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16. Abstract

Previous studies have shown that increased risk in the dark is particularly strong for pedestrian crashes, suggesting that attempts to improve headlighting should emphasize possible effects on those crashes. The current project was designed to provide information about how details of pedestrian crashes may differ between daylight and darkness. All pedestrian crashes that occurred in daylight or dark conditions in Michigan during 2004 were analyzed in terms of the variables included in the State of Michigan crash database. Additional analysis of the narratives and diagrams in police accident reports was performed for a subset of 400 of those crashes—200 sampled from daylight and 200 sampled from darkness. Several differences were found that appear to be related to the characteristic asymmetry of low-beam headlamps, which provide more light on the right than the left. These results provide preliminary quantification of the how the photometric differences between the right and left sides of typical headlamps may affect pedestrian crash risk.

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Introduction

In prior research, darkness has been shown to increase a pedestrian's risk of fatality in a traffic accident by a factor of about seven (Sullivan & Flannagan, 2006). No other crash type is as strongly linked to light level as pedestrian crashes. With this in mind, there has been renewed interest in the vehicle lighting community to find ways to enhance distribution of low-beam headlighting to address the needs of pedestrians (e.g., Kosmatka, 2006; Rice, 2004). Specific concern is focused on the consequence of the bias of all low-beam headlamps to direct greater illumination toward the right side of the roadway and away from the left side, in order to reduce glare to oncoming drivers. While it is anticipated that such a bias influences pedestrian crashes, there has been little published data describing such effects (but see Kosmatka, 2003).

In this report, we examine whether specific characteristics of the light distribution afforded by conventional low beam headlamps are also reflected in the geometric characteristics of the crash incidents. Because conventional crash databases are often limited in the amount of detail about a crash they support, the present analysis collected additional information from copies of the original police reports. We were primarily interested in determining whether additional information could be retrieved from the crash diagrams and narratives that would allow a more complete determination of crash configuration.

The light distribution provided by conventional low-beam headlamps is a compromise between providing sufficient seeing light for the vehicle's driver, while avoiding glare to drivers of oncoming vehicles. This has resulted in a general bias in the distribution of light downward and to the right side of the roadway. One might therefore expect that pedestrians would become less visible on the driver's side of a vehicle compared to the passenger side of the vehicle. When two vehicles are actually meeting, it is reasonable to expect that they will both be using low-beam headlamps. Thus, pedestrians on the driver's side, from the perspective of one of the vehicles, will be less strongly illuminated by that vehicle's headlamps and may also be affected by glare from the lamps of the other vehicle. However, even in nonmeeting situations, it is likely that low-beam headlamps will be used, since most drivers seldom use high-beam headlamps (Mefford, Flannagan, & Bogard, 2006; Sullivan, Adachi, Mefford, & Flannagan, 2003).

The approach taken in this report is to examine the location and direction of travel of a pedestrian relative to an approaching vehicle just prior to a crash. Unlike previously reported dark/light comparisons in which there was a strategy to control variables such as driver fatigue, alcohol involvement, and demographics using daylight saving time analyses (Sullivan & Flannagan, 2001), the analyses described in this report are not subject to the same confounds. Here we are assessing the differences in risk that are associated with direction of pedestrian approach toward an (eventually) striking vehicle in darkness compared to light. If a pedestrian's direction of travel prior to a collision is independent of time of day, fatigue level, demographics, or alcohol use then light/dark differences in the ratios of a driver-side versus passenger-side approach might be attributed to an effect of light distribution. In the case of low-beam headlamps, in which illumination is biased toward the passenger side, we might expect to find a shift in the distribution of pedestrian collisions to the driver side of the vehicle in darkness when compared to the distribution in daylight.

