al. 2004). However, additional problems related to safety arise with the decision to work at night such as impaired drivers, higher speeds, and visibility [U.S. Dept. of Transportation (USDOT) and Federal Highway Administration (FHWA) 1998; Arditi et al. 2005]. The problem of limited visibility during nighttime roadway operations can affect the project cost, work quality, worker productivity, and worker and motorist safety. According to Arditi et al. (2005) one of the primary causes of nighttime accidents relates to worker visibility issues. Workers need to be visible to oncoming traffic and heavy equipment operators to ensure the safety of both the workers and the motorists and to reduce struck-by incidents (ANSI/ISEA 2004). High-visibility safety garments have been developed to improve the visibility and safety of workers at night.

The "American National Standard for High-Visibility Safety Apparel and Headwear," referred to as ANSI/ISEA 107-2004, provides recommendations for the use, design, and testing of high-visibility apparel. The standard defines three performance classes for high-visibility apparel (Class 1, Class 2, and Class 3) depending upon the minimum area of the materials to be included in the safety garment. Class 1 garments are usually not recommended for workers exposed to roadway traffic. The minimum required amount of background material specified by ANSI/ISEA 107-2004 are $775\ \text{in.}^2$ $(0.50\ \text{m}^2)$ and $1{,}240\ \text{in.}^2$ $(0.80\ \text{m}^2)$ for Class 2 and Class 3 safety garments, respectively. The minimum required amounts of retroreflective or combined performance material are $201\ \text{in.}^2$ $(0.13\ \text{m}^2)$ for Class 2 safety garments and $310\ \text{in.}^2$ $(0.20\ \text{m}^2)$ for Class 3 safety garments.

In November 2006, the Federal Highway Administration (FHWA 2006) issued a new section in the Code of Federal Regulations (CFR) entitled 23 CFR 634 Worker Visibility. In order to decrease the likelihood of worker fatalities or injuries for both daytime and nighttime operations, the new regulation required the use of high-visibility safety apparel for workers who work within

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the federal-aid highway right-of-way and who are exposed either to traffic or to construction equipment within the work area. It provides specific requirements such as the use of garments with ANSI/ISEA 107 Performance Class 2 or 3.

The performance of high-visibility garments during nighttime hours has been evaluated in the past by determining the recognition distance (the distance between the subject and the point at which the driver recognizes the presence of a subject). Luoma et al. (1995) studied the effects of retroreflector positioning on the recognition of pedestrians. The study considered four retroreflector configurations (no retroreflectors, torso, wrists and ankles, and major joints) on pedestrians who were located in different locations within the roadway. The evaluation included ANOVAs considering recognition distance, retroreflector position, and walking direction. The study found that pedestrians with retroreflectors at the major joints of their bodies had the greatest mean recognition distance (249 m/817 ft), followed by pedestrians with the material at the wrists and ankles (241 m/790.5 ft), torso (136 m/446 ft), and no retroreflectors (35 m/115 ft).

Sayer et al. (2002) assessed the effects of color on the detection of pedestrians who were wearing different colors of retroreflective markings on the legs for normal and color deficient drivers. Drivers sitting in the driver's seat of a stationary automobile observed a pedestrian walking along the road. The analysis consisted of the modeling of detection distances as a function of the specific intensity of the unit area of the colored retroreflective markings and ANOVA. The effect of the participants' ages was not significant, but for persons with normal color vision, the color of the retroreflective marking affected the distance at which the pedestrian was detected.

Sayer and Mefford (2004a) assessed the attributes of 18 retroreflective personal safety garments on pedestrian conspicuity at night by having drivers passing through a replicated work zone attempt to detect pedestrians. ANOVA was performed considering factors such as detection distance, garment configuration, trim color, trim intensity, and driver's age. 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, but gender and retroreflectivity were not significant. A second study by Sayer and Mefford (2004b) considered the detection distance, scene complexity, garment type (Class 3 jacket, Class 2 safety vest, and Class 2 vest with sleeves), and pedestrian orientation. That study found that the garment type and pedestrian orientation relative to the driver were not significant factors. Both the scene complexity and arm motion did have significant impact on the results.

Arditi et al. (2004) evaluated six safety vests in highway work zones by measuring their luminescence when they were displayed in a work zone. The study involved the videotaping of the vests and considered the luminance values of the safety vests, the vest position within the work zone, and the vest face (front or side). A system was developed to perform a field test, calculate the luminance of the safety vests, and rank the safety vests according to their luminance. Two of the vests that were very similar and which had the largest amount of retroreflective material were superior to the other vests, three of them orange and one of them yellow.

