Ultra-Violet Headlamp Technology for Nighttime Enhancement of Fluorescent Roadway Delineation and Pedestrian Visibility

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Safety on the roadways at nighttime has been a major concern for many years. Motorists driving at night are 2 to 3 times more likely to be involved in an accident at night than during the daytime. About half of the motor-vehicle deaths occur at night; however, death rates based on mileage are about four times higher at night than during the day (*1*). Nighttime driving is especially frustrating to the older population. The American Association of Retired Persons surveyed 1,400 of their members, and over half of the respondents indicated that they drive less at night due to reduced visibility and problems with glare (*4*).

Detection of traffic control devices and hazards on the roadway is an essential part of safe driving. It has been shown that at night most drivers tend to overdrive their low beam headlights and operate at very short preview times, which could possibly explain the increase in accidents (*5*).

Researchers have investigated ways of making objects and pedestrians more visible at night, thus increasing their preview time for drivers. There is a current FHWA effort to evaluate the use of ultra-violet lighting in conjunction with low beam headlights to provide increased nighttime visibility.

Although the concept of ultra-violet headlamps has been in existence for some time, a new ultra-violet (UV) lamp technology developed in Sweden has given researchers new insights into the possibilities of its use. The prototype UV headlamps configured similarly to high beam headlamps and are intended for use with fluorescent traffic control devices. The headlamps emit UV radiation in the spectral range of 320-380 nm, which is invisible to the human eye. The short wavelength light emitted by the UV headlamps reacts with the fluorescent properties of objects it comes into contact with to produce long wavelengths of light or visible light. In order to improve the visibility of pavement markings, the markings would have to include a fluorescent component. The UV headlamps could potentially offer high beam performance of headlights without glare. The pavement markings used in the current study were all thermoplastic; however, fluorescent pigments or dyes could also be added to the more common painted markings. The fluorescent thermoplastics markings are more than double the cost of conventional thermoplastic markings; however, fluorescent paint markings are expected to cost less than 10% more than their conventional counterpart. The UV headlamps would always be used with the existing low beams, and it is not anticipated that the high beam units would be removed.

PREVIOUS RESEARCH

Swedish Studies

A great deal of research has been conducted in Europe, particularly by the Swedish National Road Administration under the ARENA program (*6*). It was determined that pedestrians could be seen much more clearly and the path of the roadway could be seen far beyond oncoming vehicles with UV headlamps. The Swedish Road and Traffic Research Institute also determined that the UV lamps do not constitute a health hazard.

UV lamps are currently being tested by Saab and Volvo on various cars and a bus. Since 1990, these Swedish car manufacturers have been involved in a joint development company called Ultralux. Ultralux states that road markings can be seen at a distance of 150 meters with UV light, compared with 60 to 70 meters with low beams alone (*7*). Fluorescent roadside posts were found to be detectable at distances exceeding 200 meters.

Ultralux also found that pedestrians were much more visible with UV lamps. Since most detergents contain a fluorescent whitening agent, clothes which are washed in the detergents tend to fluoresce in the presence of ultra-violet light. Ultralux found a 50% increase in the detection of pedestrians clothed in light colors. Dark clothes, like black wool, however, were no more visible with UV light than with normal low beams (*1*).

United States Preliminary UV Evaluation

Having obtained prototype ultraviolet headlamps from Ultralux, the Federal Highway Administration (FHWA) undertook an evaluation of the technology (*3*). Forty-one subjects in two age groups (25-45 & 65+) participated in the study. The field test was conducted on a section of the Clara Barton Parkway, a four-lane divided highway, in Montgomery, Maryland. Three UV headlamps were affixed to a 1993 Volvo 960, which was used as the test vehicle.

