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IMPLICATIONS OF FATAL AND NONFATAL CRASHES FOR ADAPTIVE HEADLIGHTING

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16. Abstract

Fatal and nonfatal pedestrian crashes spanning daylight saving time were analyzed to assess the relative magnitude of risk in darkness for crash scenarios related to each of three forms of adaptive headlighting—curve lighting, motorway lighting, and cornering light. For curve lighting, pedestrian crashes on curved roadways were examined; for motorway lighting, crashes with attributes associated with motorways were examined; and for cornering light, crashes involving turning vehicles at intersections were examined. Fatal crashes were sampled from FARS 1987-2004; fatal/nonfatal crashes were sampled from the North Carolina crash dataset, 1991-1999.

In the curve analysis, lower dark/light crash ratios were observed for curved sections of roadway compared to straight roads. This pattern was observed in both the fatal and nonfatal crash data. In the analysis of motorway attributes, posted speed limit was the dominant predictor of crash risk in darkness for the fatal crash dataset; road function class was the dominant predictor for the fatal/nonfatal dataset. Finally, in the analysis of intersection crashes, dark/light ratios for turning vehicles were lower than for nonturning vehicles; and dark/light ratios at intersections were lower than at nonintersections.

The risk for each crash scenario was paired with the corresponding annual rate of crashes in darkness for each scenario so that a relative safety need could be determined. While all three scenarios suggested a potential for safety improvement, scenarios related to the motorway environment showed the largest potential. The actual safety benefits from various forms of adaptive lighting can be expected to depend on both the relevant safety needs, for which this report provides estimates, and the visual effectiveness with which various forms of adaptive lighting can be implemented.

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Introduction

In previous work, the influence of natural light level on crash risk was found to differ across various scenarios. For example, strong effects of natural light level were found in pedestrian crashes (Sullivan & Flannagan, 2001) and rear-end collisions involving trucks (Sullivan & Flannagan, 2004) using an analysis of crash frequency across daylight saving time transitions. This method is intended to isolate the effect of light level from other factors (e.g., fatigue, alcohol use, driver demographics) that are typically confounded with light level when day-night comparisons are made (Sullivan & Flannagan, 1999), providing a relatively pure assessment of the influence of light level on crash risk. The purpose of the present analysis is to examine the role of ambient light level in crash scenarios associated with some of the major forms of adaptive headlighting that have been proposed, thereby providing estimates of the potential safety benefits from this technology.

In contrast to prior analyses, we will determine the potential benefit of curve lighting, motorway lighting, and cornering lighting using scenarios tailored to each of these three forms of adaptive headlighting. Curve lighting, which has already been introduced on several vehicles, directs light to follow horizontal curves, allowing a driver to see farther down the road. It is especially effective for short-radius curves (Sivak, Schoettle, Flannagan, & Minoda, 2004). The analysis scenario for curve lighting compares the effect of light level on dark/light crash risk on curved roads and straight roads. Motorway lighting increases forward visibility on high-speed, limited access or divided roadways by modifying a conventional low-beam light distribution to project more light further down the road. On such roadways, there is both greater need for seeing distance because of the higher speeds and diminished glare to opposing drivers because of greater lateral separation. We will evaluate the potential safety benefit of motorway lighting by examining how the variables that differentiate motorways or highways from other roads (posted speed, function class, trafficway characteristics, lanes, and rural versus urban locale) affect the relative risk in darkness. Finally, we will examine the potential benefit of cornering lighting, which is intended to illuminate the side of the roadway during acute turning maneuvers. For cornering lighting, we will examine the effect of natural light on the frequency of pedestrian crashes at intersections when a vehicle is turning.

It should also be noted that the potential crash reductions discussed here do not involve any evaluation of how effective a certain innovation in lighting might be as it is actually implemented. For example, in order for curve lighting to achieve all of the potential crash reduction as quantified here, it would have to be perfect in addressing the problems of darkness that are encountered on curves. That is, the visibility provided by the curve lighting system would have to approximate daylight visibility. How close any specific vehicle lighting system could come to that ideal is not currently known, given the innovative nature of adaptive lighting. We believe it is reasonable to assume that the various forms of adaptive lighting discussed here will improve visibility in the relevant traffic scenarios, and we believe that the potential safety benefits as quantified here are important to consider in developing specific forms of adaptive lighting, but no single analysis can provide a complete assessment of the benefits of all forms of adaptive front lighting.

Method

The general method of this analysis is first to determine the degree to which a crash scenario is influenced by natural light using daylight saving time analysis, and then to determine the annual number of crashes in darkness for that scenario. The influence of natural light on crash risk is determined by the dark/light risk ratio—the number of crashes in a certain period of darkness divided by the number of crashes during a comparable period of daylight. A dark/light ratio greater than 1 indicates that darkness is more risky than daylight; a dark/light ratio equal to 1 indicates no difference between dark and light; and a dark/light ratio less than one indicates less risk in darkness. If we suppose that some improvement in artificial lighting at night could create conditions more like daylight, we would expect the dark/light ratio to approach 1. A large dark/light ratio for a certain crash type suggests an important potential for improvement with better lighting. However, to quantify such a potential improvement, it is also necessary to consider the frequency of that crash type. This number provides a measure of how much opportunity there is for crash reduction in each scenario. It is important to recognize that a large dark/light risk ratio coupled with few opportunities may result in a smaller safety benefit than a modest risk ratio coupled with many opportunities. Both risk and frequency must be considered in evaluating potential safety benefits, which are indexed here in terms of potential reduction in crashes.

The following analyses use two principal datasets: the Fatality Analysis Reporting System (FARS) maintained by the National Highway Traffic Safety Administration (NHTSA), which is a complete census of all fatal traffic accidents in the United States; and the North Carolina Department of Transportation Crash dataset (NCDOT), which contains fatal, injury, and property-damage-only crashes. Some data fields in the two datasets are not directly comparable. For example, with respect to locale of the crash, the FARS dataset designates crashes as either URBAN or RURAL, whereas NCDOT also includes a MIXED category. Where possible, these differences have been resolved by grouping crashes into more general categories.

For each dataset, crashes that occurred in the one-hour time window that transitions from dark to light (or light to dark) over the spring and fall daylight saving time (DST) changeover were compiled over several years. The FARS dataset, included crashes from 1987 through 2004 (18 years), while the NCDOT dataset included crashes from 1991 through 1999 (9 years). The interval identified as "dark" began at the local (standard) time of civil twilight, and extended one hour later. In the spring, this interval transitions from dark to light when the local time is adjusted forward by one hour. In the fall, this interval was based on the local time of civil twilight after the transition back to standard time. Prior to the fall transition, this interval is identified as "light," and becomes "dark" after the transition. Note that in North America, the nominally light interval therefore actually extends from about half an hour before to half an hour after sunset. Crashes occurring in this one-hour time window during the five weeks before and after the spring and fall DST transition were compiled for this analysis. Only evening transitions were included in this analysis because in the morning light level fluctuates over the ten-week spring and fall calendar windows (for details see Sullivan & Flannagan, 1999, 2002, and 2004).

