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CHARACTERISTICS OF PEDESTRIAN RISK IN DARKNESS

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16. Abstract

In a previous report (UMTRI-99-21), data analysis using the Daylight Saving Time (DST) changeover and the Fatality Analysis Reporting System (FARS) showed that the added safety risk in darkness versus light is much higher for pedestrians than any other road users. This report extends those analyses to determine the specific magnitude of darkness effects for all harmful events, and focuses on how pedestrian risk is affected by features of the roadway environment. The new results show that pedestrian risk in darkness is related to posted speed limits and is particularly high on high-speed, limited-access roadways, where the combination of speed and limited sight distance may multiply pedestrian risk. Use of alcohol by pedestrians appears to strongly magnify the effect of darkness on the risk of being killed. No similar effect of alcohol was found among the drivers involved in the same crashes. Given the apparent effect of speed on pedestrian risk, there may be substantial safety benefits of innovative headlighting systems that could adjust to the greater visibility needs of higher speeds.

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INTRODUCTION

This report examines the increased safety risk to pedestrians in darkness by analyzing the distribution of fatal crashes across the annual Daylight Saving Time (DST) transitions, a technique described in a previous report (Sullivan & Flannagan, 1999). In brief, the technique examines the change in the distribution of fatal crashes during periods just before and just after DST changeovers at times of day that transition from darkness to daylight and vice versa. In comparing crash data from a one-hour clock window across the DST transition, we assume that levels of many factors known to play a role in fatal crashes remain relatively constant, leaving ambient light level as a quasi-independent variable. Thus, for example, in the Detroit area the one-hour period between 19:30 h and 20:30 h is entirely dark before the spring changeover to DST, and entirely light afterwards. Our key assumption is that traffic conditions are the same in the weeks immediately before and after the changeover to DST, as traffic is principally governed by clock time rather than by the position of the sun in the sky. Observed differences in crash levels between these two periods are likely related to the difference in ambient light level, and therefore can be used to quantify the effect of light in fatal crashes.

In this report, we examined different types of pedestrian crashes to discover which characteristics of those crashes produced increased risk. In particular, we looked at roadway function and posted speed limit, because we expected that in high-speed environments, the risk to pedestrians in darkness may be especially high. In darkness, the driver's forward view is constrained by the reach of the vehicle's headlamps. Because this distance is the same regardless of vehicle speed, the faster the vehicle is moving, the smaller the time interval between detecting an object in the vehicle's path and potentially colliding with that object. With progressively smaller amounts of time to react, we should expect to see more failure to avoid pedestrians.

The risk analysis was then coupled with annual counts of fatalities in darkness using the same crash types to identify the overall magnitude of the problem. This magnitude was used to make projections of the potential number of lives saved if darkness could be turned into daylight. By combining the risk estimate and the annual fatality level, we can obtain some guidance about where light is most needed on the roadway. In addition, we extended the analysis of the relationship between darkness and alcohol that was begun by Owens and Sivak (1993). In that report, they examined alcohol use by drivers and found that it did not seem to contribute to fatal pedestrian crashes. In this study we investigated the consequences of alcohol use by pedestrians as well as drivers.

METHOD

Crash data from the Fatality Analysis Reporting System (FARS) of the National Highway Traffic Safety Administration (NHTSA) were selected from the 11-year period from 1987 to 1997. Cases selected for analysis straddled the daylight saving time changeover periods in time windows that abruptly changed from dark to light (or light to dark) across the time change.

To explain this selection method, we first note that twice a year, in most of the United States, clocks are reset: In the spring, clocks are adjusted one hour ahead, making sunrise and sunset one hour later than in standard time. In the fall, clocks are adjusted back to standard time, effectively making sunrise and sunset earlier. To perform the DST analysis, the exact start and end of civil twilight was computed for the dates of the spring and fall adjustments for DST. The start and end of civil twilight are the points at which the sun is 6 degrees below the horizon in the morning and evening, respectively. The ambient light at this time is generally insufficient to read by, but the sky is light enough to distinguish the horizon. For our purposes, we considered the hour before the start of civil twilight (in the morning) and the hour after the end of civil twilight (in the evening) as dark. The computation was done for each of the 11 years (1987-1997) covered in this analysis and for each county in the United States, excluding those in Arizona, Hawaii, and Puerto Rico because they do not observe DST. Indiana was excluded from the analysis because 77 of its 95 counties do not observe DST. Finally, Alaska was excluded because at its extreme northern latitudes the solar cycle substantially deviates from that found in the lower 48 states.

Once each county's times for the start and end of civil twilight were determined (in standard time), crash-record clock times were tagged to indicate if the crash occurred in the one-hour interval just after the end of civil twilight, in the evening. As shown in Figure 1, in the spring, this interval is dark before DST and light (or twilight) after the DST changeover. In the fall, the interval is light before the DST changeover, and dark following it. For the present analysis, crashes were taken from three weeks before and three weeks after the transitions in both the spring and fall, and tagged as falling into either a *light* or a *dark* period. Although transitions also occur in the morning time periods (see Figure 1), they are not included in this analysis because the three-week time window before and after DST transitions is neither uniformly dark nor uniformly light throughout the period. As illustrated in Figure 1, during the three-week period before the spring transition in the morning, light levels are nearly dark at the beginning and lighten as the DST transition is approached. After the transition, the light level changes from dark to light. Inclusion of these morning crash data over the three weeks before and after the DST transition would reduce the light level difference between the dark/light conditions. It should also be noted that the time period before the end of formally defined civil twilight actually contains about 30 minutes of what might informally be described as twilight, and 30 minutes of daylight, for the latitudes considered here. Thus, for this manipulation, the nominally light condition is actually somewhat darker than conventional daylight, especially near the day of the changeover.