The first test consisted of a dynamic task in which subjects were driven on sections of roadway with various types of markings, worn paint, new thermoplastic, and florescent thermoplastic. After observing each condition of roadway markings, subjects were asked to rate how well the markings indicated where to drive the vehicle by using a five point rating scale (1-poor to 5-excellent). The observations were done with both low beams only and with the addition of ultraviolet. The UV headlights in combination with the fluorescent pavement markings showed the highest mean rating (4.40). As was expected, there was no significant difference in the non-fluorescent thermoplastic and worn paint in the two headlighting conditions. There was a statistical main effect of UV on versus UV off, and the difference between the UV/fluorescent pavement marking condition and the other types of pavement markings (paint and thermoplastic) was found to be statistically significant at probability of 99%.

Subjects also performed a static test in which they were asked to count the number of skip lines they could see, determine the right edge line visibility distance relative to traffic cones, and provide a rating of the overall visibility of the roadway markings. Subjects could see 30% more center skip lines and 24% more of the right edge line with the help of UV headlamps. The UV headlamps also received higher subjective evaluations in terms of visibility.

Safety Issues

One major obstacle that UV headlamp technology has to deal with is the popular opinion that all UV light is dangerous. The ultra-violet light tested in past research and in the current study is in the UV-A range of approximately 330 nm to 380 nm. This is not to be confused with the potentially harmful UVB wavelengths that the public frequently associates with skin cancer, cataracts, and tanning beds.

Sliney and Fast documented the safety aspects of UV headlamps with the prototype headlamps of the Swedish program (*8*). They found that most individuals do not experience a strong visual stimulus from the UV-A light, unless they were standing directly in front of the source. They also investigated whether direct exposure to UV radiant (UVR) energy was potentially dangerous to the eye or skin, even at close range.

They concluded that actual hazard to the eye or skin does not exist. The UVR exposures from the UV headlamp were "virtually the same" as that experienced when exposed to a conventional white-light headlamp.

METHODOLOGY

Having achieved positive results in the preliminary evaluation of UV headlamps, a more detailed study was initiated by FHWA to investigate the safety implications of the UV technology. This study took a more objective approach to the research than did past research and provided the first extensive field evaluation of the pedestrian safety benefits provided by UV headlamps.

Test Site

A driver training facility in Quantico, VA on the grounds of the FBI Training Academy was used for the test site. The facility can be seen in Figure 1. New pavement markings were installed on the oval and a 0.8 km section of access road.

The oval track is predominantly two-lane with a short section on the South side expanded to four lanes. The north side of the track consists of a long straight tangent section which has been marked as a passing zone. Fluorescent green delineator posts were installed on the Northwest corner of the track. The delineator posts on the outside of the curve contained patches of retroreflective material which faced the traffic approaching in the outside lane. The retroreflective material on the posts on the inside of the curve was covered. The track also contains two one-lane roads which transverse the oval, which are referred to as: the reverse curve, and the blind curve. Both the oval track and the 0.8km access road contained no overhead lighting. The new white and yellow thermoplastic fluorescent markings were installed over the existing, well-worn, markings.

Research Tools

Research Vehicles

The Data Acquisition System for Crash Avoidance Research (DASCAR) installed in a 1994 Ford Taurus Station Wagon is a fully instrumented test vehicle developed by the National Highway Traffic Safety Administration (NHTSA). The vehicle has the ability to record 33 parameters at a rate of 30 points per second. Steering, global positioning, braking, and accelerator movement are fed as inputs into the hard drive, located in the rear of the vehicle. There are also four video cameras concealed inside the vehicle which capture two views of the driver and forward and rear views out of the vehicle.

The study did not require all of the 33 parameters which DASCAR can record; therefore, several of the channels were disabled to conserve memory in the hard drive. Since the study was done at night, the video cameras could not be utilized. The parameters that were examined in this study included: speed, throttle, braking, steering, and lateral placement.

The Taurus wagon was fitted with three UV headlamp units. Two of the units were located just above the bumper in the center of the vehicle, and the third unit was located just above the lower two to create a triangle configuration. A special steel rack was added to the front of the vehicle, which contained mountings for both SAE US headlamps and ECE (European) headlamps. The light rack covered the existing headlamps. The control switches for the US, ECE, and UV headlamps were mounted inside the Taurus, just below the radio.