Hirasawa et al. (2007) conducted an experiment in a replicated 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 daytime hours, nighttime hours, and at dusk. Two lighting conditions were evaluated at night (spotlighting and balloon lighting). The study compared the color recognition distance and worker recognition distance for the different colors. The most recognizable colors were yellow during daytime and orange at dusk and nighttime.

None of these previous studies integrated in their assessments the combination of different high-visibility personal protective equipment (PPE), the perspective of drivers regarding the visibility of different PPE, and the features in a maintenance work zone. This study is a new approach, which evaluates the visibility of different safety garments combined in multiple assemblies. A field test was designed to display different safety garments in a maintenance work zone and drivers evaluated the visibility of the garments. In order to evaluate the visibility of the safety garments, a statistical analysis was performed considering the characteristics of the garment and the driver.

Table 1. Description of High-Visibility PPE Used in the Study

Item number	PPE description	Amount of retroreflective material [in.^{2} (cm^2)/ front face]	Amount of background material [in.^{2} (cm^2)/ front face]
1	INDOT safety vest	132 (851.6)	467 (3,012.9)
2	Short sleeve safety vest	149 (861.3)	543 (3,503.2)
3	Breathable safety pants	96 (619.4)	876 (5,651.6)
4	High-visibility headgear	0	0
5	Arm and knee bands	42 (271)	0
6	Self-illuminated vest	136 (877.4)	614 (3,961.3)
7	High-visibility t-shirt	101 (651.6)	593 (3,825.8)
8	Mesh vest	112 (722.6)	538 (3,471.0)

Study Approach

This study sought to provide insight into the perceived visibility of safety garments given certain characteristics of the drivers and certain characteristics of the field test setup. The approach was divided into four main phases: selection of the high-visibility garments and garment assemblies for testing, field test setup, perception of drivers regarding visibility, and the data analysis.

Selection of the High-Visibility Garments for Testing

Fourteen different types of high-visibility PPE, described in Table 1, were considered in this study, all of which were yellow-green in color with white retroreflective material. The garments were selected by personnel from the Indiana Department of Transportation (INDOT) and included weather-related safety garments, safety pants, retroreflective bands, safety vests, and the safety vest and safety t-shirt currently used by INDOT workers. Various coefficients of retroreflection (R_A) measurements were taken for each high-visibility PPE using a retroreflectometer. This coefficient with units specifies the amount of light that is retroreflected for a given unit of light incident on a given area of the material and the units are given by candelas per incident lux per square meter ($\mathrm{cd/lx/m^2}$). The measurements were taken at an angle of incidence of 2°, which was used to simulate the observation angle of the driver, and $-4°$, which was used to simulate the entrance angle of the illumination. As shown in Fig. 1, the retroreflectivity values were not uniform across the garments.

Eight assemblies were created by using two or more high-visibility items: eight weather-related assemblies and eight gen-

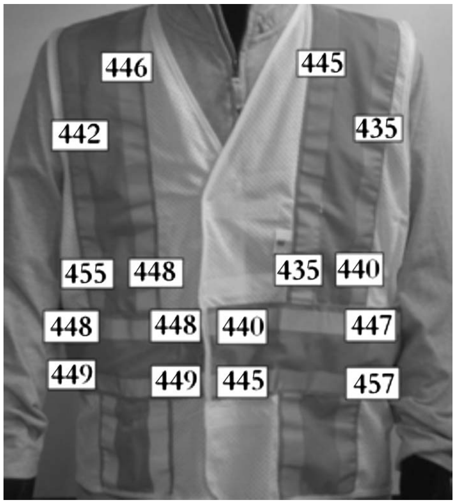

Fig. 1. Retroreflectivity measurements $(\mathrm{cd/lx/m^2})$ for INDOT safety-vest assembly

eral assemblies. Because the study focused on trying to improve current safety garment practices, the statistical analysis was performed considering only the eight general assemblies and the safety vest currently used by INDOT (the composition of the general assemblies is shown in Table 2). The general assemblies consisted of a main garment (safety vest) or a combination of a main garment and secondary garments (safety pants, ankle retroreflective strips, or wrist retroreflective strips). The high-visibility PPE assemblies met the minimum requirements for Performance Classes 2 or 3 of the ANSI/ISEA 107-2004.