This is not to suggest that a particular direction of approach is more risky than another in darkness or light. Merely that the *distribution* of pedestrian crashes between a driver-side and pedestrian-side approach is likely to be shifted toward the driver side when it is dark. We may find that in *both* daylight and darkness, passenger-side crashes predominate because of the relatively close proximity of a pedestrian entering a roadway to the passenger-side of an approaching vehicle. Such close proximity allows the approaching driver little time to make an evasive maneuver. On the other hand, upon entering the roadway from the left (or driver side), a pedestrian is usually at least one full lane width from the path of the approaching vehicle. This additional safety margin may often be sufficient for the approaching driver to successfully avoid a collision.

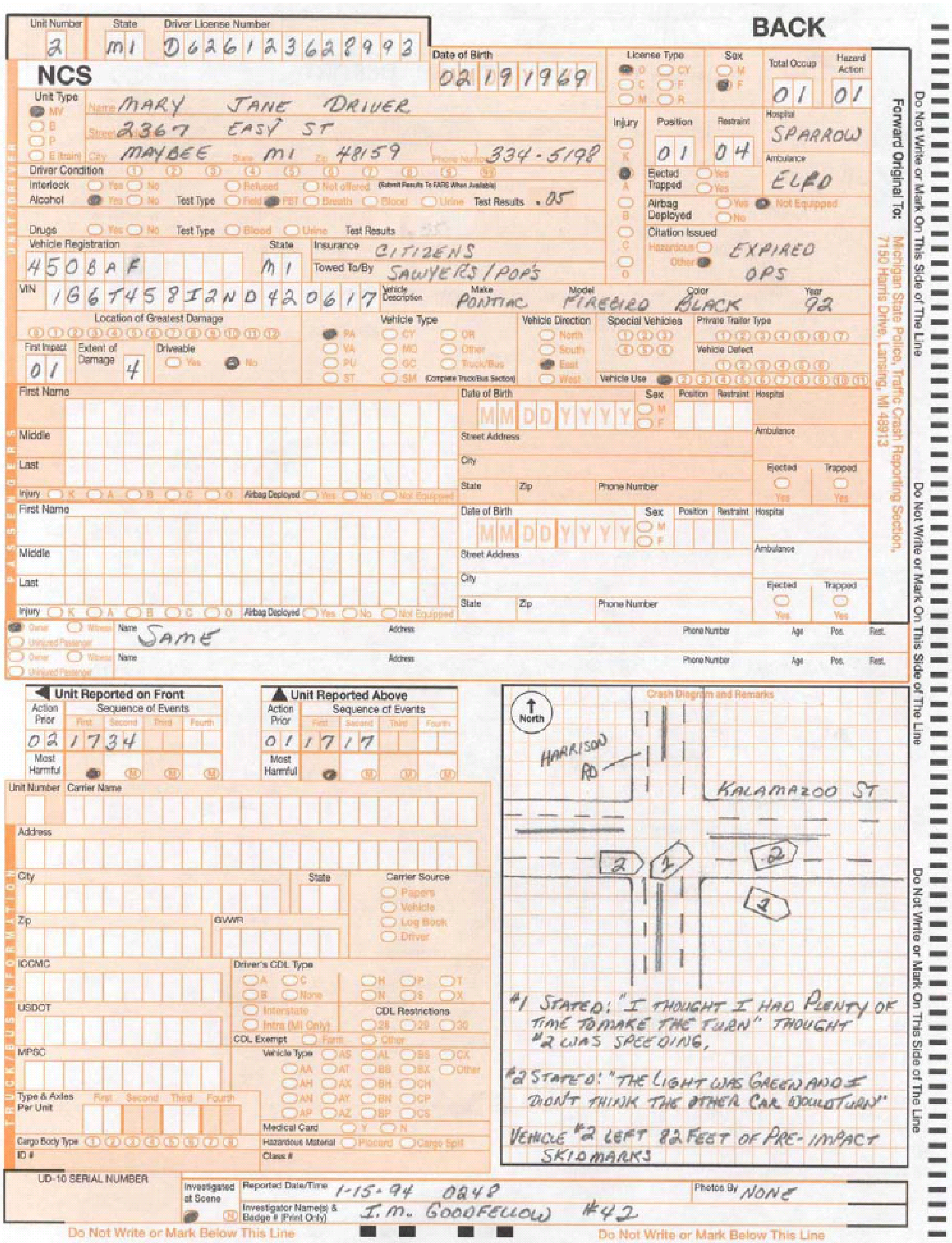
Crash datasets are generally useful in ensuring that crashes are described in a standard way so that common characteristics among crashes can be recognized and reported. However, crash datasets might fail to capture key pieces of information about a crash that could be informative either because there is no defined field for this information, or because there is no good way to express a causal chain of events that plays out over time.