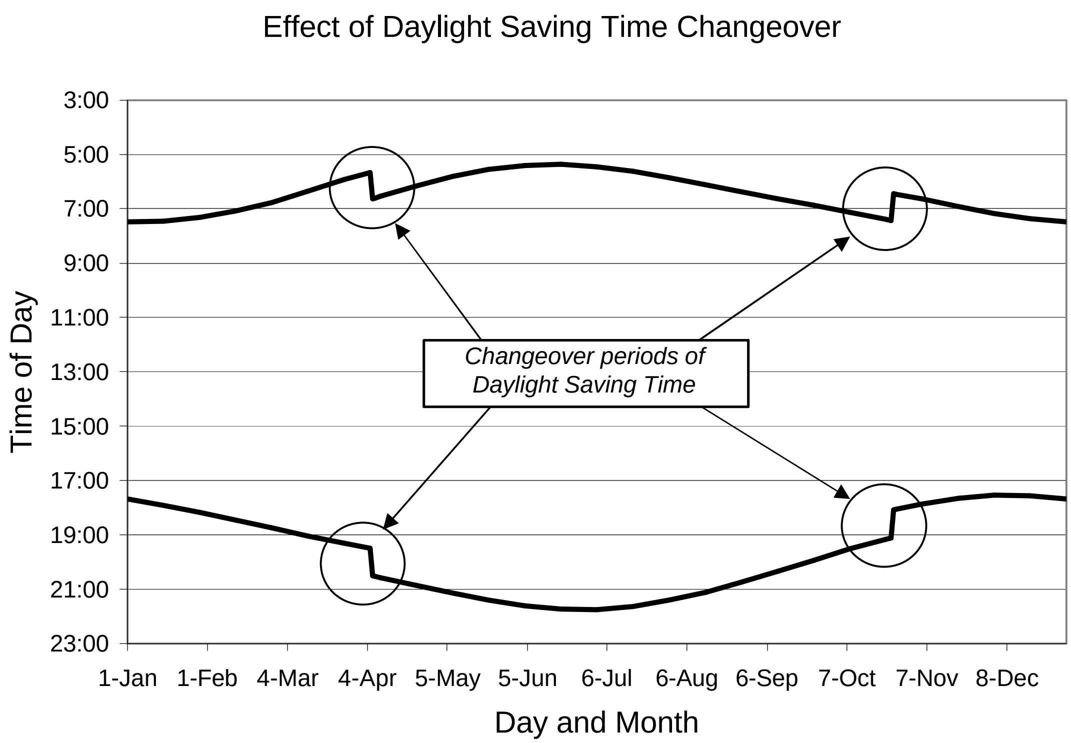

Figure 1. Daylight saving time changeover characteristics for spring and fall. The solid line is the clock time of the start (top) and end (bottom) of civil twilight throughout the year for the Ann Arbor/Detroit area (1997).

To establish confidence intervals on the magnitude of the distribution, the following logic was applied. A given crash record within the six-week time windows straddling each DST changeover period can either fall within a dark period or a light period, much like a coin toss might produce either a heads or tails outcome. If there was no difference between crash incidence during the dark and light periods, a given crash would have an even chance of falling within a dark or light period. That is, the ratio of dark to light crashes should be 1; approximately 50% of the crashes should occur in the dark and 50% should occur in the light. (The test is similar to testing whether a coin is biased by tallying the number of heads and tails after a series of tosses.) A confidence interval on the observed proportion of crashes can be established by estimating the standard error of the mean:

$$s_M = \sqrt{\frac{PQ}{N-1}}$$

where: *P* is the observed proportion of crashes in darkness,
Q is *(1-P)*, and
N is the number of cases.

The 95% confidence interval on the observed proportion is given by:

$$P - 1.96 s_M \leq p \leq P + 1.96 s_M$$

where: *p* is the true population proportion and
1.96 standard errors is the 95% confidence limit on *p*.

RESULTS

Harmful events and the magnitude of effect of darkness

In FARS, all crashes are categorized by their first harmful event—the first damage-producing event in a motor vehicle crash that may involve many more harmful events. The first harmful event is considered at least temporally proximate to the cause of the fatal crash and likely related to the root cause of the crash. This first analysis examined all harmful events for effects of darkness to establish a more complete context in which to view pedestrian vulnerability in darkness. In our previous report (Sullivan & Flannagan, 1999), the safety risk to pedestrians was estimated to be between four and seven times greater in darkness than in light. We compared this with single vehicle road departures, which showed little or nor effect of darkness. By examining all harmful events, we obtain a broader picture of the possible mechanisms underlying the role of light in fatal crashes. This risk profile was supplemented by crash frequencies for the same types of crashes in darkness for 1999 so that the magnitude of potential benefit of reducing the risk associated with darkness could be determined. This projection assumes an admittedly simple model of how light influences crashes. It generalizes the dark effects found during the DST transition period throughout the night and throughout the year without consideration of how other factors might interact with darkness. Nevertheless, it provides a coarse gauge of the potential safety improvement that might be realized with improved lighting.