A 1993 Volvo 960 was equipped with three prototype UV headlamps. The Ultralux UV headlamps were affixed to a steel frame in front of the grill and on top of the front bumper. The units contained both horizontal and vertical adjustments, which were used to align the headlamps straight ahead and parallel to the horizontal plane. The UV headlamps were controlled by toggle switches inside the vehicle.

Windshield Shutter

A shutter was used to limit the exposure time of the subjects to the various scenes. The shutter consisted of a 12" x 21" panel which was rotated by a rotational solenoid connected to a 12-volt battery. The placement of the shutter was specific for each subject, such that the subject was able to see 30 meters in front of the vehicle with the shutter in the closed position. The 30 meter sight distance allowed subjects to retain their adaptation to the pavement luminance and reduced the refocusing distance required to detect the stimuli. Based upon information from pilot studies and past research, the shutter was set for a two second exposure time.

Conspicuity and Visual Search

Cole and Jenkins define a conspicuous object as one that will be seen with certainty for a given background within a short observation time (250 msec) regardless of the location of the object in relation to the line of sight (*10*). The task of detecting pedestrians and roadway markings at night is more than just an issue of conspicuity. The task of detecting a right curve, for instance, requires inputs from a variety of locations, such as the center lines and edge lines both near and far, as opposed to a single point. Pedestrian scenes are also complex in nature and required a visual search to detect the stimulus. Therefore, it was decided that a search time of greater that 250 msec, as recommended by Cole and Jenkins, was required.

Description of Various Tests

Static Testing Using Limited Exposure Time

The windshield shutter was used to give subjects a limited exposure time to various roadway conditions and pedestrian scenes. Subjects were seated in the passenger side of the test vehicle and driven to a point several hundred meters away from the stimulus. Vehicle alignment devices, which extended from the front and rear of the vehicles, were used to position the vehicles in the lane in a consistent manner. The subject was given a brief description of the stimulus, before the observations began. The shutter was opened for two seconds, and subjects were asked to respond if they did not see anything, if they thought they saw, or if they were sure they saw the stimulus. The subject was driven in 30.5m increments towards the stimulus with a two second exposure at each stop. The point at which the subject thought they saw and the point at which they were sure they saw the stimulus was recorded as the detection and recognition distances, respectively.

No Passing Zone, Right Curve, and Cross Walk The three pavement marking conditions on the oval test track were used as stimuli. The no passing zone was located at the end of the long tangent section on the North side of the track (refer to Figure 1). The first exposure began 274 meters away from the start of the double yellow lines. The right curve was located on the Southwest corner of the track. The first exposure began 335 meters away from the start of the curve. The cross walk was located on the tangent section of North side of the track. The first exposure began 274 meters away. A team member in the back seat recorded the responses of the subject. The Volvo 960 was used to conduct this test.

Pedestrian Dummies Silhouettes of pedestrians were cut out of 1/4" plywood. The pedestrian dummies were clothed in garments bought at a department store and washed one time in a commonly used detergent. These plywood forms were used to create two scenes of pedestrians. Both scenes were set up on the tangent section of the oval track. The first scene included a fluorescent bicycle and small child wearing a lavender skirt and shirt located in the left lane and a large pedestrian wearing khaki pants and polyester shirt (medium to lightly colored) located on the right edge line. The second scene included a pedestrian dummy in the right lane which appeared to be jogging across the roadway. The jogger was wearing light grey shirt and shorts made of cotton. The subjects were driven in the Volvo 960 and exposed to the first scene at an initial distance of 274 meters and the second scene at 290 meters.

Walking Pedestrian One of the research team members acted as the walking pedestrian. Upon a cue from the researcher in the Volvo test vehicle, the pedestrian began walking, such that the pedestrian walked across the road as the shutter was opened. A 1990 Ford Tempo was positioned in the left travel lane with low beam headlights on, and the pedestrian walked from the right pavement edge to the left pavement edge a few feet behind the glare vehicle. The subject was told that the pedestrian may or may not be present. The subject was given two exposures at each of the 30.5 meter intervals beginning at 213 meters away. Since the pedestrian was not always present, the subjects were prevented from responding prematurely.