Design of the Field Test Setup

A maintenance work zone was selected as the basis for experimentation. A nighttime maintenance crew working for INDOT "set up" the field test site to replicate a typical maintenance work zone that would be encountered on an interstate highway. The layout of a maintenance work zone was used for the purpose of creating the videos for data collection. The work zone was located on I-74 in southeast Indianapolis between Exits 96 and 99. The cones at the work zone were placed at every other skip of the pavement markings. The work zone included the use of four truck-mounted attenuators and typical signage for nighttime maintenance operations. Fig. 2 shows the setup of this work zone. In this scenario, a worker wore the high-visibility assemblies and was videotaped in the active work zone in two different positions:

Table 2. Composition of PPE Assemblies

Assembly number	High-visibility PPE item as shown in Table 1: 1	2	3	4	5	6	7	8
1 (control)	✓			✓				
2	✓			✓	✓			
3	✓		✓	✓				
4		✓	✓	✓				
5		✓		✓				
6				✓	✓		✓	
7				✓			✓	
8				✓		✓		
9				✓				✓

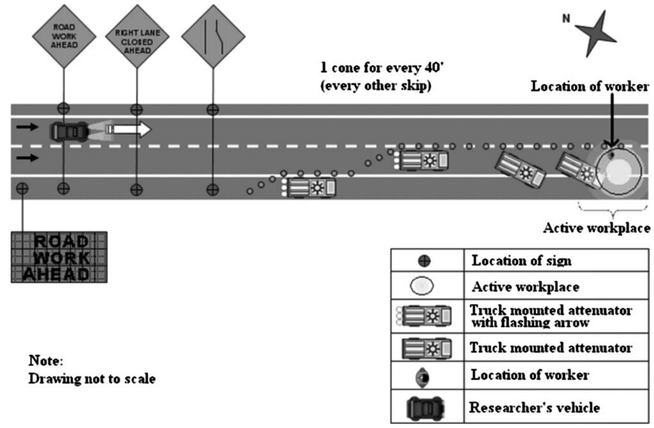

Fig. 2. Test layout for data collection

(1) facing the traffic and (2) facing away from the traffic. These positions are typically assumed by workers in maintenance operations and were identified during prior visits to nighttime projects.

Once the field test was set up, a video camera was mounted on the dashboard inside a passenger car. The research team passed multiple times through the open lane of the work zone and recorded the approach view of the worker. The videos were recorded at 45 mph (72 kmh), which is the posted work-zone speed limit on Indiana's interstates. During the time the videos were being recorded, there were free flow traffic conditions on the highway. A video was made for each assembly in both worker positions for a total of 30 videos (15 assemblies, two positions). The purpose of this setup 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.

Because 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 candles and lux using an electronic light meter. During the test, the worker modeling the assemblies was told to take a light reading by locating the light meter at the middle of the garment view that was facing the traffic. The measures were taken to obtain a range of representative lighting levels in the work zone when the test car was passing at two points selected within the work zone to take the lighting measurements (one a distance from the worker and one closer to the worker). These points were approximately located at 180 ft (55 m) and 1,000 (305 m) ft before the testing assembly. The car driver, using a short wave radio, then informed the worker wearing the test PPE when the automobile had reached the measurement point so the worker would know when to record the light intensity.

Perspective of Drivers regarding Visibility of the Garments

A questionnaire was developed to compare the visibility of the different garments from the perspectives of drivers. In April 2007, the surveys were distributed to different groups of Civil Engineering and Construction Engineering students at Purdue University. Each video was approximately 7 s long and showed the last portion of the work zone. In August 2007, the questionnaire was distributed and the videos were shown to a group of INDOT employees in the agency's state headquarters.

The survey included questions about the demographics and other characteristics of the driver including factors such as age and whether they wore contact lenses/glasses. In addition, the participants made pairwise comparisons between the visibility of each of the assemblies and that of the safety vest currently used by INDOT to determine which of the assemblies shown in the two videos were the most visible or if there was no difference in their visibility. The high-visibility PPE currently used by INDOT (shown in Fig. 1) is a yellow-green vest with a 4-in.-wide fluorescent orange band with two strips of reflective silver material spanning front to back over each shoulder and around the waist. This safety vest was used as the standard for comparisons in the driver visibility evaluations. The video of the INDOT safety vest assembly was shown first in each of the comparisons. For each comparison pair, the subjects were asked if the assembly in the first video was more visible; if the assembly in the second video was more visible; or if there was no difference in the visibility of the two assemblies.