Take, for example, a situation in which a pedestrian crosses a 5-lane arterial in two steps—first crossing to the middle turn lane, and then continuing the rest of the way across the street. If the pedestrian is struck in the turn lane, the pedestrian action is likely to be identified as "standing in the street." However, the fact that the pedestrian was attempting to cross the street, and that the pedestrian was likely to be in the driver-side area of the approaching vehicle just prior to a crash is unlikely to be determinable from the data in the database alone. If the diagram and narrative content from the original police report are consulted, we may be able to obtain other details that provide a better picture of the causal chain of events just before the collision occurred.

Method

Pedestrian crashes occurring in darkness (coded as dark or dark but lighted) and daylight were drawn from the 2004 State of Michigan DOT crash dataset. To simplify crash circumstances, the sample was first restricted to crashes involving only one vehicle. The sample was further restricted to include only vehicles in which the prior vehicle action had some likely causal connection to the crash (for example, going straight, turning left, turning right, slowing or stopped in roadway, slowing or stopped in another area, or starting up in the roadway). This eliminated crashes in which forward vehicle lighting was unlikely to play a role in the crash (for example, backing crashes, crashes involving stopped vehicles, driverless vehicle crashes, or vehicles involved in a prior crash). (One could argue that a crash in which a pedestrian is injured by walking into a stationary vehicle has little to do with the driver's visual capabilities.) The crash sample was further restricted to crashes involving a single pedestrian. This was done, in part, to simplify locating the involved pedestrian. If the crash involves many struck pedestrians, it is less likely that the accompanying crash diagrams would accurately identify the direction of travel of all involved. Finally, crashes were further limited to involve only pedestrians over 18 years of age, in order to eliminate the likely day/night exposure difference in children. Crashes were then binned as occurring in daylight or dark conditions, with "dark" including both dark and dark-but-lighted conditions. Cases involving dawn, dusk, or unknown light conditions were discarded. The resulting dataset contained 1,240 pedestrian crash records.

From this "base" sample of crashes, 200 crashes in darkness and 200 crashes in daylight were randomly selected. The serial number of each crash was then used to retrieve a digitized facsimile of the UD-10 police report filed for each crash. Each report was reviewed alongside the corresponding crash database record for consistency. Narrative information, usually incorporated with a diagram in the lower right corner of the second page of the form (see Figure 1), was reviewed and the diagram was examined to retrieve supplemental information about the location and movement of the pedestrian prior to the crash.



BACK

Unit Number: 2 | State: MI | Driver License Number: D626123628993

NCS

Date of Birth: 02 19 1969

Unit Type: MV

Name: MARY JANE DRIVER

Street: 2367 EAST ST

City: MAYBEE | State: MI | Zip: 48159 | Phone Number: 334-5198

License Type | Sex: F | Total Occup: 01 | Hazard Action: 01

Injury | Position: 01 | Restraint: 04 | Hospital: SPARROW

Ambulance: ELRD

Ejected | Trapped

Airbag Deployed: Not Equipped

Driver Condition

Interlock: Yes No Refused Not offered (Submit Results To FARS When Available)

Alcohol: Yes | Test Type: PBT | Test Results: .05

Drugs: Yes No | Test Type: Blood Urine | Test Results

Citation Issued: Other — EXPIRED OPS

Vehicle Registration: 4508AF | State: MI

Insurance: CITIZENS

Towed To/By: SAWYERS/POPS

VIN: 1G6T458I2ND420617 | Vehicle Description — Make: PONTIAC | Model: FIREBIRD | Color: BLACK | Year: 92