The analysis will first establish which crash types are most affected by light level; these crash types will then be further partitioned based on factors relevant to the various adaptive headlighting scenarios. This analysis extends earlier work (Sullivan & Flannagan, 2001) by using new FARS data and introducing the NCDOT dataset, which contains both fatal and nonfatal crashes. In addition, the analysis also partitions pedestrian collisions by age to assess the extent to which dark/light exposure differences between pedestrian children and other pedestrians may affect the determination of pedestrian risk in darkness.

Results

The Effect of Ambient Light by Crash Type

A breakdown of the frequency of different fatal crash types during dark and light periods is shown in Table 1, from the FARS DST dataset. Ratios that significantly depart from 1 (where 1 would indicate no difference between dark and light) are shown in Figure 1. This analysis is consistent with previous analyses (Sullivan & Flannagan, 2001) in which fatal crashes involving pedestrians, animals, and other motor vehicles showed the most reliable increases in risk in low light levels. Additionally the updated analysis breaks pedestrian crashes into three categories by pedestrian age—children (under 18 years), adult (18-65), and elderly (65 and older). Although children show a reliably greater risk in darkness, it is much smaller than the risk observed for adult and elderly pedestrians. This is likely a consequence of a light-related exposure difference for children—parents are likely to require children to be inside after dark, thereby reducing their exposure. With children separated from the sample, it becomes apparent that crash risk among both adult and elderly pedestrians is nearly seven times greater in darkness. Even when the data are not separated by age, the apparent increase in pedestrian risk in the dark is very strong, by a factor of 2829/621 = 4.56. However, because the results for children likely reflect the special protective effects of restricting children's exposure in the dark, it appears that the "true" or "inherent" effect of darkness on pedestrian risk (i.e., when no special precautions are taken) is even more dramatic.

Table 1
Breakdown of crash types by light level over the DST interval. Ratios significantly greater than 1 are in bold with darker shading; ratios significantly less than 1 are in bold italics with lighter shading.

Crash Type	**Dark**	**Light**	**Total**	**Dark/Light Ratio**
Pedestrian – Child	**349**	**252**	**601**	**1.38**
Pedestrian – Adult	**1635**	**243**	**1878**	**6.73**
Pedestrian – Elderly	**845**	**126**	**971**	**6.71**
Animal	**61**	**11**	**72**	**5.55**
Rear End	**440**	**198**	**638**	**2.22**
Angle	**1507**	**1239**	**2746**	**1.22**
Head On	**1058**	**748**	**1806**	**1.41**
Misc.	**522**	**460**	**982**	**1.13**
Side Swipe, Opposite Direction	46	35	81	1.31
Parked in Roadway	**82**	**58**	**140**	**1.41**
Fixed Item	480	517	997	0.93
Fixed Object-Off Road	***955***	***1088***	***2043***	***0.88***
Side Swipe, Same Direction	50	61	111	0.82
Overturn	***492***	***691***	***1183***	***0.71***
Rear to Rear	3	3	6	1.00
Grand Total	8525	5730	14255	1.49

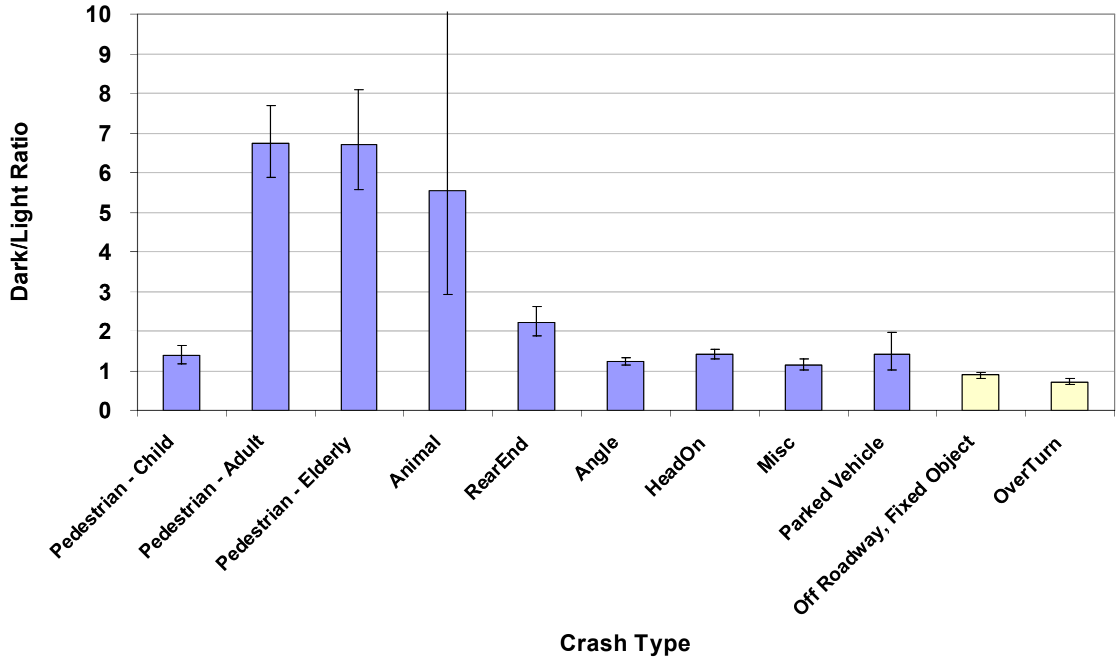

Figure 1. Fatal crash types affected by ambient light level. The blue (darker) bars identify crashes that show significantly greater risk in darkness, and the yellow (lighter) bars identify crashes that show significantly greater risk in lighter periods. Error bars represent the 95% confidence interval around the dark/light ratio.

As before, risk of an overturn was found to be reliably *less* likely in darkness. In addition, collisions with fixed objects off the roadway were found to be less likely in darkness. It is unclear why darkness would reduce the risk of any collision, given the accompanying degradation in visibility. Perhaps darkness prompts drivers to operate their vehicles more conservatively (in respect to some aspects) by creating a heightened awareness of risk. Alternatively, the apparent reduction in risk could be attributable to differences in exposure in the dark for these types of crashes. Further work is needed to evaluate these possibilities.

A similar breakdown of crash types for the NCDOT dataset is shown in Table 2. However, some differences in how crashes are coded in the NCDOT dataset prevent direct comparisons with FARS for many crash types. Observed crash ratios for select crash types are also shown in Figure 2 along with 95% confidence intervals on the observed ratios. This figure also includes some crashes in which no light effect was observed to allow comparison to related crashes.