FARS classifies each fatal motor vehicle crash into one of 48 categories, based on the first circumstance that resulted in a harmful outcome. The FARS harmful event categories vary in precision. As shown in Table 1, harmful event categories distinguish between several types of single-vehicle crashes (e.g., overturns, collisions with trees, guardrails, embankments), while grouping most crashes involving other vehicles into the category *motor vehicle in transport*. Crash circumstances in this latter category are typically further resolved using additional coding fields associated with the harmful event. For example, the field Manner of Collision elaborates the form of a two-vehicle collision into rear-end, head-on, rear-to-rear, sideswipes, etc. As shown in the fatality counts in Table 1, the highest number of annual fatalities occurs as collisions with another *motor vehicle in transport* (42%) followed by collisions with *pedestrians* (11%) and vehicle *overturn* (10%). Table 1 also identifies the number of these fatalities that occurred during darkness. These numbers alone, however, are insufficient to determine the relative risk in darkness because differences in exposure can account for some of this variation. For example, vehicle miles traveled in the daytime are about four times those traveled at night (NPTS, 1995). Based purely on exposure differences, we might expect to observe four times the number of fatalities during the daytime as at night. But, as Table 1 shows, there are only about 1.2 times as many fatalities in the daytime as at night, suggesting nighttime vehicle miles traveled are riskier than daytime miles. Table 1 serves to establish the general size and pattern of annual fatalities, but it does not provide a clear picture of how ambient light directly affects safety.

Table 1
1999 fatalities by first harmful event, sorted by frequency.

Harmful Events – (Collision with)	Total Fatalities	Percent of Total	Fatalities in Darkness	Percent in Darkness
Motor Vehicle in Transport	17,411	41.9%	5,436	31.2%
Pedestrian	4,668	11.2%	3,077	65.9%
Overturn	4,311	10.4%	1,993	46.2%
Tree	3,302	7.9%	1,842	55.8%
Guardrail	1,185	2.8%	616	52.0%
Utility Pole	1,070	2.6%	648	60.6%
Ditch	880	2.1%	486	55.2%
Pedalcycle	763	1.8%	258	33.8%
Curb	745	1.8%	298	40.0%
Motor Vehicle in Transport in Other Roadway	642	1.5%	396	61.7%
Culvert	601	1.4%	349	58.1%
Embankment – Earth	587	1.4%	316	53.8%
Embankment - Material Type Unknown	548	1.3%	291	53.1%
Fence	512	1.2%	308	60.2%
Other Fixed Object	508	1.2%	271	53.3%
Parked Motor Vehicle	479	1.2%	227	47.4%
Highway/Traffic Sign Post	401	1.0%	234	58.4%
Other Post, Other Pole, or Other Support	352	0.8%	190	54.0%
Railway Train	314	0.8%	92	29.3%
Concrete Traffic Barrier	280	0.7%	150	53.6%
Fell from Vehicle	231	0.6%	106	45.9%
Bridge Pier or Abutment	190	0.5%	107	56.3%
Animal	168	0.4%	90	53.6%
Other Object (not fixed)	152	0.4%	106	69.7%
Bridge Rail	145	0.3%	68	46.9%
Other Non-Collision	133	0.3%	63	47.4%
Luminary/Light Support	125	0.3%	82	65.6%
Embankment - Rock, Stone, or Concrete	114	0.3%	39	34.2%
Wall	111	0.3%	67	60.4%
Immersion	91	0.2%	51	56.0%
Other Type Non-Motorist	81	0.2%	42	51.9%
Boulder	76	0.2%	37	48.7%
Building	64	0.2%	19	29.7%
Bridge Parapet End	51	0.1%	24	47.1%
Overhead Sign Support	46	0.1%	16	34.8%
Fire Hydrant	39	0.1%	4	10.3%
Shrubbery	34	0.1%	12	35.3%
Transport Device Used as Equipment	32	0.1%	20	62.5%
Traffic Signal Support	27	0.1%	20	74.1%
Collision With Snow Bank	24	0.1%	15	62.5%
Unknown	21	0.1%	13	61.9%
Fire/Explosion	20	0.0%	10	50.0%
Injured in Vehicle	18	0.0%	3	16.7%
Thrown or Falling Object	13	0.0%	6	46.2%
Impact Attenuator/Crash Cushion	10	0.0%	5	50.0%
Other Longitudinal Barrier Type	9	0.0%	3	33.3%
Pavement Surface Irregularity	8	0.0%	0	0.0%
Vehicle Occupant Struck or Run Over by Own Vehicle	5	0.0%	1	20.0%
Total	41,597	100%	18,507	44.5%

To determine the increased safety risk in darkness, we looked at all fatalities occurring during the three-week periods before and after the two annual transitions to and from DST and standard time, during one-hour times of day that change from being dark (light) before the changeover to being light (dark) after the changeover. Grouping fatalities as occurring in either the dark interval or light interval, we calculated the dark/light ratio and 95% confidence intervals for these ratios. Ratios greater than 1 suggest a higher risk during darkness; ratios less than 1 suggest a higher risk during daylight. This means that given the observed ratio, there is a 5% chance that the actual ratio might fall outside the confidence interval. Confidence intervals that do not include the dark/light ratio of 1 suggest that there are reliable differences between the number of fatalities observed in darkness and daylight.

Table 2 lists harmful events by fatality frequency, identifying harmful events that exclude the 50% null hypothesis (dark/light ratio equal to 1) with 95% confidence. Figure 2 shows selected dark/light ratios and their 95% confidence intervals for harmful events that show a strong dark/light effect. Among the harmful events, collisions with animals seemingly show the largest dark/light effect (4.6 times the cases in the dark versus light), however it is unlikely that animal activity patterns follow clock time as is assumed in this comparison. The activity patterns of many animals increase after sunset. Consequently, both their increased numbers in darkness as well as low visibility likely contribute to the high dark/light fatality ratio. For them, the risk associated with ambient light level is ambiguous.

Collisions with pedestrians show the next largest dark/light effect: there are 4.1 times as many fatalities in darkness as in daylight. Here one might also argue that the activity pattern of pedestrians could be influenced by darkness—that is, a person might be less inclined to walk in darkness. (However, if this is true, then the size of the pedestrian risk is somewhat *underestimated* in this analysis.) The estimate here is comparable to other reported reductions in pedestrian fatalities with daylight saving time and in environments with fixed lighting (Ferguson, Preusser, Lund, Zador, & Ulmer, 1995; Tanner & Harris, 1956).