Location of Greatest Damage

First Impact: 01 | Extent of Damage: 4 | Driveable: No

Vehicle Type: PA | Vehicle Direction: East | Special Vehicles | Private Trailer Type | Vehicle Defect | Vehicle Use

First Name | Middle | Last | Injury K A B C O | Airbag Deployed Yes No Not Equipped | Date of Birth MM DD YYYY | Sex M F | Position | Restraint | Hospital | Street Address | City | State | Zip | Phone Number | Ambulance | Ejected | Trapped

First Name | Middle | Last | Injury K A B C O | Airbag Deployed Yes No Not Equipped | Date of Birth MM DD YYYY | Sex M F | Position | Restraint | Hospital | Street Address | City | State | Zip | Phone Number | Ambulance | Ejected | Trapped

Owner | Witness | Uninjured Passenger | Name: SAME | Address | Phone Number | Age | Pos. | Rest.

Owner | Witness | Uninjured Passenger | Name | Address | Phone Number | Age | Pos. | Rest.

Unit Reported on Front — Action Prior: 02 | Sequence of Events: 17 34 | Most Harmful

Unit Reported Above — Action Prior: 01 | Sequence of Events: 17 17 | Most Harmful

Unit Number | Carrier Name | Address | City | State | Carrier Source: Papers, Vehicle, Log Book, Driver | Zip | GVWR | ICCMC | Driver's CDL Type | USDOT | CDL Restrictions | CDL Exempt | MPSC | Vehicle Type | Type & Axles Per Unit | Medical Card | Cargo Body Type | Hazardous Material | ID # | Class #

Crash Diagram and Remarks

North

HARRISON RD

KALAMAZOO ST

#1 STATED: "I THOUGHT I HAD PLENTY OF TIME TO MAKE THE TURN" THOUGHT #2 WAS SPEEDING.

#2 STATED: "THE LIGHT WAS GREEN AND I DIDN'T THINK THE OTHER CAR WOULD TURN"

VEHICLE #2 LEFT 82 FEET OF PRE-IMPACT SKIDMARKS

UD-10 SERIAL NUMBER | Investigated at Scene | Reported Date/Time: 1-15-94 0248 | Photos By: NONE

Investigator Name(s) & Badge # (Print Only): I.M. GOODFELLOW #42

Do Not Write or Mark Below This Line

Forward Original To: Michigan State Police, Traffic Crash Reporting Section, 7150 Harris Drive, Lansing, MI 48913

Do Not Write or Mark On This Side of The Line

Figure 1. Back page of the Michigan Department of Transportation UD-10 crash report showing an accident diagram on the lower right. The example is taken from Appendix B of the State of Michigan UD-10 Traffic Crash Report Instruction Manual (State of Michigan, 2004).

Because the current analysis was designed to relate the light distribution originating from the striking vehicle to pedestrian risk, the geometry of the crash must be recast using the striking vehicle as the primary point of reference. Although the Michigan crash dataset provides fields identifying the direction of travel for all units involved in a given crash (i.e., vehicle, pedestrian), the pedestrian direction of travel is frequently omitted from the record. Indeed, in the sample of pedestrian crashes used in this report, 75% of the pedestrian directions are reported as unknown. In examining the UD-10 reports, this information is often omitted entirely from the pedestrian report, although it may be either implied or explicitly mentioned in the accompanying diagram and narrative. There are also many cases in which the prior pedestrian direction is genuinely unknown—as in fatal hit-and-run collisions.

Even if a pedestrian's direction of travel was fully reported, absolute geographical directions would need to be recoded into a vehicle-relative framework. Thus a southbound vehicle colliding with a westbound pedestrian would be recoded as a pedestrian approach from the vehicle's driver side, as would a northbound vehicle and an eastbound pedestrian, a westbound vehicle and a northbound pedestrian, and an eastbound vehicle and a southbound pedestrian.