Subjective Evaluations

Subjects were the passengers in the Volvo 960 and were told to imagine that they were driving and to observe the pavement markings. Subjects were driven a practice loop around half of the oval track, after which they were asked the following question: How did the roadway markings you just saw compare to the ones you generally see when you drive? A second team member recorded the subject’s answers. After the practice loop, the subject was driven for an additional two loops around the other half of the oval track, once with low beams only and once with UV headlamps enabled (refer to Figure 1). After each of the two loops subjects were asked the same question as for the practice loop and the following question: How well did the roadway markings you just saw compare to the ones you saw on our last drive?

Replication of Clara Barton Static Test

In order to provide a point of comparison between the second study and the preliminary field evaluation, the static test performed on the Clara Barton was replicated on the oval track in Quantico. The long tangent section on the North side of the track, which contained dashed lines for a passing zone, was used for the test. Subjects were seated in the same vehicle (Volvo 960) and given the same instructions as in the preliminary evaluation study. Subjects were asked to count the skip lines, tell how far the right edge line was illuminated, and to a rate how visible the roadway markings were (1-poor to 5-excellent). The test was initially done with low beams and then followed by low beams with UV.

Dascar Drive

The subject drove the Dascar-equipped Taurus Wagon on five round trips of the closed, single lane access road (refer to Figure 1). The subject was allowed a short period to acclimate to the vehicle and to adjust the seat and controls. The subject was given a brief description of the route, which would include an oncoming vehicle, and that he/she would be asked two questions concerning the headlights and roadway markings. The subject was asked to drive at a safe and comfortable speed, and not to exceed 48k/hr (30 mph). The first loop was termed a practice run which utilized US beams only. The remaining loops consisted of the following headlamp conditions in varying orders of presentation: Low Beam, Low beamUV, Low beam Euro, Low beam EuroUV. The access road consisted of two straight tangent segments, two right curves, and two left curves. A 1990 Ford Tempo was positioned in the oncoming lane, with low beams on, just after the halfway point of the loop. At the end of each loop the subject was asked the following two questions:

1. How well did the headlights and roadway markings work for you compared to what you generally see when you drive your car?
2. Compared to the last ride down to the gate and back, how well did these headlights and roadway markings work for helping you see where to steer the car?

The subject was made aware that the vehicle did contain an onboard computer, but was not made aware of its capabilities.

Subjects

The sample of subjects included of 28 persons, 16 females and 12 males. The distribution of subject ages was: 8 (16-25 yr), 14 (26-59yr), 6 (60yr +). The subjects were recruited via advertisements in the newspapers of communities in close proximity to the Quantico area. Pre-screening sessions were held to meet potential participants, give them an idea of what is required for participation, and to give them the required visual acuity and color discrimination test. At the pre-screenings, subjects were also given a waiver form to sign.

Two subjects per evening participated in the research. Subjects received instruction concerning the schedule of events for the evening and an overview of the study. In the overview, it was explained that the study was examining a different type of headlights and roadway markings.

RESULTS

Static Testing Using Limited Exposure Time

Right Curve, Cross Walk, No Passing Zone

The average detection and recognition distances for the three pavement marking conditions can be seen in Table 1 and Figure 2. The differences between the Low beam and Low beam with UV conditions were found to be significant for all recognition distances. The differences for detection distances were also found to be significant with a probability of 95% using a T-test, with the exception of the right curve.

Pedestrian Scenes

An average increase of 117 % in detection distance and 93.2 % increase in recognition distance was found with the use of the UV headlamps. The pedestrian detection and recognition distances can be seen in Table 2 and Figure 3. Using a T-test, the differences between the two headlight conditions were found to be significant at a probability of 95%, for every stimulus with the exception of the detection distance of the adult pedestrian.

Subjective Evaluations

In response to the question concerning how the roadway markings worked in comparison to the markings they had seen in the past, subjects responded in the following manner:
Condition: Low beam only - - Not as good as: 18.5%, As good as: 66.7%, Better than: 14.8%.
Condition: Low beam with UV - - Not as good as: 11.1%, As good as: 14.8%, Better than: 74.1%.