The dark/light ratio of collisions between motor vehicles in transport is also significantly greater than one (1.3 times higher in darkness). Note that the large number of these accidents allows more precision in estimating this ratio (the confidence interval is narrow). Although the ratio is smaller than estimates of pedestrian risk, the narrow confidence limits exclude a ratio of 1. That is, darkness seems to heighten risk in these crashes, but to a smaller extent. Dark effects were also found for collisions with parked motor vehicles and collisions with railway trains, suggesting low light levels play a role in these crashes as well.

Finally, we found that vehicle overturns appear to occur *more* frequently in daylight than in darkness (dark/light ratio = 0.7). The reason for this is unclear. Perhaps the better visibility of obstacles in the roadway prompts drivers to more frequently engage in avoidance maneuvers at high speed, resulting in overturns. At night, the same obstacles might otherwise be struck. In any case, the effect appears to be small.

Table 2
The number of fatalities that occurred during intervals of darkness and light three weeks before and after the DST changeover, sorted by frequency. Highlighted entries indicate significantly greater (dark shading) or less (light shading) than 50% of the crashes occurred in darkness. Data were compiled from evening DST transition periods three weeks before and after spring and fall changeovers, over an 11-year period (1987-1997).

Event	Dark	Light	Total	Dark/Light Ratio	% Crashes in Darkness
Motor Vehicle in Transport	1454	1091	2545	**1.33**	57.1%
Pedestrian	1147	277	1424	**4.14**	80.5%
Overturn	174	239	413	0.73	42.1%
Tree	168	170	338	0.99	49.7%
Pedalcycle	77	86	163	0.90	47.2%
Utility Pole	45	58	103	0.78	43.7%
Ditch	43	51	94	0.84	45.7%
Guardrail	46	44	90	1.05	51.1%
Motor Vehicle in Transport in Other Roadway	36	40	76	0.90	47.4%
Culvert	27	37	64	0.73	42.2%
Curb	25	34	59	0.74	42.4%
Embankment - Material Type Unknown	26	32	58	0.81	44.8%
Parked Motor Vehicle	38	18	56	**2.11**	67.9%
Other Fixed Object	30	25	55	1.20	54.5%
Railway Train	35	18	53	**1.94**	66.0%
Embankment – Earth	23	22	45	1.05	51.1%
Highway/Traffic Sign Post	19	22	41	0.86	46.3%
Fence	20	20	40	1.00	50.0%
Fell from Vehicle	14	20	34	0.70	41.2%
Other Post, Other Pole, or Other Support	13	18	31	0.72	41.9%
Concrete Traffic Barrier	16	14	30	1.14	53.3%
Animal	23	5	28	**4.60**	82.1%
Bridge Pier or Abutment	11	11	22	1.00	50.0%
Bridge Rail	9	11	20	0.82	45.0%
Wall	7	11	18	0.64	38.9%
Other Non-Collision	5	12	17	0.42	29.4%
Other Type Non-Motorist	8	7	15	1.14	53.3%
Embankment - Rock, Stone, or Concrete	6	7	13	0.86	46.2%
Other Object(not fixed)	5	6	11	0.83	45.5%
Boulder	5	4	9	1.25	55.6%
Building	3	4	7	0.75	42.9%
Bridge Parapet End	2	4	6	0.50	33.3%
Fire Hydrant	1	3	4	0.33	25.0%
Immersion	2	2	4	1.00	50.0%
Pavement Surface Irregularity (1993 only)	1	3	4	0.33	25.0%
Luminary/Light Support		3	3	-	-
Other Longitudinal Barrier Type		3	3	-	-
Shrubbery	1	2	3	-	-
Impact Attenuator/Crash Cushion	1	1	2	-	-
Thrown or Falling Object	2		2	-	-
Transport Device Used as Equipment (Since 1993)	2		2	-	-
Unknown		2	2	-	-
Injured in Vehicle		1	1	-	-
Grand Total	1454	1091	6008	1.46	59.4%