The coding of a vehicle's direction of travel can also be ambiguous and misleading with respect to determining the geometric configuration just prior to a pedestrian crash. For example, an originally northbound vehicle may initiate a left turn and strike a southbound pedestrian. This is sometimes coded as "eastbound going straight" or as "northbound turning left," depending on whether the collision occurred *during* the turn or *after* the turn was completed. For the purposes of this analysis, we would like to know what kind of preview of the roadway a driver had in the seconds prior to the collision. It may matter less whether the driver was *in* the turn or had completed the turn, since we are interested in the situation seconds *before* the collision occurred. Fortunately, crash diagrams in the original police reports often include trajectories or implied trajectories of both the vehicle and pedestrian so that a more complete picture of the sequence of events can be determined. In this particular case, we would describe the scenario as a pedestrian crossing southbound on what was originally the driver's side of vehicle executing a left turn.

With these considerations in mind, each police report was reevaluated with respect to: whether a vehicle was or had been executing a turn prior to the collision, the direction of the turn, and the direction of pedestrian travel relative to the striking vehicle.

Crash Report Recoding Procedures

The 400 selected pedestrian crashes from the MDOT-2004 crash dataset (200 occurring in daylight, and 200 in darkness) were recoded into several supplemental data fields using the UD-10. As is common with any experimental coding scheme, many of the new fields proved to be of limited usefulness in resolving crash characteristics related to light distribution. For example, the vertical position of a pedestrian was encoded with the purpose of revealing how much of that person's body may have been illuminated by the approaching vehicle's beam pattern. The vertical position of a pedestrian was identified as upright, sitting or crouching, reclined, or unknown. Among the 400 cases, only 1% (5) of the cases was identified as lying in the roadway (all in darkness), 3% (12) were identified as sitting or crouching (evenly split between darkness and daylight), and 90% (361) were identified as upright (evenly split). With such small numbers, it would take a much larger sample to resolve real differences between the darkness and daylight distributions of this attribute. Furthermore, even if it was found that pedestrian crashes in darkness involve more reclined pedestrians, several non-light-related explanations are plausible (e.g., incidence of alcohol involvement is higher at night, a person reclining in the roadway in daylight is likely to attract public attention and be removed quickly). This report will therefore restrict discussion to the supplemental data fields which proved to be useful in suggesting low-beam light distribution might influence pedestrian crashes. These fields include:

1) **Lateral position of the pedestrian.** This field identified the lateral position of the pedestrian relative to the striking vehicle just prior to the crash. Field values could be one of the following: left, right, straight ahead, or unknown.
2) **Intended vehicle maneuver.** A vehicle was characterized as intending to make a left turn, right turn, no turn, or an unknown maneuver. The purpose of this field was to capture the likely direction a driver was attending to just prior to the crash, regardless of the vehicle position at the point of collision. For example, a driver

attempting to execute a right turn to merge into oncoming traffic would likely be looking left for clearance. A driver executing a left turn would likely be looking in both directions for clear traffic. And a driver traveling straight ahead would likely be looking straight ahead.

3) **Pedestrian crossing configuration relative to the striking vehicle.** Crossing configuration was encoded using a crossing classification system based on an intersection diagram (but not restricted to intersection crashes) in which the prior vehicle position was used as the frame of reference. Four locations were identified as starting and end points of the intended pedestrian trajectory (shown in Figure 2). Although the topology was developed with reference to an intersection and a turning vehicle, the coding scheme was also applied to nonintersection-related crashes to capture pedestrian crossing directions that were perpendicular to a vehicle's direction of travel.