The dimensions of the background and reflective segments in the garments were measured to calculate the area of background material and retroreflective material for each garment. Variables were created to represent the mean, standard deviation, and variance of these areas. Since the pairwise comparisons were made between the INDOT safety vest and a competing assembly, the difference between the amount of retroreflective and background material ($\text{in.}^2/\text{cm}^2$) in the two assemblies were used as variables.

Data Analysis

To analyze the data, two processes were considered in comparing various assembly options with the current INDOT safety vest. First, whether the subject could detect a difference between the INDOT safety vest assembly and a competing assembly; and second, if a difference could be detected, was the INDOT or a competing assembly more visible. Different statistical models, including the nested logit, multinomial logit, mixed logit, and binary probit models, were used for the preliminary analysis of the discrete data obtained from the survey (Table 3).

A nested logit model groups alternate outcomes suspected of sharing unobserved effects into nests. In this study, a nested logit model was estimated considering the following main branches: (Branch 1) no difference was found between the visibility levels of the garments; and (Branch 2) a difference was found between the visibility levels of the garments. From Branch (2), two subbranches were defined: INDOT safety garment more visible and (2) competing assembly more visible. In this case, the assumed shared unobserved effects in the nest were not significant, suggesting the model could be reduced to a simple multinomial logit model. When estimating a multinomial logit model, three probability-generating functions were defined for three discrete outcomes: (1) no difference was found between the visibility levels of the garments; (2) the INDOT safety garment was found to be more visible; and (3) the competing assembly was found to be more visible. However, the statistical performance of this model in terms of the number of variables was found to be statistically significant and the magnitude of log-likelihood at convergence was not as good as the binary model eventually estimated. Finally, a mixed logit model was estimated with probability-generating functions the same as those used in the multinomial logit estimation. However, none of the estimated parameters were found to vary significantly across the respondent population, thus, suggesting that a mixed logit analysis was not warranted (see McFadden and Train 2000; Milton et al. 2008).

Table 3. Selected Subject and Experiment Sample Statistics for All the Data

Variable	Values
Percent male/female	73/27
Average age of drivers/standard deviation/min/max	28.6/12.5/18/62
Average number of years with driver's license/standard deviation/min/max	11.4/11.4/0/44
Average mean of retroreflectivity of main garment in $\text{cd}/\text{lx}/\text{m}^2$/standard deviation/min/max	451.2/42.2/410.3/554.4
Average mean of retroreflectivity of secondary garment in $\text{cd}/\text{lx}/\text{m}^2$/standard deviation/variance/min/max	213.8/225.37/0/530
Width of retroreflective strips in inches min/max (cm)	1/2 (2.54/5.08)
Average of amount of retroreflective material of main garment in in.^2/standard deviation/variance/min/max (cm^2)	126.2/18.4/100.5/149.0 (814.2/118.7/648.4/962.3)
Average of amount of retroreflective material of secondary garment in in.^2/standard deviation/variance/min/max (cm^2)	34.7/39.5/0/96 (223.9/254.8/0/619.4)
Average of the total amount of retroreflective material of the assembly in in.^2/standard deviation/variance/min/max (cm^2)	160.9/48.7/100.5/245 (1038/314.2/648.4/1580.7)
Average of amount of background material of main garment in in.^2/standard deviation/variance/min/max and in (cm^2)	403.5/120.3/300.9/593.5 (2603.2/776.1/1941.3/3829)
Average of amount of background material of secondary garment in in.^2/standard deviation/variance/min/max (cm^2)	220.2/380.3/0/876 (1420.6/2453.5/0/5651.6)
Average of the total amount of background material of the assembly in in.^2/standard deviation/variance/min/max (cm^2)	623.7/337.8/300.9/1178 (4024/2179.4/1941.3/7600)
Orange fabric in in.^2/standard deviation/variance/min/max and in (cm^2)	141.3/88.4/0/242.1 (911.6/570.3/0/1561.93)
Percent of drivers driving at night: daily/weekly/monthly/3–4 times a year/never/unsure [min, max]	43/51/4/0/0/2 [1,6]
Percent of drivers encountering a nighttime work zone on highways: daily/weekly/monthly/3–4 times a year/never/unsure [min, max]	7/9/42/33/3/6 [1,6]
Speed in mph at which the subject would drive through a nighttime work zone if the speed limit is 45 mph (72 kmh) mean/standard deviation/min/max (kmh)	49.7/6.0/37.5/70 (80/9.7/60.4/112.7)
Average lux at 180 ft (55 m) from the assembly display/standard deviation/min/max	4.54/2.89/1/18.45
Average lux at 1,000 ft (305 m) from the assembly display/standard deviation/min/max	3.93/1.61/0.84/5.92