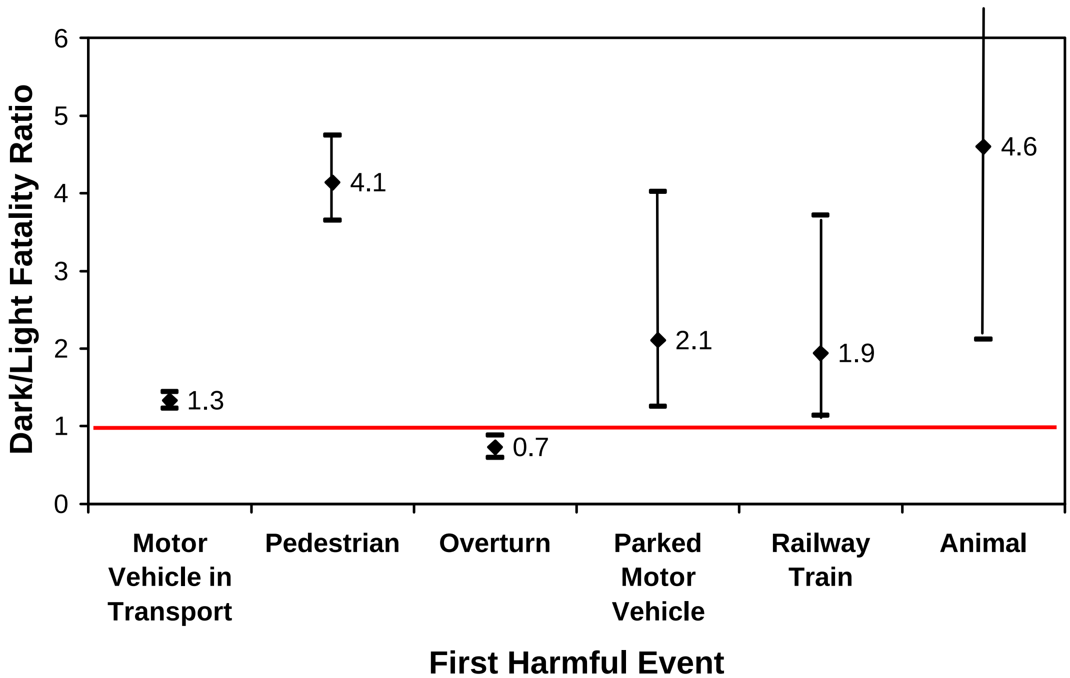

Figure 2. Dark/Light ratios of those *first harmful events* not equal to 1. The bracketing lines surrounding each point identify the 95% confidence interval around the ratio. The horizontal line indicates no difference between the daylight and night crash levels. Data were compiled from evening DST transition periods 3 weeks before and after spring and fall changeovers, over an 11-year period (1987-1997).

To estimate the magnitudes of potential safety improvements, we tallied the number of fatalities for 1999 that occurred in darkness (*dark* and *dark but lighted*) for the harmful event categories showing an effect of darkness. This was divided by the dark/light fatality ratio to estimate the number of comparable crashes during daylight, and then subtracted from the number of fatalities in darkness to provide an estimate of the potential number of lives saved. The results are shown in Table 3. If darkness were turned into daylight, pedestrians would show the greatest benefit, measured as the potential number of lives saved. Not only is the comparative risk of a pedestrian crash much higher in darkness than in daylight (by a factor of 4.14), but the annual number of pedestrian crashes in darkness is sufficiently large to suggest that lighting countermeasures targeted toward pedestrian visibility would save nearly twice as many lives as would be saved in collisions with other motor vehicles.

Table 3
Estimation of lives per year potentially saved by eliminating the safety hazard associated with darkness.

Harmful Event (Collision)	Dark/Light Ratio	Fatalities in Darkness (1999)	Lives Potentially Saved (Lost)
Motor Vehicle in Transport	1.33	5,436	1,357
Pedestrian	4.14	3,077	2,334
Overturn	0.73	1,993	(744)
Parked Motor Vehicle	2.11	227	119
Railway Train	1.94	92	45

Pedestrian collisions and speed

Using the above procedure, we next examined characteristics of the roadway environment in pedestrian collisions to see whether those characteristics affect the magnitude of the lighting effect. We might, for example, expect to find a strong lighting effect with vehicle speed. In darkness, a driver's seeing distance is limited by the reach of the headlamps; in daylight, although seeing distance might occasionally be limited by physical obstructions, no such general limit on seeing distance exists. Nighttime seeing distance is fixed by the reach of the headlamps regardless of vehicle speed. Estimates of low-beam seeing distance are approximately 50 m. Driver reaction time is typically estimated to be 1.5 seconds (Johansson & Rumar, 1968). On a dark roadway, with illumination exclusively supplied by low-beam headlamps, the stopping distance of a vehicle exceeds forward seeing distance at about 58 km/h (National Highway Traffic Safety Administration, 1996). Above this speed, the time to react becomes too short to successfully avoid an obstacle in the path of the vehicle. For example, at 110 km/h, before the brake is even applied, the vehicle would travel 46 m.

Given these estimates, high-speed roadways should be especially dangerous for pedestrians in the dark. Note that driver expectation might also play a role, such that recognition of a pedestrian in an unexpected place is delayed, increasing driver reaction time (e.g., Roper & Howard, 1938). Limited access roadways are usually free of pedestrians, so that the appearance of one would normally be quite unexpected, increasing a driver's reaction time to brake. Similarly, pedestrians are more common on urban than rural roadways, reducing likely reaction times. The additional *perception* time that is probably needed to react to pedestrians on limited access and other high speed roads, coupled with the shorter overall time available to take evasive action at high speeds, may multiply a pedestrian's risk on those roads.

Pedestrian fatalities before and after the DST changeover were first sorted by broad road function. For this analysis, we combined data into three categories based on road function: limited access roadways (*rural principal arterial-interstate, urban principal arterial-interstate, urban principal arterial-freeways or expressways*), arterials (*rural and urban principal and minor arterials*), and local and collectors (*rural, and urban collector and local streets*). The resulting dark/light ratios are given in Figure 3. Lifesaving potential was also estimated based on the annual pedestrian crash counts for each roadway function for 1999.