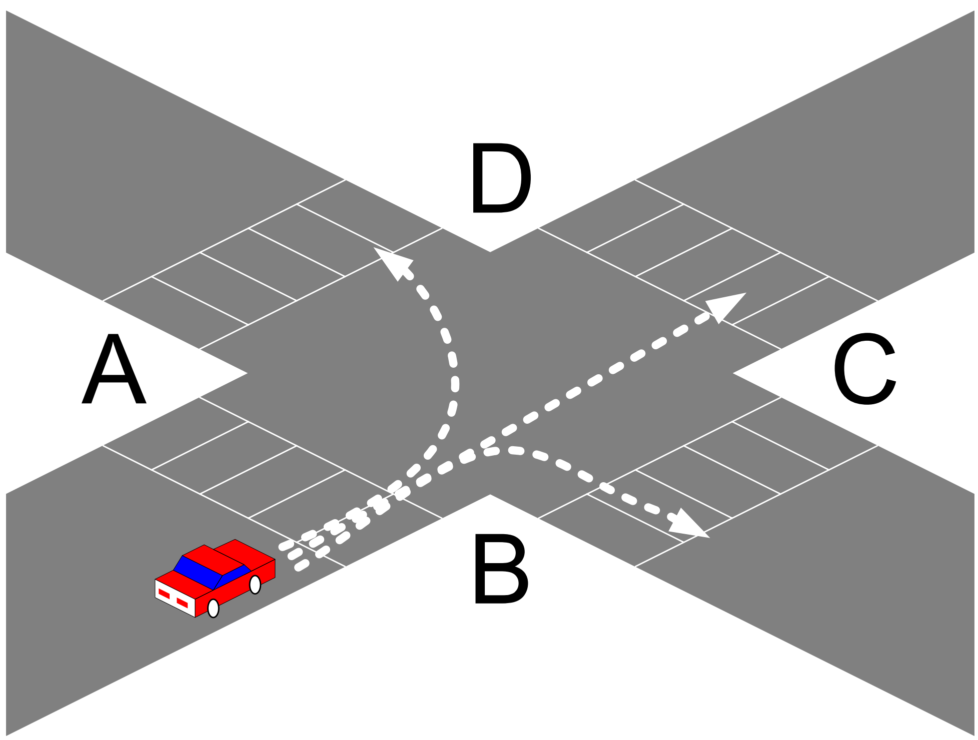


Figure 2. Intersection diagram identifying pedestrian reference points (A, B, C, D) and vehicle trajectory.

4) **Crash unrelated to lighting.** Crash records that occurred in darkness were further tagged with regard to whether lighting was clearly not a factor. For example, crashes that involved a deliberate assault on a pedestrian, occurred under severe weather-related visibility restrictions (e.g., white-out conditions in a snowstorm), or involved a loss of vehicle control, were identified as unrelated to lighting.

Analysis Overview

An initial group of crash analyses on the "base" sample of pedestrian crashes was performed to establish a general context for these crashes. The purpose of the analysis is to provide both a clear picture of the prevalence in darkness for particular pedestrian crash conditions, and to compare this to the daylight conditions for contrast. While the dark-light comparison provides a broad picture of how pedestrian crashes in darkness may differ from crashes in daylight, it admittedly does not provide an unambiguous reason for any differences, since factors such as light level, driver fatigue, alcohol use, and demographics are confounded.

The contextual analysis is subdivided into person factors related to pedestrian and driver behavior, and environmental factors related to the roadway conditions. The person factors examined include the driver and pedestrian actions prior to the collision, and the levels of suspected drug or alcohol use. The environmental factors examined include the roadway area (e.g., freeway, nonfreeway, and within each category, the roadway characteristics), road class (interstate, US route, state route, connector, business routes, service drives, city/street roads), trafficway type (not divided, divided without a barrier, divided with a barrier, one-way), number of traffic lanes, posted speed limit, road surface conditions (dry, wet, icy, slushy, snowy, muddy, debris-covered), and weather conditions (clear, cloudy, rain, snow, fog, sleet, wind).