Table 2
Breakdown of fatal and nonfatal crash types by light level over the DST interval for the NCDOT dataset. Ratios significantly greater than 1 are in bold with darker shading; ratios significantly less than 1 are in bold italics with lighter shading.

Crash Type	Dark	Light	Total	Dark/Light Ratio
Pedestrian - Child	***80***	***117***	***197***	***0.68***
Pedestrian - Adult	**292**	**115**	**407**	**2.54**
Pedestrian - Elderly	30	26	56	1.15
Animal	**4656**	**560**	**5216**	**8.31**
ParkedVeh	**894**	**747**	**1641**	**1.20**
Rear End, Slow	**5466**	**3708**	**9174**	**1.47**
Rear End, Turn	279	279	558	1.00
Angle	2764	2721	5485	1.02
Head On	**205**	**162**	**367**	**1.27**
Right Turn	**233**	**198**	**431**	**1.18**
R Turn Cross Traffic	**362**	**310**	**672**	**1.17**
Left Turn	**2265**	**1819**	**4084**	**1.25**
L Turn Cross Traffic	**1340**	**1167**	**2507**	**1.15**
Sideswipe	**1069**	**785**	**1854**	**1.36**
In Road, Other	84	107	191	0.79
Overturn	***52***	***98***	***150***	***0.53***
Fixed Object	280	310	590	0.90
Ran Off Road, Left	907	903	1810	1.00
Ran Off Road, Right	2074	1998	4072	1.04
Ran Off Road, Straight	**205**	**96**	**301**	**2.14**
Backing	1136	1103	2239	1.03
Grand Total	24678	17333	42011	1.42

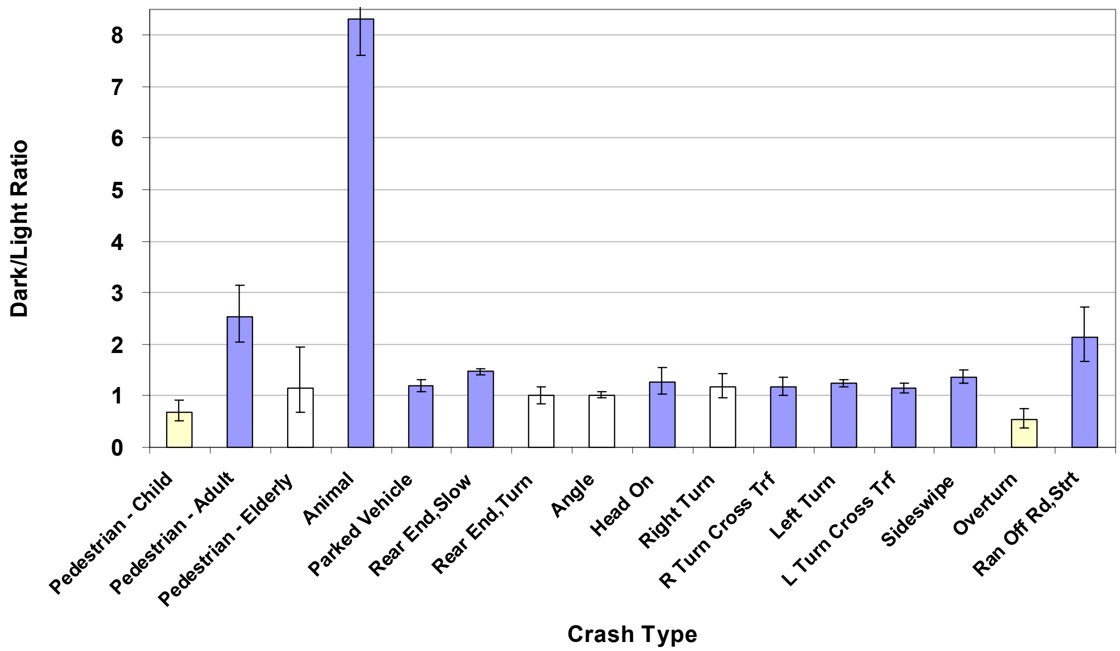

Figure 2. Fatal and nonfatal crash types affected by ambient light level from the NCDOT dataset. The blue (darker) bars identify crashes that show significantly greater risk in darkness, and the yellow (lighter) bars identify crashes that show significantly greater risk in lighter periods. The white bars indicate crashes that show little effect of light level. Error bars represent the 95% confidence interval around the dark/light ratio.

Some noteworthy differences between Figures 1 and 2 are the diminished dark/light ratios found in the NCDOT fatal and nonfatal crash data. This may be because the influence of light is stronger for more severe crashes, and the NCDOT data are dominated by less severe crashes than are found in the FARS dataset. In the DST sample of the NCDOT data, fatal crashes comprised only about 0.5% of all crash types; among pedestrian crashes, fatalities comprised about 9% of the cases. Moreover, crashes involving property damage only (PDO) accounted for about 60% of all crashes. (The crash severity breakdown in the DST sample closely mirrors the breakdown found in the overall NCDOT sample—in the 1999 NCDOT crash data, 0.6% of all reported crashes were fatal, 8% of all pedestrian crashes were fatal, and 60% of all crashes involved property damage only.) Lower severity crashes are less likely to involve high speed than fatal crashes. And, because speed is one key factor that drives crash risk in darkness, its diminished role in the NCDOT dataset is also likely to reduce the magnitude of the observed dark/light risk ratios.

Despite the observed reduction in the dark/light risk ratios, there are clear similarities between the two samples. The dark/light crash ratio is greatest for crashes involving struck animals in the roadway in both the FARS and NCDOT datasets. For crashes involving animals, it is difficult to separate exposure effects from effects of light level. Many animals are known to vary their activity level with natural light, and crepuscular animals, including deer, are likely to be more active just around dusk and dawn. The apparent effect of darkness on animal collisions may therefore be exaggerated in the DST data because the dark interval in early evening may coincide with the period of the animals' peak activity. The next largest dark/light risk ratio is for adult pedestrians for both datasets. There are also large differences between child-pedestrian risk and adult-pedestrian risk. In the fatal crash analysis, the dark/light risk ratio for pedestrian children is small, albeit greater than 1. In the NCDOT dataset, the dark/light risk ratio for children is less than 1, indicating a substantially higher risk in daylight. This difference is likely caused by a light-related exposure difference for children. That is, if most children are required to be inside after dark, significantly fewer children are available to be involved in pedestrian crashes after dark. The effect of this exposure difference appears to be especially pronounced in the NCDOT crash data.