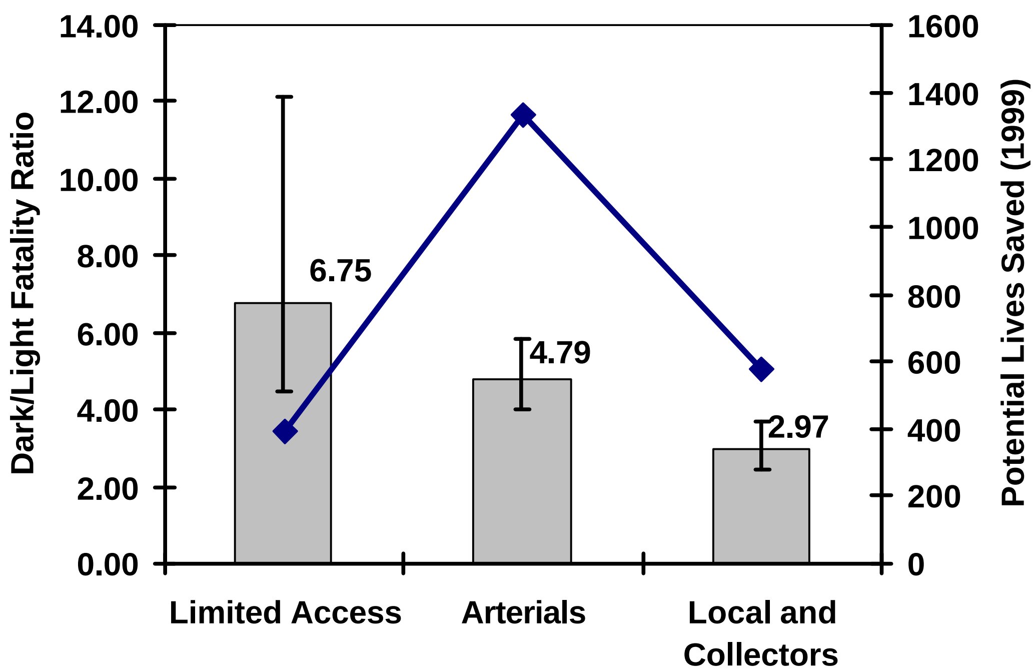

Figure 3. Ratio of pedestrian crash fatalities in the dark and light periods three weeks before and after DST changeovers, along with potential lives saved. Error bars are 95% confidence limits on the observed ratios.

Figure 3 shows that pedestrian risk is especially high, as expected, on dark limited-access roadways (6.75 times daylight risk). This is consistent with the earlier suggestion that higher vehicle speeds limit a driver's ability to successfully perform an avoidance maneuver within the preview time offered by headlamps. However, arterial roadways show the greatest potential for reducing pedestrian fatalities, probably because of higher pedestrian density around arterials, especially urban arterials. The risk associated with arterial speeds, coupled with the greater density of pedestrians, suggests that as many as 1,333 lives per year might potentially be saved with lighting countermeasures. Although vehicle speed is implicated in pedestrian nighttime risk, the potential benefit of better lighting is also related to the level of pedestrian exposure, which is small on limited access roadways.

Figure 4 details how pedestrian risk varies with detailed roadway function. The magnitude of the effect of darkness on pedestrian risk is consistent with probable roadway speed, both in rural and urban locales. High-speed rural roadways, which are most likely dark, show a more pronounced risk than high-speed urban roadways, which are most likely illuminated. The difference between urban and rural roadway risk is smaller on the low-speed roadways. Note that on each rural roadway type, pedestrian crashes predominantly occurred on dark (no street lighting) roadways—supplemental lighting was present in only 10 to 22% of the nighttime cases; on the urban roadways, supplemental lighting was available in 50 to 70% of the nighttime cases in darkness.