A second group of analyses was conducted to associate pedestrian crash risk in the dark with the geometric characteristics of the low-beam headlamp light distribution and the pedestrian's location and movement relative to the striking vehicle just prior to the crash. These analyses ask the simple question: is there a difference in the way pedestrians are distributed about the roadway in a crash that occurs in the dark versus the light. The analyses are divided into three parts based on the striking vehicle's intended maneuver prior to the crash—turning left, turning right, and driving straight. This was done because the geometric configuration of the crash, and the driver's lookout behavior and/or speed, are different in each case. For example, referring to Figure 2, if a vehicle is executing a right turn, only pedestrians crossing from A to B, B to A, B to C, or C to B can be struck. Moreover, in many of these turns, the driver will be attempting to merge with traffic approaching from the driver's side of the vehicle and thus we might expect that attention will be directed to the left side of the vehicle. Likewise, a left-turning vehicle is only capable of striking pedestrians traveling from A to B, B to A, A to D, or D to A. Depending on the number of crossing lanes of traffic and the presence of traffic controls, the lookout behavior of a driver attempting a left turn can be considerably complex—an adequate gap must be found in each direction of the crossing traffic as well as in the oncoming traffic to accommodate the maneuver. In the "going straight" scenario, only pedestrian trajectories perpendicular to the vehicle's path can result in a collision; we might also expect that the driver's attention would be primarily directed straight ahead (unless the driver is required to yield to crossing traffic).

Results

Pedestrian and Driver factors. There were 1,240 crashes in the selected sample of pedestrian-single vehicle crashes drawn from the 2004 Michigan DOT crash dataset and used in this analysis. Of these, 553 (45%) occurred in darkness and 687 occurred in daylight (55%). The most common pedestrian actions prior to a collision under dark and light conditions are shown in Table 1. The distributions of prior pedestrian actions differ in the dark compared to daylight, $\chi^2(12, N = 1{,}218) = 44.04, p < 0.01$). In the dark, there appear to be proportionally fewer pedestrian crashes at intersections (27%) compared to daylight (36%); and proportionally more occurring away from intersections (e.g., mid-block crossings) in darkness (31%) compared to daylight (24%). In the dark, there is also a higher proportion of crashes involving pedestrians walking in the roadway compared to daylight—either with traffic (10% versus 5%), or against traffic (4% versus 2%).

Table 1
Percentage of crashes involving different prior actions by a pedestrian in darkness and light. Rows with fewer than 5 total observations are omitted.

	Light Condition	
Prior pedestrian actions	Dark	Light
Crossing at an Intersection	27.3%	36.2%
Crossing not at an Intersection	30.7%	24.3%
Entering roadway	0.5%	0.3%
Getting on/off vehicle	0.7%	1.5%
Going straight ahead	4.9%	4.8%
In roadway walking against traffic	3.8%	1.7%
In roadway with traffic	9.6%	4.7%
In roadway other reason	3.8%	4.9%
Not in roadway	3.3%	4.1%
Other	2.5%	5.4%
Other working in roadway	1.8%	2.5%
Standing/lying in roadway	5.6%	2.8%
Unknown	4.5%	4.4%
Total percent	100%	100%
Total crashes	553	687

On the vehicle side, Table 2 shows the breakdown of prior vehicle actions before a pedestrian collision. As with the previous prior pedestrian action analysis, the crash distributions differ between dark and light, χ^2 (11, N = 1,240) = 62.76, $p < 0.0001$). There are proportionally more pedestrian collisions in the dark involving vehicles going straight (69%) than in daylight (51%). There are also proportionally fewer right turn collisions in darkness (4%) than in daylight (11%).

Table 2
Percentage of pedestrian crashes involving different prior actions by a vehicle in darkness and light. Rows with fewer than 5 total observations are omitted.