Our main concern in this analysis is to describe the implications of crash data for various possible forms of adaptive headlighting. We will therefore concentrate on the crashes that exhibit the strongest increased risk in darkness that is unambiguously attributable to darkness and for which improvements in headlighting appear to be suitable countermeasures—pedestrian crashes involving adults. Several types of multiple-vehicle crashes also show moderate increases in risk in the dark, but given the strong role of marking lamps and retroreflective markings on vehicles these crashes are not likely candidates for headlighting countermeasures. The primary research question is: Given a crash type that shows an increased risk in darkness, how is that risk influenced by roadway characteristics that are relevant to various possible forms of adaptive headlighting? For curve lighting, we contrast curved and straight roadways; for motorway lighting, we examine posted speed, road class, locale, and trafficway; and for cornering light we examine pedestrian crashes involving turning vehicles at intersections.

Curve Lighting

Fatal Crashes. Curve lighting is best suited to address crashes occurring in darkness on curved sections of roadway. Based on the FARS 2004 dataset, about 6% (273 of 3871) of all fatal pedestrian crashes were reported on roadways with curved (as opposed to straight) alignment (see Table 3); this is about the same proportion found in the NCDOT 1999 dataset of fatal and nonfatal crashes (also 6%; 119 out of 1918, shown in Table 4). If we further restrict consideration to cover only dark conditions, 4% (172 cases) of pedestrian fatalities and 2% (46 cases) of the NCDOT pedestrian crashes occurred on darkened curved roadways.

Table 3
Counts of fatal pedestrian crashes in the United States on curved and straight roadways in 2004 (from FARS 2004).

Alignment	Light	Dark or Dark with Lights	Dawn/Dusk	Unknown	Total
Curved	91	172	10		273
Straight	1099	2728	131	13	3971
Unknown	12	28		28	68
Total	1202	2928	141	41	4312

Table 4
Counts of fatal and nonfatal crashes in North Carolina on curved and straight roadways in 1999.

Alignment	Light	Dark or Dark with Lights	Dawn/Dusk	Unknown	Total
Curved	70	46	2	1	119
Straight	1042	670	72	2	1786
Unknown	4	1	1	7	13
Total	1116	717	75	10	1918

Using daylight saving time transition data from the FARS dataset for fatal crashes and from the NCDOT dataset for fatal and nonfatal crashes, a logistic analysis was conducted to model the probability of a crash in the dark interval for a given crash type and alignment level (curved versus straight). The results of the FARS dataset analysis shows a strong main effect of crash type (χ^2=337.7, *df*=15, *p* < .001) and an interaction between fatal crash type and alignment (χ^2=34.0, *df*=15, p = .003). The interaction effect is shown in Figure 3. For some crash types, a curved roadway tended to moderate the effects of ambient light level toward indifference. Thus, a dark/light ratio on a straight section of roadway that is significantly greater than 1 tends to be reduced toward 1 on a curved roadway (e.g., crashes involving adult pedestrians). Conversely, a dark/light ratio significantly less than 1 (e.g., overturns) tends to be increased toward 1 on a curved roadway.

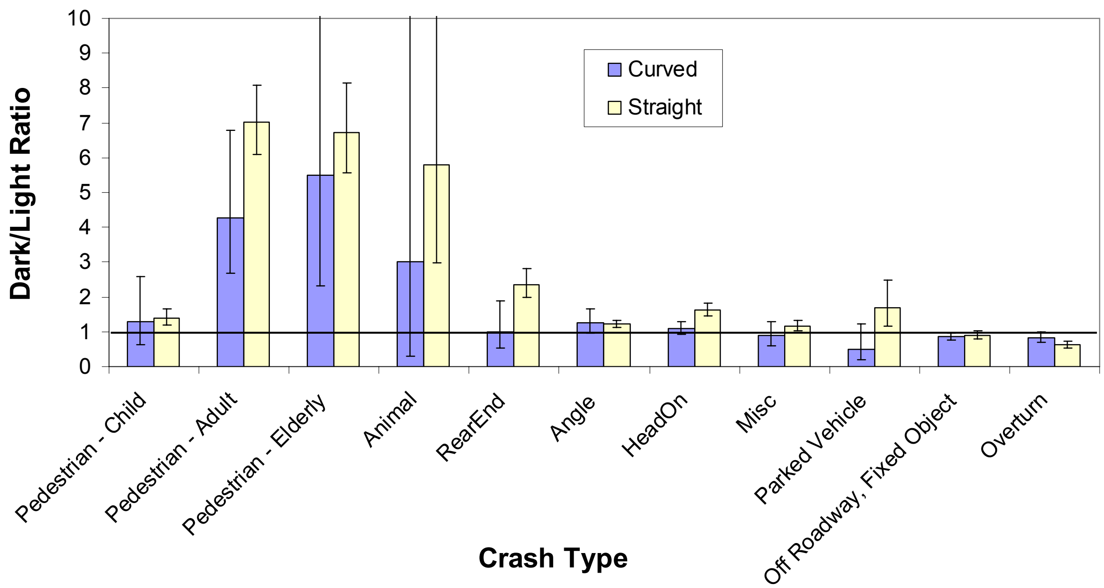

Figure 3. Interaction effects of roadway alignment (curved versus straight) on fatal crash risk in darkness. This figure shows the results of data fit to a logistic regression of the daylight saving time crash data from FARS (1987-2004).

A separate logistic analysis of the fatal adult pedestrian crashes in the FARS daylight saving time dataset found a main effect of roadway alignment (χ^2=4.0, *df* = 1, $p < 0.05$). In this case, there were about seven times as many crashes in darkness as in light on a straight roadway; on a curved roadway, there were only about four times as many crashes. If a form of curve lighting were to improve road visibility on curves to a level similar to daylight, we might expect to reduce the number of fatal crashes in darkness from an annual rate of 172 (fatal pedestrian crashes in the dark on curved roadways—Table 3) to about 43 (172/4) or 128 fewer fatal crashes annually.