Given the preliminary statistical findings with regard to nested, multinomial, and mixed logit models, binary outcome models were estimated. Although a binary logit model was considered, the binary probit model was selected because of the assumption of normally distributed error terms (statistical results from the two models were virtually identical). To illustrate how the binary probit model was applied, consider whether or not the subject could detect a difference between the INDOT safety vest assembly and the competing assembly. The probability of detecting a difference for each test i can be written as (see Washington et al. 2003)

$$P_i(D) = P(\beta_D X_{Di} + \xi_{Di} \geqslant \beta_{ND} X_{NDi} + \xi_{NDi}) \tag{1}$$

where β_D and β_{ND}=vectors of estimable parameters for difference and no-difference outcomes, respectively; X_{Di} and X_{NDi} =vectors of observable characteristics that determine whether a difference or no-difference (respectively) is indicated in test i. The observable characteristics in this case are related to the characteristics of the assembly, the subject, the video, and the display room.

Following Washington et al. (2003), to arrive at a binary probit model, let ξ_{Di} and ξ_{NDi} be normally distributed with mean of 0, variances σ_D^2 and σ_{ND}^2, respectively, and with covariance σ_{cov}. Rearranging terms, Eq. (1) becomes $P_i(D)=P(\beta_D X_{Di}-\beta_{ND}X_{NDi} \geqslant \xi_{NDi}-\xi_{Di})$. Because the subtraction of two normal variates also produces a normally distributed variate, $\xi_{NDi}-\xi_{Di}$ in this equation is normally distributed with mean zero and variance $\sigma_D^2+\sigma_{ND}^2 -2\sigma_{\text{cov}}$ and the cumulative normal function is

$$P_i(D) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{(\beta_D X_{Dn}-\beta_{ND}X_{NDi})/\sigma} \exp\left(-\frac{1}{2}w^2\right) dw \tag{2}$$

With $\Phi(\ )$ being the standardized cumulative normal distribution Eq. (2) can be written as

$$P_i(D) = \Phi\left(\frac{\beta_D X_{Dn} - \beta_{ND} X_{NDn}}{\sigma}\right) \tag{3}$$

where $\sigma=(\sigma_D^2+\sigma_{ND}^2-2\sigma_{\text{cov}})^{0.5}$. The parameter vector ($\beta$) can be estimated by maximum likelihood as

$$L = \prod_{i=1}^{I} P(D)^{\delta_{Di}} P(ND)^{1-\delta_{Di}} \tag{4}$$

where δ_{Di} is equal to 1 if a difference is observed in test i and zero otherwise; and I=total number of tests. This gives the log-likelihood as

$$LL = \sum_{i=1}^{I} \left[\delta_{Di} LN\Phi\left(\frac{\beta_D X_{Di} - \beta_{ND} X_{NDi}}{\sigma}\right) + (1-\delta_{Di}) LN\Phi\left(\frac{\beta_{ND} X_{NDi} - \beta_D X_{Di}}{\sigma}\right)\right] \tag{5}$$

which is used to estimate parameter vectors in standard model estimation packages. The same probit approach is used for the conditional binary test outcome (conditioned on the fact that a difference could be detected) of whether the INDOT or a competing assembly was more visible.

In the analysis undertaken here, survey subjects made multiple comparisons that will likely share unobserved effects that can result in the underestimation of the standard errors of the model's parameters (see Washington et al. 2003). This situation can result in inflated t statistics, potentially misleading levels of significance, and possible biases in parameter estimates. These problems can be addressed with a random effects model that adds a normally distributed individual-specific error term for each subject k (φ_k) to account for the shared unobserved effects in addition to the traditional disturbance term of each observation (see Shafizadeh and Mannering 2006). In this case, Eq. (1) can be rewritten as

$$P_i(D) = P(\beta_D X_{Di} + \xi_{Dn} + \omega_\varphi \varphi_k \geqslant \beta_{ND} X_{NDi} + \xi_{NDi} + \omega_\varphi \varphi_k) \tag{6}$$