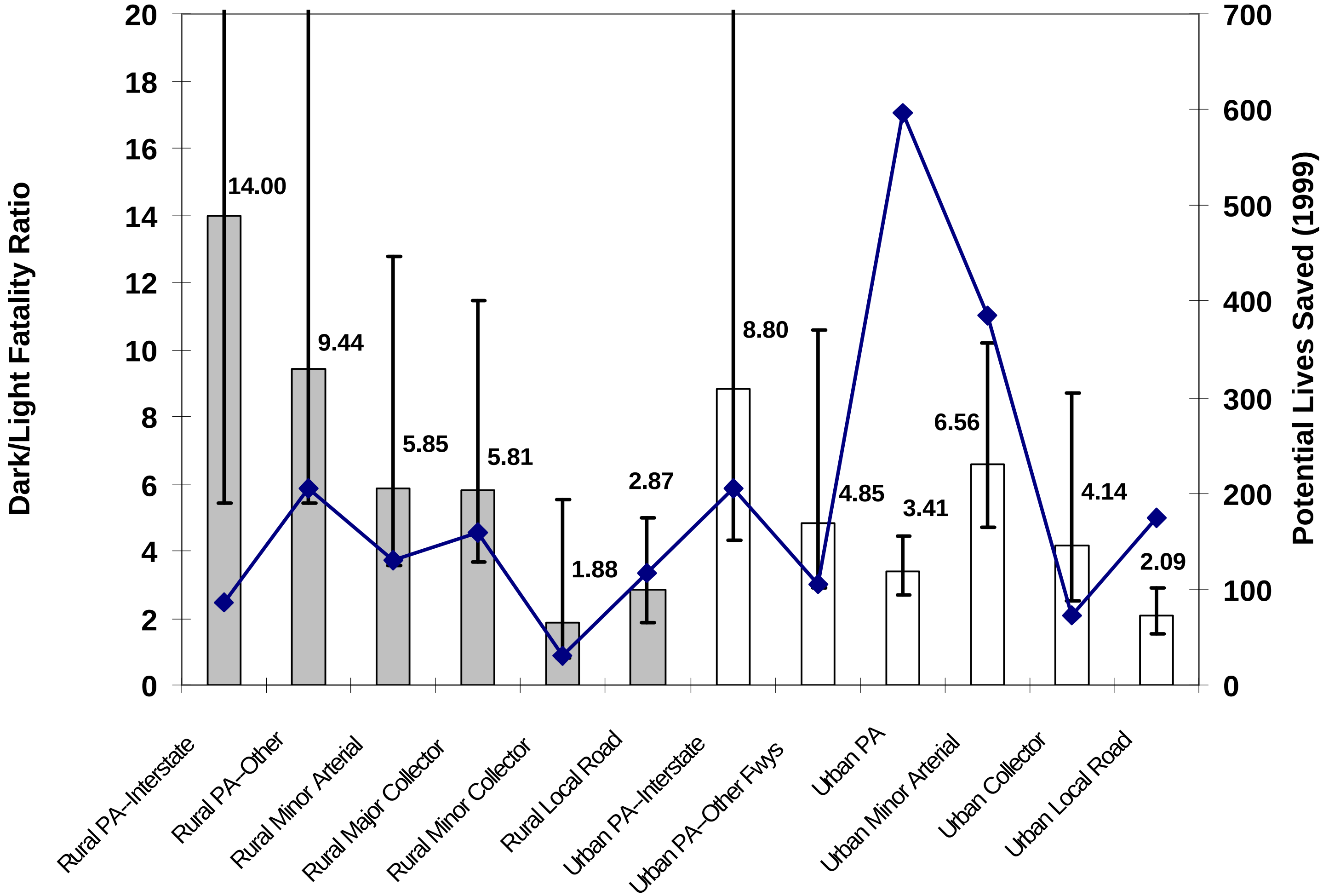

Figure 4. Dark/light fatality ratio and lifesaving potential of light by road function type. Dark bars indicate rural roadways; light bars are urban roadways. Error bars depict 95% confident intervals on the dark/light ratio. PA designates principal arterial.

An alternative way to demonstrate the influence of speed on pedestrian risk is to examine risk as a function of the posted speed limit. Although the posted speed limit does not necessarily correspond to actual vehicle speed at the time of the collision, it is reasonable to assume that they are closely related. Figure 5 shows that pedestrian risk increases with posted speed limit and perhaps reaches a maximum somewhere after 45 mph (72 km/h). Earlier, it was estimated that the speed at which braking distance (to a full stop) reached low-beam seeing distance is about 58 km/h (36 mph). At 45 mph, stopping distance is approximately 227 feet (69 m), 67 feet (20 m) past the estimated seeing distance of low-beam headlamps. The speed of the vehicle at the likely impact point (50 m from the location of the driver when the pedestrian is first detected) would be about 50 km/h, and higher with increasing speed. The speed of a vehicle's impact on a pedestrian does not appear to be strongly related to its deadliness (Harruff, Avery, & Alter-Pandya, 1998). That is, beyond some low speed, any contact with a pedestrian is equally likely to be lethal. Thus, we should expect that above some level of vehicle speed any mitigating action by the driver will be ineffective and pedestrian risk should asymptote. Consistent with this analysis, the data suggest that risk increases with vehicle speed, but asymptotes a little above 45 mph (73 km/h).

As an interesting aside, the urban and rural dark effects along local roadways appear to be similar despite the fact that overhead illumination is far less available in rural settings. This suggests that perhaps at low speed on local roads the illumination from low-beam headlamps is sufficient to reduce the additional advantage of lighting.