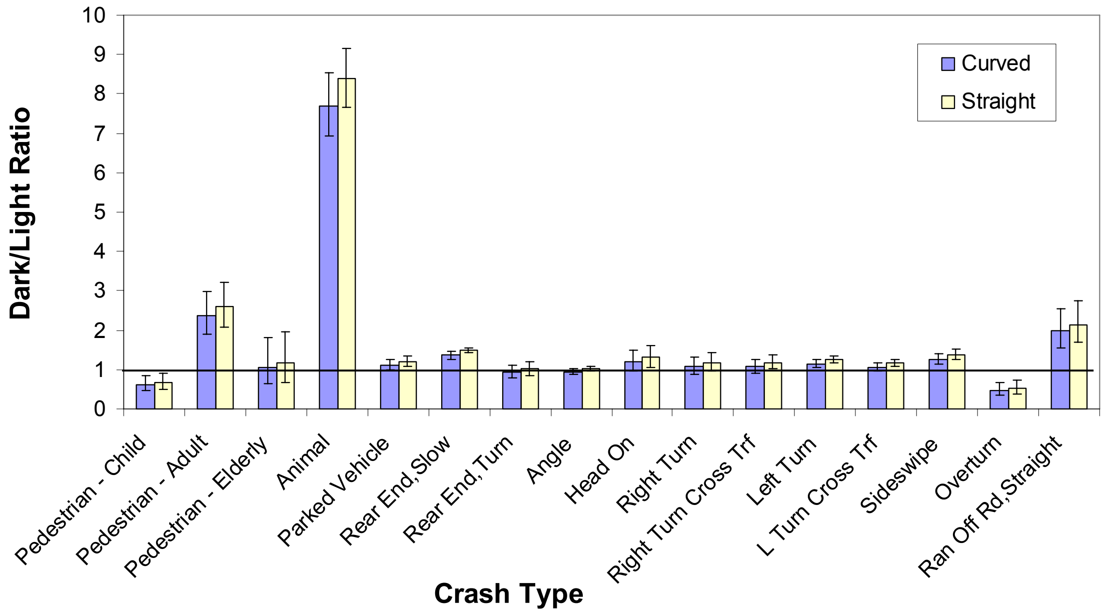

Figure 4. The effect of roadway alignment (curve versus straight) on fatal and nonfatal crash risk in darkness. This figure shows the results of data fit to a logistic regression of the daylight saving time crash data from NCDOT (1991-1999).

Nonfatal Crashes. A similar logistic analysis of the NCDOT daylight saving time dataset found no effect of roadway alignment (χ^2=1.49, *df* = 1, *p* = 0.23) among adult pedestrian crashes (see Figure 4). Indeed, there are only 28 cases of adult pedestrian crashes on curves (out of 404 total cases). To estimate the crash reduction among adult pedestrians in the NCDOT dataset, we therefore applied the general estimate of the effect of a curved road (across all pedestrians types) to the observed dark/light ratio (2.48) of adult pedestrians on straight roads.

The resulting dark/light risk for adult pedestrians on curved roadways is about 2.28. An estimate of accident reduction for the NCDOT data in darkness on curves would be from about 46 annual pedestrian crashes in darkness to about 20 (46/2.28), or about 26 pedestrian accidents eliminated.

To extrapolate beyond North Carolina to the general US population, we used the 1999 National Accident Sampling System's General Estimate System (NASS-GES) dataset to estimate non-fatal crashes and the 1999 FARS dataset to estimate fatal crashes. In 1999, there were a total of 499 non-fatal (337) and fatal (162) pedestrian crashes in darkness on curved roads. The estimated reduction would be from about 499 to 219 (499/2.28) crashes, or about 280 crashes eliminated.

Motorway Lighting

Fatal Crashes. Motorway lighting is best suited to improving visibility in situations where speed is high and, because of large lateral separation from opposing traffic, the risk of glare to oncoming drivers is lower than on other roads. It may be accomplished by shifting a low beam upward and perhaps to the left (for right-hand traffic). In the following analysis, we examine which characteristics of roadways most affect crash risk in darkness. To do this, adult pedestrian crashes are identified by posted speed limit, road class (interstate, arterial, collector, local), number of travel lanes (1, 2, 3 to 4, 5 to 6, and greater than 6), locale (urban or local), and trafficway type (no median, median, left turn median, or one-way). Each factor is included in a stepwise logistic regression that models the probability of a crash in darkness as a result of levels of each factor. Factors are added to the model based on their predictive strength. The strongest factor is added first, followed by the next strongest, and so on, until there is little further improvement in the predictive capability of the model. Note that because many of the modeled factors are correlated with each other (for example, speed is likely associated with road class), inclusion of one factor may eliminate the predictive power of other factors.

The results of this analysis found that crash risk in darkness is overwhelmingly predicted by posted speed limit (χ^2=20.6, df = 1, p < .0001). No other factors added significantly to the power of posted speed to predict crash risk in darkness. The model predictions along with the observed dark/light ratios are shown in Figure 5. Using this figure, we can see that if the posted speed on a motorway is 45 mph or greater, the average predicted dark/light ratio would be about 10—i.e., in darkness, the chance of a fatal crash is 10 times greater than in daylight.

To estimate the safety value of motorway light, we applied this dark-related risk factor to the observed number of fatal pedestrian crashes that occurred in darkness in road environments with motorway characteristics. In 2004, there were 853 fatal pedestrian crashes in darkness on interstates, arterials, or collectors with median strips and posted speed limits of 45 mph or greater (see Table 5 for a breakdown). If this number is actually 10 times as great as it would be with more light, it suggests that improved lighting could reduce fatal crashes to about 85 a year, eliminating 768 crashes.

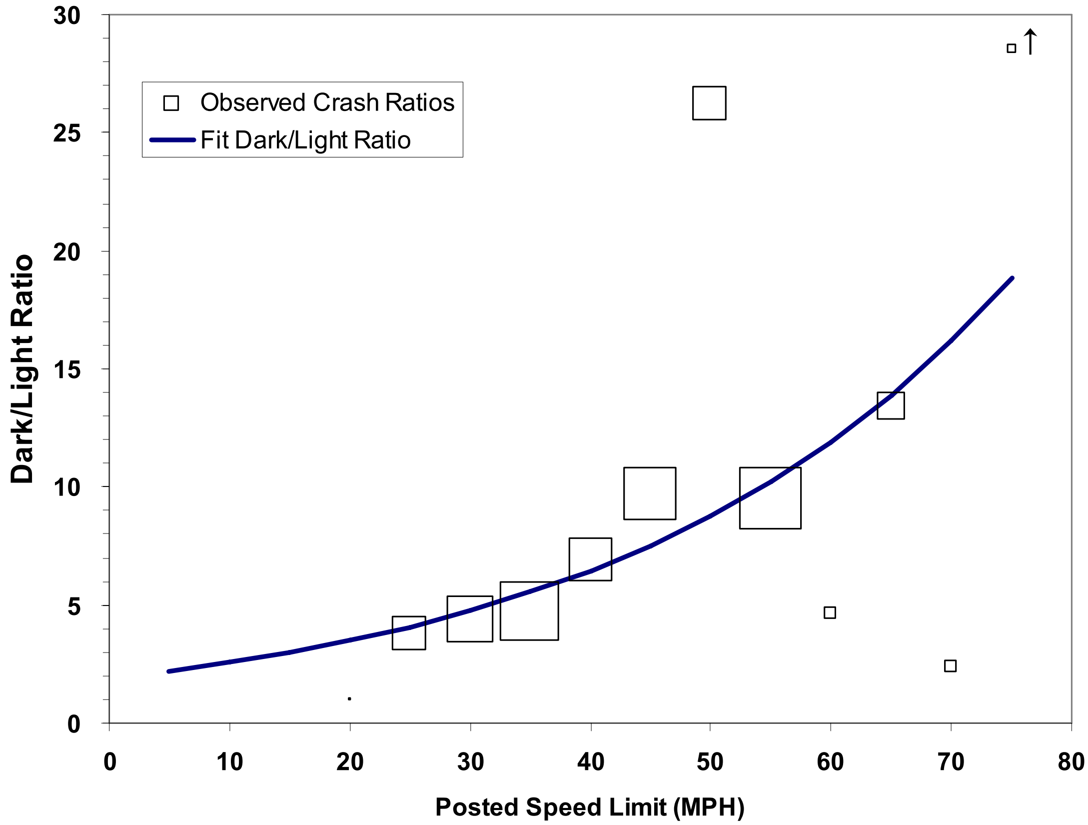

Figure 5. Relationship between posted speed limit and dark/light crash ratios for fatal adult pedestrian crashes. The open squares show the observed ratios from the FARS DST dataset. The fit is weighted by number of observations, indicated by the areas of the open squares. At 75 mph, all of eight observations occurred in the dark, producing an infinite dark/light ratio indicated by the arrow.