Replication of Clara Barton Test

In the static test, subjects could see an average 2.4 more skip lines with the ultraviolet headlamps. Subjects could also see the right edge line an average of 38.4 meters more with UV. The results of the static test can been seen in Table 3. A T-test indicated that the difference between the two headlamp conditions was significantly different for each portion of this test with a 95% level of probability.

Dascar Drive

Dascar Data

Results from the DASCAR system were not yet available at the time of this report. Since the system records 30 data points per second, the collected data files are enormous and will require a sizeable effort to analyze. The measures of effectiveness which will be examined include: variance of speed, number of steering reversals, number of braking occurrences, variance of lateral tracking, number of centerline and edgeline violations.

Subjective Questions

In response to the first question: How well did the headlights and roadway markings work for you compared to what you generally see when you driver your car? Subjects responded as follows for the various headlight conditions:

US Low Beam-	Not as good as:	21.4%
	As good as:	50.0%
	Better than:	28.6%
US Low Beam with UV -	Not as good as:	21.4%
	As good as:	32.1%
	Better than:	46.4%
European Low Beam -	Not as good as:	7.1%
	As good as:	28.6%

	Better than:	64.3%
European Low Beam with UV-	Not as good as:	10.7%
	As good as:	17.9%
	Better than:	71.4%

The second question presented to the subjects allowed a relative comparison between headlamp conditions. Since the order of presentation was varied, a relatively small number of subjects directly compared each of the combinations of the four conditions. Generally speaking, subjects preferred the European over the US headlamps. A majority of the subjects preferred the addition of the UV headlamps to both the US and European headlamps.

DISCUSSION

Limitations of Study Method

The method of static testing, which incorporated the use of a windshield shutter, provided a measure of only the relative detection and recognition distances of the various targets under the different headlight conditions. Past research has shown that the two second exposure time provides a realistic opportunity to detect or recognize the stimulus at the given locations. It is suggested, however, that the distances derived from the static testing method be interpreted as relative.

Since the pavement markings were recently (9 months) installed, they were generally better than the average road, even with the normal low beam headlamps. Therefore, the subjective ratings provided by the subjects may be somewhat optimistic.

CONCLUSIONS

Static Testing Using Limited Exposure Time

Right Curve, Cross Walk, No Passing Zone

The addition of UV provided for large increases in the detection and recognition of all of the pavement marking conditions with the exception of the right curve. The right curve was situated at the end of a taper from a 4-lane to a 2-lane roadway, and the curve occurred after the crest of a hill. With these factors in place, the detection and recognition of the right curve was not a clean test.

Although the deviation in the distances appears to be large, this can be accounted for by the fact that the distances were recorded in 30 meter increments. Overall the UV-activated fluorescent pavement markings were far superior to the pavement markings under low beams only.

Pedestrian Scenes

A large increase in detection and recognition distances of pedestrians was realized with the addition of UV. The only difference that did not gain statistical significance was the adult pedestrian. This appeared to be due to the fact that the fluorescent bicycle present in the scene was so bright under the UV light that the subjects concentrated on identifying what the object was, while ignoring other objects present in the scene. As can be seen from the results, the pedestrians in the lighter clothing had a noticeable advantage in their detection and recognition.

Subjective Evaluations

In response to subjective questions, subjects consistently indicated that the addition of UV was beneficial. In a direct comparison between the two conditions analyzed, a majority of subjects preferred the addition of UV compared to low beams only. Interestingly, subjects who saw the UV light after the low beams only, were more apt to give the UV light a better rating.

Replication of Clara Barton Test

As in the preliminary field experiment, subjects could see farther and generally liked the effect (as was indicated by the subjective rating) of UV. There was a slight difference in the data from the current study and the preliminary evaluation. This could be accounted for by the difference in the length and spacing of skip lines between the two test sites.