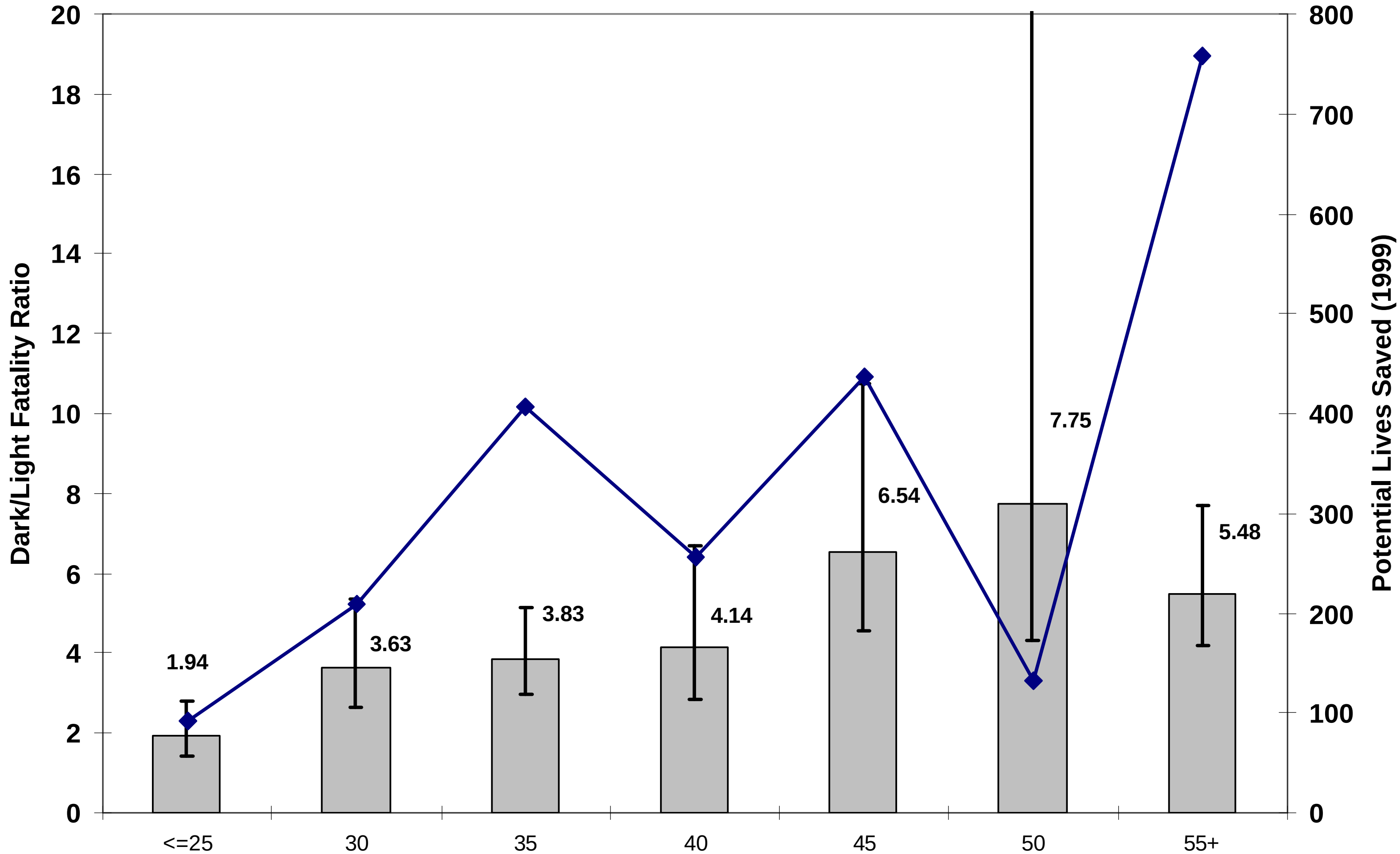

Figure 5. Dark/light fatality ratio and lifesaving potential of light by posted speed limit. Error bars depict 95% confident intervals on the dark/light ratio.

Pedestrian collisions and alcohol use

We next examined whether alcohol use by either drivers or pedestrians contributes to the fatality risk in darkness. To do this, we counted the pedestrians involved in each crash and tallied up those for which alcohol was and was not involved. (Note that the drinking status of over half (715) of the pedestrian victims was identified as either *unknown* or *not reported.*) A similar count was performed for drivers involved in the same crash data. In a previous report (Owens & Sivak, 1993), the driver's use of alcohol in pedestrian crashes was reported to show little correlation with seasonal twilight variation and was lower than the use of alcohol by drivers involved in other crash types. Given these previous results, we would expect a similar overall proportion of drinking drivers in this analysis, and no difference in the dark/light distribution of drinking drivers. The results are shown in Table 4.

Table 4
Pedestrian crashes during dark and light periods of DST changeover by pedestrian and driver drinking.

Person	Drinking	Dark	Light	Total	Ratio Dark/Light
Pedestrian	No	359	120	479	3.00
	Yes	204	22	229	9.27
Driver	No	1034	240	1274	4.30
	Yes	92	33	125	2.78

For pedestrians, drinking in combination with darkness appears to be exceptionally lethal. In our sample, 32% of the pedestrians were identified as drinking. This is similar to the annual data on pedestrian alcohol involvement (National Highway Traffic Safety Institute, 2000)—38% of pedestrians killed in fatal crashes were using alcohol. Of the drinking pedestrians, 9.27 times as many were killed in darkness as in the light (c^2 =22.4, $df = 1$, $p < 0.001$). By contrast, only 9% of the drivers in our sample were identified as drinking. This is a smaller percentage than the overall reported driver alcohol involvement in pedestrian crashes (20%), but comparable to the 11.9%, reported by Owens and Sivak (1993). Drinking by drivers during the same time periods does not appear to affect pedestrian risk in the same way. In fact, the risk appears to be lower, although the reasons for this are unclear (c^2 =4.14, $df = 1$, $p < 0.05$).

Initially we thought that the differences in the observed risk associated with drinking pedestrians might be somehow related to an exposure effect—that the incidence of drinking increased in darkness (independently of clock time). However the driver data suggest that, if such a phenomenon occurs, it does not extend to drivers. A more plausible account would be that drinking pedestrians engage in roadway behavior that interacts with darkness to multiply their risk. In daylight, erratic pedestrian behavior may be detected by drivers and either anticipated in a way that reduces or completely avoids the likelihood of a collision. In the dark, the erratic pedestrian behavior may be detected too late to successfully avoid a collision. Note that it appears that daylight affords either the driver or pedestrian with some ability to mitigate the level of risk. Thus perhaps even the danger created by unreasonable pedestrian behavior can be mitigated by improvements in a driver's ability to see. On the other hand, the intoxicated pedestrian may be a much poorer judge of traffic danger at night than in the daytime. The evidence only suggests that light and pedestrian drinking jointly affect the level of risk, leaving unresolved the relative contributions of driver and pedestrian behavior.

CONCLUSIONS

The risk of pedestrian deaths is substantially greater in darkness, and that difference appears to increase continuously with traffic speed. A likely mechanism for the effect of speed is that, because the visibility distance provided by low-beam headlamps is fixed, the preview time that drivers have to react to the presence of pedestrians becomes progressively shorter with higher speeds. This appears to be an important specific example of a general mismatch between conventional headlighting and realistic road conditions: although conventional headlamps provide only two states of lighting—high and low beams—road conditions vary continuously in many ways that affect lighting needs, including speed, traffic density, and lateral separation between opposing streams of traffic. Given the apparent effect of speed on pedestrian risk, there may be substantial safety benefits of innovative headlighting systems that could adjust to the greater visibility needs of higher speeds, such as various proposals for motorway lighting or midbeams (e.g., Perel, Olson, Sivak, & Medlin, 1983).

We also note that the increased risk due to darkness appears to be somewhat smaller on urban arterial roadways, where pedestrian density is greatest, than on limited access roads. Even so, the risk is more than three times as high as in daylight, and greater than that associated with lower-speed local urban roadways. Thus, the greatest lifesaving opportunity for lighting countermeasures appears to be in areas such as urban arterials, where both speed and pedestrian density are high.

Alcohol use by pedestrians appears to interact with ambient light level, greatly increasing the risk of fatality in darkness. This suggests that as erratic, unreasonable, or surprising an intoxicated pedestrian's roadway behavior might be to an approaching driver, ambient light level appears to lower this risk. It is unclear whether the driver, the pedestrian, or both are somehow responsible for the reduction in risk.

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