where φ_k is normally distributed with the mean zero and the variance one for subject k; and the term ω_φ=an estimable parameter. The development of an estimable model from this equation follows the process in Eqs. (2)–(5) above. Note that the statistical significance of ω_φ determines whether the random effects are significant in the model. In addition, a likelihood ratio test can be used determine if the random effects provide a statistically superior model (see Washington et al., 2003). The likelihood ratio test statistic is given by

$$\chi = -2[LL(\beta_{NR}) - LL(\beta_R)] \tag{7}$$

where $LL(\beta_A)$=log-likelihood at convergence of the nonrandom effects model; and $LL(\beta_B)$=log-likelihood at convergence of the random effects model. The χ^2 statistic is distributed with degrees of freedom equal to the difference in the number of parameters between the unrestricted and restricted model.

Finally, to determine the impact of the variables on the outcome probabilities, the average marginal effects are computed (averaged over all observations). For continuous variables, the marginal effects are computed from the partial derivatives and are interpreted as the effect that a change in one unit in the independent variable will have on the outcome probability. For example, a marginal effect of −0.25 implies that a unit change in that variable will decrease the probability of outcome occurrence 0.25. For indicator variables, the marginal effects are computed as the difference in the estimated probabilities with the indicator variable changing from zero to one (see Washington et al., 2003). It should be noted that marginal effects assume a change only in the variable under consideration. There is often correlation in the elements of the vector X [as defined in Eq. (1)] so some caution should be exercised in interpreting reported marginal effects.

Model Estimation Results: Difference versus No Difference

All estimated parameters included in the model are statistically significant and the signs are plausible. The sample contained 676 observations (subject binary-comparison tests). The model estimates the probability that a driver will find a visibility difference between the garments being compared, given the non-INDOT assembly-related characteristics and the drivers' characteristics. The model estimation results and marginal effects are shown in Table 4. In this table, a positive sign in the parameter means that an increase in the value of the variable or a value of 1 for the indicator variables will make the driver more likely to find a difference in the visibility of the garments being compared.

The garment-related characteristics were found to be significant. The higher the difference between the amounts of retroreflective material of the garments being compared, the more likely it was that a driver found a difference between the visibility of the INDOT safety vest assembly and that of the competing assembly. Arditi et al. (2004) found that two of the garments that did not have the largest amount of retroreflective material were found to be superior when analyzing the luminescence of the retroreflective material in the garments. Our finding suggests that the greater the difference between the area of retroreflective material on the

Table 4. Random Effects Binary Probit Model: "Difference" or "No Difference" between the Visibility of the INDOT Safety-Vest Assembly versus a Competing Assembly[a]

Independent variable	Parameter estimate	*t*-statistic	Marginal effect
Constant	2.168	4.06	—
Difference between the amount of retroreflective material (in.^{2}) of competing assembly and INDOT safety-vest assembly	0.0071	3.95	0.0021
Difference between the amount of background material (in.^{2}) of competing assembly and INDOT safety-vest assembly	0.0004	1.40	0.0001
Speed (mph) at which the subject would drive through a nighttime work zone if the speed limit is 45 mph	−0.0336	−3.24	−0.010
Drivers who are older than 55 years	−0.567	−2.46	−0.169
Random effect parameter ω_φ	0.168	3.19	—
Number of observations		676	
Initial log-likelihood		−402.45	
Log-likelihood at convergence		−363.22	
ρ^2		0.097	

[a]Discrete outcomes are the following: (1) differences detected or (2) no difference detected. All parameter estimates are for the difference-detected option.

garment, the more visible the driver will find the garment when comparing two assemblies. The marginal effects indicate that increasing the area of the competing assembly's retroreflective material by 100 in.^{2} (254 cm^2) will increase the probability of finding a difference between the garments by 0.21.

In the same way, the greater the difference between the amounts of background material in the INDOT safety vest and the competing assembly, the more likely it was that a difference was noticed between the garments' visibility levels. The marginal effects indicate that increasing the area of the competing assembly's background material by 100 in.^{2} (254 cm^2) will increase the probability of finding a difference between the garments by 0.01. This shows that the amount of background material is significant but less influential than the amount of retroreflective material. However, the tradeoff between the amount of material used for the garment and the comfort of the roadway worker must be considered. For instance, at high temperatures, increasing the amount of background material can increase the level of discomfort to the worker, resulting in decreased productivity and reduced safety for the worker.