Table 5
The total number of fatal pedestrian crashes on roadways with median strips and posted speed limits of 45 mph or greater (FARS, 2004).

Road Function	Dark and Dark w Lights	Dawn/Dusk	Light	Total
Interstate or Freeway	382	16	88	486
Arterial	444	12	81	537
Collector	27	2	3	32
Total	853	30	172	1055

Nonfatal Crashes. A similar analysis was applied to the NCDOT daylight saving time crash data, although road types, locale, and road configuration (trafficway) are not classified the same way as in FARS. For example, NCDOT distinguishes three strata of locale: rural, mixed, and urban; NCDOT does not distinguish road functions (e.g., arterials versus collectors) but records road class (e.g., state road versus interstate) instead. Nonetheless, there is sufficient similarity to permit some comparison. As was done with the FARS dataset, a logistic regression model was constructed to predict the probability of a crash in darkness from roadway alignment (straight or curved), posted speed limit, road configuration (divided or undivided), number of lanes (1, 2, 3-4, 5-6, and more than 6), road class (interstate, US or state route, secondary road, local street, private road, and other), and locale (rural, mixed, and urban).

The results of this analysis found that crash risk in darkness is predicted by road class (χ^2= 18.5, df = 5, p = .0023). No other factors added to the predictive power of the model. Unlike the analysis of the FARS dataset, posted speed limit did not substantially contribute to the prediction of risk in darkness, although if road class is removed from the analysis, posted speed limit becomes the reliable predictor. These results suggest that ambient light level more strongly affects pedestrian safety on higher class roads, which are also in fact higher speed roads. On US and state routes there are about 9 times as many crashes in the dark as in the light; on interstates the ratio is about 5 times (based on 6 cases; see Figure 6). To draw a comparison with the curve lighting results, a "motorway" selection of pedestrian crashes was made from the NCDOT 1999 dataset. This motorway selection included crashes in the dark, on divided roadways, where the posted speed limit was 45 mph or greater, and the road class was an interstate, state road, or US road (the selected counts are shown in bold in Table 6), for a total of 64 crashes. Assuming that the dark/light motorway risk is about 9, the potential crash reduction with improved lighting would be about 57 crashes.

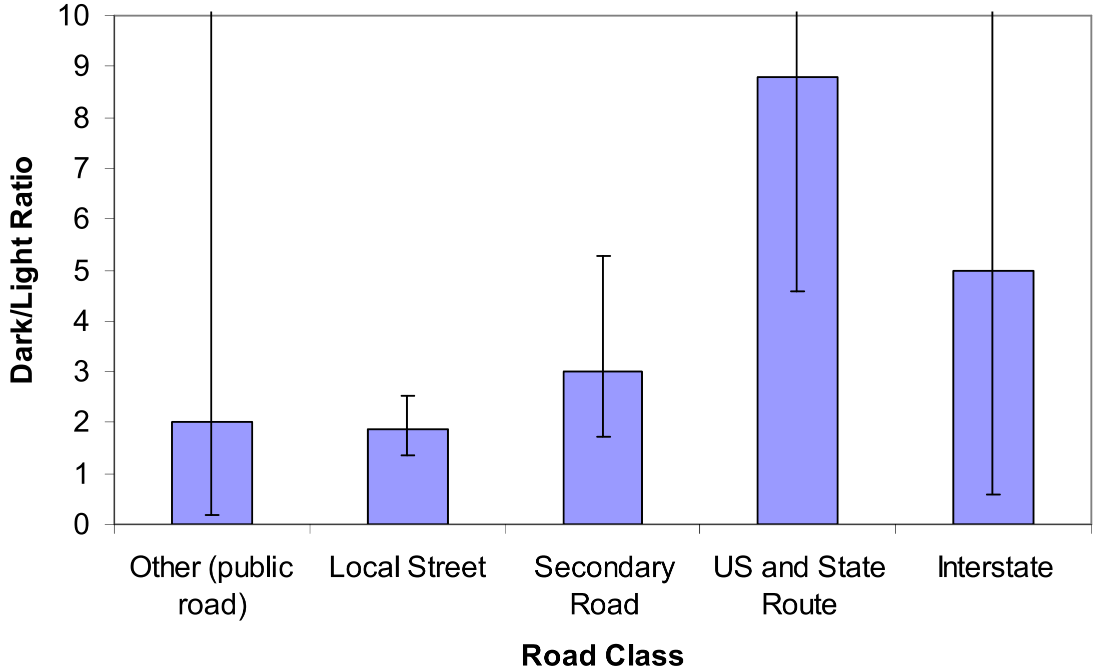

Figure 6. Dark/light ratio for fatal and nonfatal crashes involving adult pedestrians using the NCDOT DST dataset. The error bars depict the 95% confidence interval for each ratio. There is a significant difference between the dark/light ratio found on local streets and US and state routes.

Table 6
Fatal and nonfatal pedestrian crashes involving posted speed limits above 45 mph on divided roadways, by road function and light conditions using the NCDOT 1999 crash dataset. The numbers in bold were used to determine annual potential crash reduction for improved motorway lighting.

Road Function	Dark and Dark w/ Lights	Dawn/Dusk	Light	Total
Interstate	**17**	2	9	28
US and State Routes	**47**	1	13	61
Secondary Roads	4	0	3	7
Local Street	21	4	25	50
Other (Public Road)	1	0	0	1
Total	90	7	40	147

Extrapolation to the US population could not be done directly because the GES dataset does not distinguish roadway function class. To do the extrapolation, selection was based on road configuration and posted speed limit. For this analysis, a motorway environment was defined as a divided roadway with a posted speed limit of 45 mph or greater. A separate dark/light ratio for pedestrian collisions in this road environment was computed from the NCDOT daylight saving time crash data. For this definition, there were 50 cases in darkness and 14 cases in the light—resulting in a ratio of 3.57, placing it between secondary roads and interstates in risk level. As in the case of curve lighting, the FARS and GES datasets were used to obtain a US estimate of the number of fatal and non-fatal crashes for 1999. The total was 1,866 crashes in darkness. If this crash total is 3.57 times the daylight total, then the estimated potential reduction could be as much as 1,344 crashes (1,866 – 1,866/3.57).