Dascar Drive

Subjective Questions

The UV headlamps were generally rated to be superior to the non-UV condition for both the US and European low beam conditions. The surprising result, however, was the fact that the European headlamps emerged as the clear favorite over US headlamps, even exceeding the results for the US low beams with UV. Subjects commented that the European headlamps were whiter and provided a brighter light. The European headlamps combined with UV received the best rating with 71.4% of the subjects indicating that it was better than what they were use to seeing. The reader should be reminded, however, that the European headlamps offer very little light for overhead signs, which is the principal reason they are not used in the United States.

Recommendations

The UV headlamp technology clearly produces increased visibility of roadway markings and pedestrians. The UV headlamps provide an increase in the visibility of pavement markings of over 30%. Subjects also subjectively identified the pavement markings as more visible with the presence of UV (40% better in the static ratings). This increase in the visibility of roadway markings has the potential to significantly increase the safety of the nighttime driving environment.

UV headlamp technology provides exciting benefits in the area of pedestrian safety. The UV light was shown to have the capacity to provide an increase in the detection of pedestrians by over 100% and an increase in recognition by over 90%. The ideal aspect of the concept is the fact that pedestrians would not have to do anything out of the ordinary to activate the increased safety. They would only have to wash their clothes occasionally.

The results of the preliminary field experiment and the field study indicate that UV-activated fluorescent pavement marking technology can significantly increase the visibility of roadway delineation. The Federal Highway Administration has initiated further study which will involve the headlamp and automobile manufacturers and focus on any problems associated with the national implementation of this technology, including those question and problems related to manufacturing, environmental, health, highway safety, and economic impact.

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TABLE 1
Static Test Detection and Recognition Distances for Three Pavement Marking Conditions

	DETECTION (meters)						**RECOGNITION (meters)**					
	Right Curve		**Cross Walk**		**No Passing**		**Right Curve**		**Cross Walk**		**No Passing**	
UV status	**Off**	**On**	**Off**	**On**	**Off**	**On**	**Off**	**On**	**Off**	**On**	**Off**	**On**
Average	231.4	239.3	131.0	203.2	132.0	189.7	200.9	228.0	112.8	170.5	105.0	160.3
Deviation	47.3	37.5	40.4	38.7	33.8	41.7	53.7	34.2	35.7	33.0	22.9	39.3
% Increase	7.9[a]		72.3		57.6		27.1		57.6		55.3	

[a]Not statistically significant.

TABLE 2
Pedestrian Detection and Recognition Distances (meters)

	Pedestrian Scene						Jogging Ped		Walking Ped	
	Child Ped		Bicycle		Adult Ped					
UV Status	Off	On	Off	On	Off	On	Off	On	Off	On
Detection	**39.6**	**68.6**	**76.2**	**233.2**	**122.0**	**144.8**	**132.6**	**282.0**	**58.6**	**161.8**
Deviation	14.3	32.6	68.2	59.6	46.4	45.2	31.7	29.5	26.1	21.6
Recognition	**36.6**	**64.0**	**41.1**	**120.4**	**73.2**	**114.3**	**99.1**	**149.4**	**58.6**	**152.4**
Deviation	12.5	19.5	24.8	50.9	25.0	41.8	24.0	61.7	15.0	21.6
N	20	20	20	20	20	20	20	20	13	13

TABLE 3
Comparison of Fluorescent Delineation (Quantico Study)

Measure	Low Beams Only		Low Beams Plus UV	
	Mean	SD	Mean	SD
Number of center skip lines visible	4.91	0.94	7.32	1.16
Amount of right edge line visible (meters)	212.8	51.8	251.2	27.6
Subjective rating of visibility	3.21	0.79	4.50	0.88