Higher values in the speed at which the driver would drive through a work zone indicate that it is less likely that respondents will find a difference between the INDOT safety garment and a competing assembly. This finding may reflect that the attention of drivers and their detection of workers in the work zone may be compromised when drivers travel at higher speeds. In a study by Valentin (2007), drivers mentioned that when passing through a work zone, they would drive over the speed limit (45 mph/72 kmh) both when they think there are not workers (65 mph/105 kmh) in the work zone and when there are workers (55 mph/89 kmh). The marginal effects show that a 1 mph (1.6 kmh) increase in speed reduces the probability that a difference will be found by 0.01.

The drivers' related characteristics were also found to be significant in this model. Drivers over 55 years of age were less likely to find a difference between the INDOT garment and the competing assembly. A driver older than 55, therefore, will decrease the probability of finding a difference between the INDOT driver and the competing assembly by 0.169.

Finally, as previously mentioned, the respondents made multiple comparisons that are likely to share the unobserved effects, and the significance of the random effects parameter (ω_φ), with a t statistic of 3.187 indicates that the random effects element of the model is warranted. This is also supported by the likelihood ratio test [see Eq. (7)] that showed that the hypothesis that the binary probit model with random effects the binary probit without random effects were the same could be rejected with more than 99.9% confidence.

Model Estimation Results: Competing Assembly versus INDOT Safety Vest

The second model estimated considered only tests where the subjects indicated that they could tell the difference between a competing garment and the INDOT garment. Given that a difference was noted, we sought to understand the factors that make the competing assembly garment more or less visible than the current safety garment used by INDOT (there were 387 tests in which subjects indicated that they detected a difference). Table 5 shows the results of the random effects binary probit model estimation, which predicts if a driver will find the competing assembly or the INDOT assembly more visible. All of the estimated parameters included in the model are statistically significant at a 95% confidence level and the signs are plausible.

The garment-related characteristics were found to be significant for this model as well. However, in this case the amount of the retroreflective or background material was not found to be significant.

Higher mean values for the competing assembly's retroreflectivity indicate that it is more likely for a driver to choose the competing assembly safety vest as being more visible (relative to the INDOT assembly). This finding suggests, as expected, that garments with higher intensities in its retroreflective values are more visible to drivers than those with lower intensities. Also, higher values in the variance of the retroreflectivity values of the secondary garments make it more likely that a driver will find the competing assembly vest more visible. This finding may indicate that differences in the retroreflectivity values are needed to make the worker more visible and detectable and to ensure the worker does not blend with inanimate objects.

The lighting at the site was a very significant variable. The higher the intensity of light, the more likely it was that the drivers chose the competing assembly safety vest as the more visible garment. This suggests that the competing assemblies performed increasingly better than the INDOT assembly as lighting im-

Table 5. Random Effects Binary Probit Model of the Probability That the Competing Assembly Is More or Less Visible Than the INDOT Safety-Vest Assembly, Conditional on a Difference in Visibility Being Found between Competing Assembly and INDOT Safety-Vest Assembly[a]

Independent variable	Parameter estimate	t-statistic	Marginal effect
Constant	−3.096	−2.080	—
Mean of retroreflectivity (cd/lx^*m^2) of the main garment	0.0061	2.118	0.0009
Variance of retroreflectivity (cd/lx^*m^2) of the secondary garment	0.0002	4.197	0.00003
Amount of light (lux) at 1,000 ft	0.403	5.617	0.0570
Random effect parameter ω_φ	0.418	2.655	—
Number of observations		387	
Initial log-likelihood		−161.76	
Log-likelihood at convergence		−127.15	
ρ^2		0.214	

[a]Discrete outcomes are the following: (1) competing assembly more visible than INDOT safety-vest assembly or (2) competing assembly less visible than INDOT safety-vest assembly. All parameter estimates are for the competing-assembly-more-visible option.

proved (changes in lighting can be produced by the headlights of passing vehicles and by changes in weather conditions). Thus, the selection of an effective assembly is sensitive to ambient lighting.

Finally, as in the previous model, the random effects parameter (ω_φ) was significant with a t-statistic of 2.655, indicating that the random effects element of the model was warranted. This is also supported by the likelihood ratio test that again showed that the hypothesis that the binary probit model with random effects and the binary probit without random effects were the same could be rejected with more than 99.9% confidence.