Cornering Lighting

Fatal Crashes. Cornering lighting is designed to illuminate roadway areas in the direction of sharp, low-speed turns (signaled by a turn indicator) before the vehicle substantially executes the turn. This allows the driver a greater preview of the turn area, potentially illuminating pedestrians in crosswalks. In the following analysis, we examine the relative risk in darkness of fatal pedestrian crashes involving turning vehicles at intersections. Fatal adult pedestrian crashes were selected that involved single vehicles executing a left or right turn, with pedestrians located in and around intersections. To obtain more cases, both adult and elderly pedestrians were selected for the fatal crash analysis. A logistic regression modeled the probability of the crash occurring in darkness as a function of whether the involved pedestrian was at an intersection, and whether it involved a turning vehicle maneuver. This allows us to compare crash risk in darkness across four combinations of events: turning and non-turning vehicle maneuvers, and pedestrian locations at intersections and non-intersections.

This analysis found a main effect of pedestrian location ($\chi^2 = 3.9$, $df = 1$, $p < .05$) and vehicle maneuver ($\chi^2 = 7.0$, $df = 1$, $p < .01$). Crash risk in darkness was found to be lower for turning vehicles than for nonturning vehicles, and lower for pedestrians at intersections than nonintersections. Speed differences in vehicle maneuvers and road lighting near intersections may account for these reductions in risk. Turning vehicles move at lower speeds than nonturning vehicles and, because of the reduced speed, risk in darkness may be lower than for nonturning vehicles; and road lighting may be more common at intersections, thus reducing the effect of darkness at intersections relative to nonintersection parts of roadways. Based on the logistic regression, the estimated dark/light ratio for fatal pedestrian crashes involving turning vehicles at intersections is about 2.9 (see Figure 7). Table 7 shows the total counts from 2004 for fatal pedestrian collisions involving single vehicles by vehicle maneuver and pedestrian location for different lighting conditions. The most relevant cell for cornering lamps in this breakdown is turning maneuvers at intersections in the dark or dark with lights (a count of 36).

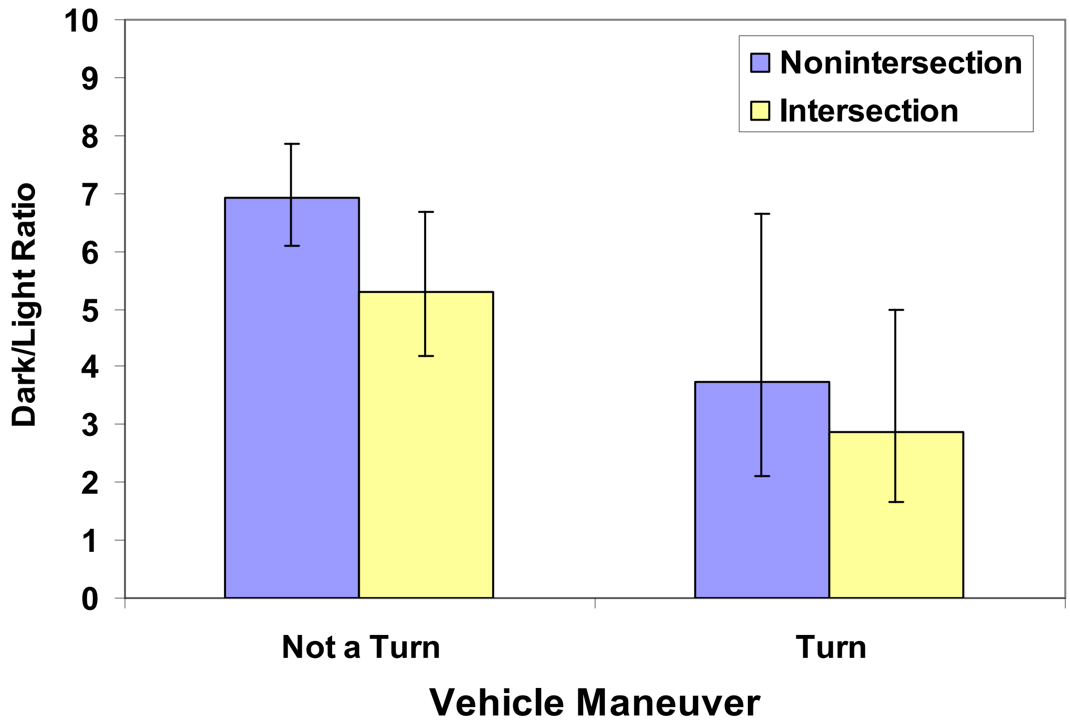

Figure 7. Dark/light ratio for fatal pedestrian crashes by pedestrian location and vehicle maneuver from the FARS DST dataset. The error bars depict the 95% confidence interval for each ratio. There is a main effect of pedestrian location (intersection/nonintersection) and vehicle maneuver (turning/nonturning).

Table 7
Breakdown of single-vehicle fatal pedestrian crashes by light condition, pedestrian location, and vehicle maneuver for FARS 2004. There were 36 fatal collisions involving turning vehicles around intersections.

Non-Motorist Location	Vehicle Maneuver	Dark and Dark w/ Lights	Dawn/Dusk	Light	Total
Non-Intersection	Not a Turn	2204	104	761	3069
	Turn	21	0	44	65
Intersection	Not a Turn	453	25	214	692
	Turn	**36**	6	130	172
Total		2714	135	1149	3998

Nonfatal Crashes. A logistic regression was performed on the NCDOT DST dataset, examining adult pedestrian crashes and the effect of pedestrian location and vehicle maneuver on crash risk in darkness. Unlike the fatal crash analysis, no effect of pedestrian location or vehicle maneuver was observed. The distribution of crashes is shown in Figure 8. This lack of effect can be attributed to the relatively small number of observations for crashes involving turning vehicles (14 cases for nonintersection; 10 cases for intersection crashes) as well as for intersection, nonturning vehicles (36 cases). Table 8 shows the total number of single-vehicle/pedestrian crashes in the NCDOT 1999 dataset, grouped by light level, vehicle maneuver, and pedestrian location. The most relevant scenario for cornering light includes pedestrian crashes in darkness involving turning maneuvers at intersections. There are only 19 cases in the NCDOT database that fit this scenario. Using the observed dark/light ratio for turning maneuvers at intersections from the NCDOT DST analysis (1.43), we can compute the potential annual reduction for comparison with other AFS measures—about 6 pedestrian crashes annually (19-19/1.43).