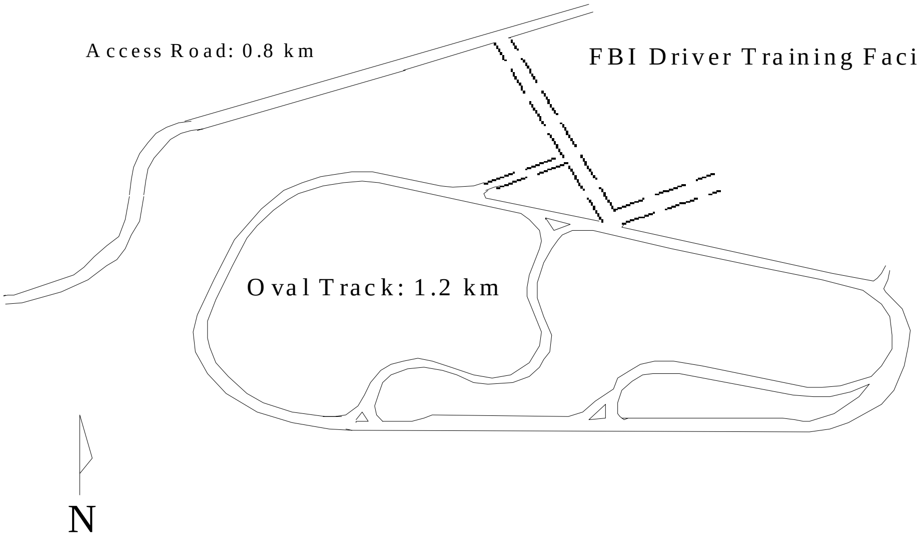

FIGURE 1: Map of Test Site

FIGURE 2: Mean Detection and Recognition Distances for Pavement Marking Conditions

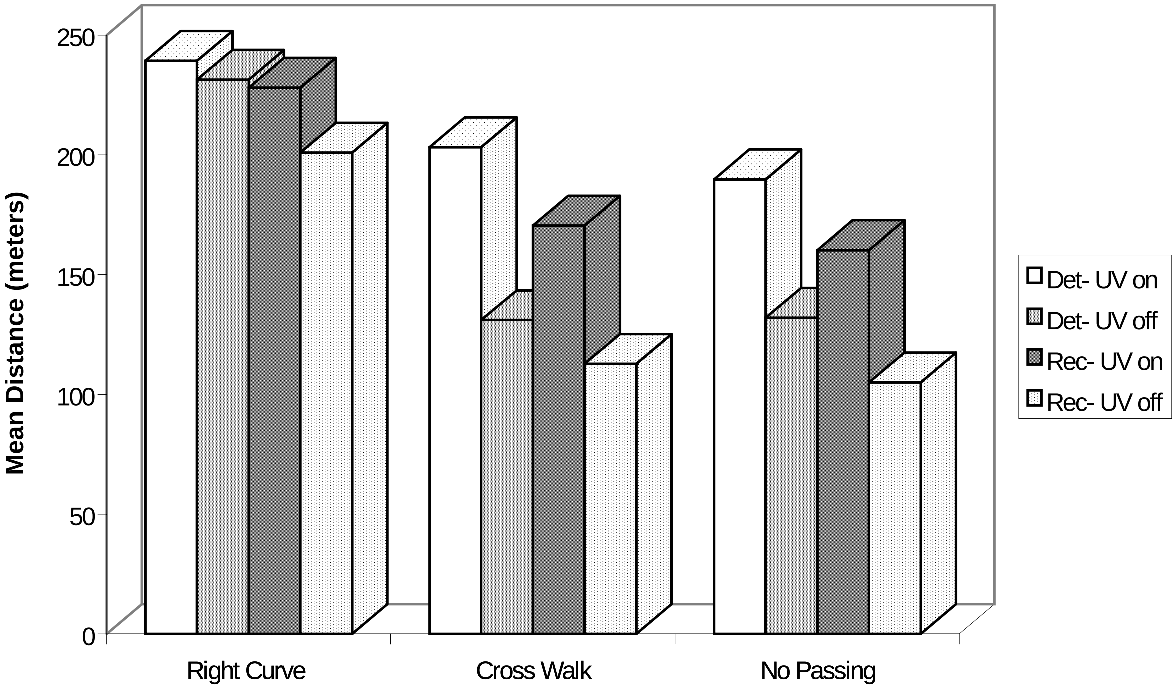

FIGURE 3: Mean Detection and Recognition Distances of Pedestrians