Conclusions

The visibility of workers during nighttime roadwork operations is crucial to ensure safety. A testing procedure to compare the visibility of different types of high-visibility PPE is described in this paper. 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 driver and the work environment.

This paper described the feasibility of using a binary probit model with random effects for determining the characteristics that influence, in a pairwise comparison, the selection of a PPE assembly as the more visible assembly. 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 compared to the main garment. These findings can be used when developing strategies to improve the visibility of workers. The application of this statistical method can be used to further evaluate the garments used by other state departments of transportation and to improve current practices related to safety garment selection for nighttime roadway operations.

This study used a setup for a single maintenance nighttime work zone. However, other than the changing traffic in a work zone throughout the night, the study did not consider variations in the use of different lighting equipment, which could affect the visibility of the garments, as well as variations in the complexity of the surrounding environment that could be addressed by using additional sites. The consideration of these factors could be a fruitful direction for future research.

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References

American National Standards Institute (ANSI), International Safety Equipment Association (ANSI/ISEA). (2004). "American National Standard for high visibility safety apparel." *ANSI-ISEA 107-2004*, Arlington, Va.

Arditi, D., Ayrancioglu, M., and Shi, J. J. (2005). "Worker safety issues in night-time highway construction engineering." *Eng., Constr. Archit. Manage.*, 12(5), 487–501.

Arditi, D., Ayrancioglu, M. A., and Shi, J. (2004). "Effectiveness of safety vests in nighttime highway construction." *J. Transp. Eng.*, 130(6), 725–732.

FHWA. (2006). "Final rule: Worker visibility." *Federal Register* (23 CFR Part 634.F).

Hirasawa, M., Takemoto, A., Asano, M., and Takada, T. (2007). "Study on improving worker safety at roadway sites in Japan." *Transportation Research Record. 2015*, Transportation Research Board, Washington, D.C.

Luoma, J., Schumann, J., and Traube, E. C. (1995). "Effects of retroreflector positioning on nighttime recognition of pedestrians." *Rep. No. UMTRI-95-18*, Univ. of Michigan, Ann Arbor, Mich.

McFadden, D., and Train, K. (2000). "Mixed MNL models for discrete response." *J. Appl. Econ.*, 15(5), 447–470.

Milton, J., Shankar, V., and Mannering, F. (2008). "Highway accident severities and the mixed logit model: An exploratory empirical analysis." *Accid. Anal. Prev.*, 40(1), 260–266.

Rebholz, F. E., Al-Kaisy, A., Nassar, K., Liu, L. Y., El-Rayes, K., and Soibelman, L. (2004). "Nighttime construction: Evaluation of construction operations." *Rep. No. ITRC FR00.01-5*, Illinois Transportation Research, Southern Illinois University Edwardsville, Edwardsville, Ill.

Sayer, J. R., and Mefford, M. L. (2004a). "High visibility safety apparel and nighttime conspicuity of pedestrians in work zones." *J. Safety Res.*, 35(5), 537–546.
Sayer, J. R., and Mefford, M. L. (2004b). "The roles of retroreflective arm treatments and arm motion in nighttime pedestrian conspicuity." *Rep. No. UMTRI-2004-21*, Univ. of Michigan, Ann Arbor, Mich.
Sayer, J. R., Mefford, M. L., Flannagan, M. J., and Sivak, M. (2002). "Effects of retroreflective marking color on the detection of pedestrians by normal and color deficient drivers." *Rep. No. VIS2002-29*, Human Factors Division, Univ. of Michigan Transportation Research Institute, Ann Arbor, Mich.
Shafizadeh, K., and Mannering, F. (2006). "Statistical modeling of user perceptions of infrastructure condition: An application to the case of highway roughness." *J. Transp. Eng.*, 132(2), 133–140.
U.S. Dept. of Transportation (USDOT) and Federal Highway Administration (FHWA). (1998). "Meeting the customer's needs for mobility and safety during construction and maintenance operations." *Publication No. FHWA-PR-98-01-A*, Office of Program Quality Coordination, Washington, D.C.
Valentin, V. (2007). "Effectiveness of personal protective equipment for improving worker visibility in nighttime construction and maintenance projects." Master's thesis, Purdue Univ., West Lafayette, Ind.
Washington, S., Karlaftis, M., and Mannering, F. (2003). *Statistical and econometric methods for transportation data analysis*, Chapman & Hall/CRC, Boca Raton, Fla.