Extrapolation to the US population was done by applying the observed dark/light ratio in the NCDOT DST dataset to crash estimates for the same scenario derived from the FARS and GES 1999 datasets. With GES, we obtained an estimate of the number of nonfatal pedestrian crashes in darkness around an intersection involving a turning vehicle (Pedestrian/Bike Accident type: Vehicle Turn/Merge); in FARS, a similar estimate was made using vehicle maneuver and pedestrian location information. Using the 1.43 risk ratio for darkness versus light, the estimated potential reduction in fatal and nonfatal crashes could be as many as 1059 annually (3,522 – (3,522/1.43)).

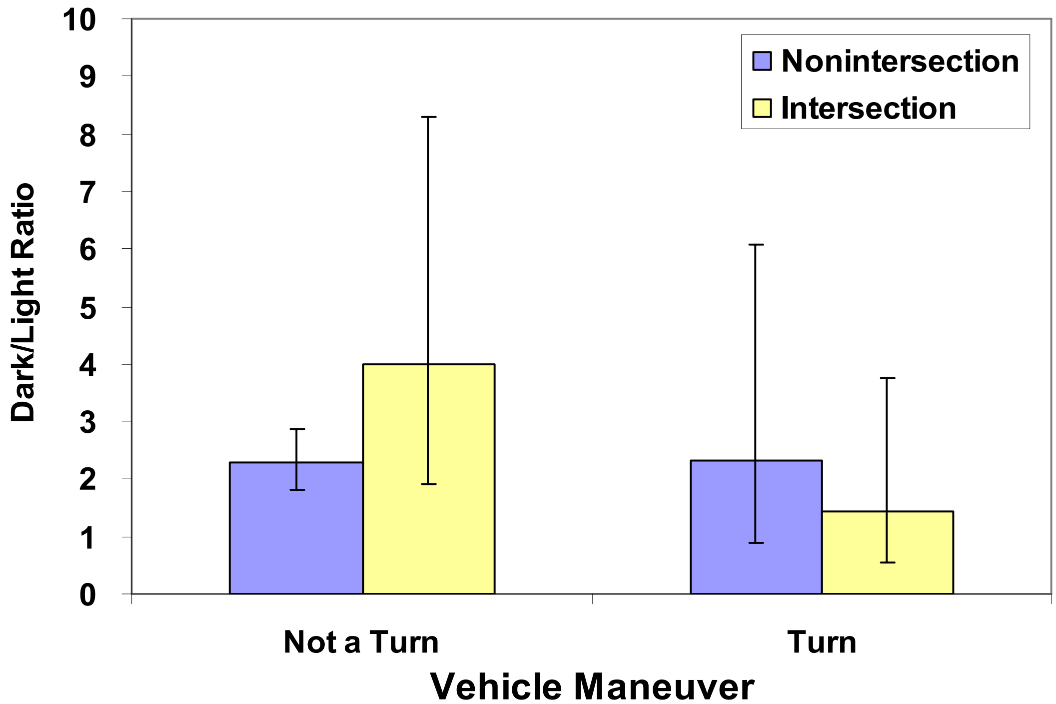

Figure 8. Observed dark/light ratio for fatal pedestrian crashes by pedestrian location and vehicle maneuver from the NCDOT DST dataset. Error bars show the 95% confidence interval for each ratio. No significant effects were observed for location or maneuver.

Table 8
Breakdown of single-vehicle pedestrian crashes by light condition, pedestrian location, and vehicle maneuver for NCDOT 1999. There were 19 fatal collisions involving turning vehicles at intersections.

Non-Motorist Location	Vehicle Maneuver	Dark and Dark w/ Lights	Dawn/Dusk	Light	Total
Non-Intersection	Not a Turn	546	54	813	1413
	Turn	19	5	71	95
Intersection	Not a Turn	41	7	81	129
	Turn	**19**	3	68	90
Total		625	69	1033	1727

Conclusions

Several conclusions can be drawn from this analysis concerning the safety potential of adaptive headlighting. Foremost is that there are potential crash reductions in all of the scenarios relevant to the three forms of adaptive headlighting considered. This is illustrated in Table 9, which summarizes the annual fatal crash reduction estimates based on the preceding FARS datasets, and the fatal/nonfatal crash reductions based on the NCDOT datasets and extrapolated to the US population. Each number is based on the dark/light risk estimated from the DST crash compilations for FARS (1987-2004) and NCDOT (1991-1999), and on the base annual rates of crashes in darkness from the FARS 2004 general dataset and the FARS and GES 1999 datasets. Because there is a relatively small overlap between the two crash datasets—only 8% of the pedestrian crashes in NCDOT were fatal—the analyses are partly independent of each other.

While all three scenarios suggested a potential for safety improvement, scenarios related to the motorway environment showed the largest potential. However, as we noted in the Introduction, it is important to keep in mind that these are estimates of the improvements that could be realized from forms of adaptive lighting that would perfectly address the visibility needs in each scenario. The actual safety benefits from various forms of adaptive lighting can be expected to depend on both the relevant safety needs, for which this report provides estimates, and the less-than-perfect effectiveness with which various forms of adaptive lighting can be implemented. For example, if currently practical forms of motorway lighting are further from the ideal than currently practical forms of curve lighting, then curve lighting might achieve better safety benefits in actual practice than motorway lighting, in spite of the fact that the situations nominally addressed by motorway lighting represent a greater safety need. The best practical approach to adaptive headlighting should be determined by considering both the safety needs that exist in current traffic and the effectiveness of the kinds of adaptive lighting that can currently be achieved.

Table 9
Estimated maximum potential annual pedestrian crash reductions for three scenarios associated with different types of adaptive headlighting.

Scenario (Associated Form of Adaptive Headlighting)	Annual Potential Fatal Crash Reduction (US)	Annual Potential Fatal/Nonfatal Crash Reduction (US, extrapolated from GES and FARS)
Curved Roadways (Curve Lighting)	128	280
High Speed Roadways with Medians (Motorway Lighting)	768	1,344
Pedestrians at Intersections Turning Vehicles (Cornering Lighting)	24	1,059

We note that this analysis is also suggestive of the prominent role speed plays in contributing to crash risk in darkness. For example, curved roadways may have a lower dark/light risk ratio because they induce drivers to slow down. Similarly, the dark/light risk ratio may be low for turning maneuvers at intersections because turns are executed at lower speeds than traveling straight. It may be generally true that roadway features that induce lower travel speed will be associated with a lower dark/light risk ratio.

Finally, we note that removing children from the pedestrian crashes in the daylight saving time analysis probably provides a better estimate of the effect of darkness on pedestrian risk. The resulting estimate of the dark/light risk ratio is much greater than our earlier estimate of about four to one (Sullivan & Flannagan, 2001). It now appears that, for equal exposure, the risk of a pedestrian fatal crash in darkness is on average almost seven times greater than in daylight.

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