	Light Condition	
Prior vehicle actions	Dark	Light
Avoiding pedestrian	2.4%	2.0%
Changing lanes	1.8%	1.0%
Entering roadway	0.5%	3.1%
Going Straight Ahead	68.5%	50.8%
Leaving roadway	0.5%	0.6%
Overtaking or passing	0.7%	0.6%
Slowing/stop on roadway	2.2%	3.3%
Starting up on roadway	2.0%	5.2%
Starting up other area	0.2%	1.0%
Turning left	15.0%	19.1%
Turning right	4.3%	11.4%
Other	1.8%	1.6%
Total percent	100%	100%
Total crashes	553	687

The differences in the distributions of prior pedestrian and vehicle actions in dark and light conditions are related and somewhat complementary: there is a larger proportion of vehicle-turning crashes during daylight and a larger proportion of crashes involving pedestrian at intersections (where, presumably, the vehicles are executing the turns). Conversely, in the dark there are more crashes involving pedestrians *not* at intersections (in which case the vehicles are going straight). It is possible that the higher proportion of turning crashes in daylight is influenced by traffic density, which is likely greater in daylight than at night. To make a turn, a gap must first be found in one or more traffic streams. For a right-turn merge, a gap is required in the traffic approaching from the driver's side of the vehicle. For a left-turn maneuver, gaps must be found in each lane of crossing traffic as well as approaching traffic. With higher traffic density, the task of gap finding becomes more difficult and likely more demanding on the driver. As a consequence, the driver may fail to notice a pedestrian crossing in front of the vehicle, especially if the pedestrian is crossing from a direction that is not significant for gap-finding—e.g., a pedestrian approaching from the right side of a right-turning vehicle.

Not surprisingly, the crashes in darkness also contained a higher proportion of alcohol involvement than the crashes in daylight (shown in Table 3). Among the pedestrians, 18% (100 out of 553) of the sample in darkness involved suspected drug or alcohol use; while only 3% (18 out of 687) of the daylight sample did. Among the drivers, 10% (54 out of 553) of the sample in darkness involved suspected drug or alcohol use; while only 2% (11 out of 687) of the daylight sample did. (This analysis excluded pedestrians under 18 years of age; including underage pedestrians in the sampled crashes would reduce the observed percentage of alcohol/drug involvement to 14% in darkness and 2% in daylight.) Notably, the suspected involvement of alcohol/drugs in pedestrian crashes combined over dark and light periods (9.5%) is not very different from the 7% reported previously by daSilva, Smith, and Najm (2003); similarly the suspected involvement of alcohol/drugs among the involved drivers over dark and light periods (5.2%) is similar to the 6% also reported by these authors.

Table 3
Percentage of pedestrians and drivers suspected of alcohol or drug involvement in selected Michigan 2004 pedestrian crashes by day and night.

		Light condition	
Party	Suspected Alcohol/Drugs	Dark	Light
Pedestrian	No	81.9%	97.4%
	Yes	18.1%	2.6%
Driver	No	90.2%	98.4%
	Yes	9.8%	1.6%
Total percent		100%	100%
Total crashes		553	687

Environmental Factors. Pedestrian crashes were initially broken down by roadway area using a coarse grouping (freeway, nonfreeway intersection, nonfreeway nonintersection, and other), followed by a finer-grained analysis using the detailed categories used in the crash dataset. The two groupings are presented in Table 4. Consistent with the previous analysis of pedestrian actions, there are proportionally more intersection-related crashes in daylight than in darkness, and proportionally fewer nonintersection, nonfreeway crashes in daylight than in darkness, χ^2 (3, N = 1,240) = 23.8, $p < 0.0001$. As is shown in the breakdown, more than half of pedestrian crashes in darkness occurred on nonfreeway nonintersection straight roadways (52%); the remaining crashes in darkness generally occurred near intersections (33.8%).

The distribution of pedestrian crashes using an alternative roadway breakdown, highway class (e.g., interstates, US Routes, state roads, business routes, and local/county roads), is shown in Table 5. In both dark and light conditions, about 65% of the crashes occurred on road/city/street or unknown roadways. Crashes in darkness do not appear to be distributed any differently than crashes in daylight among the different highway classes.

Next we examined the trafficway configuration. Trafficway distinguishes whether a road supports one- or two-way traffic, and specifies whether and how the two-way traffic flows are separated (e.g., center turn lanes, barriers). Trafficway configuration could influence pedestrian visibility in several ways. For example, one-way streets and divided roadways with physical barriers are likely to permit less glare from opposing traffic than two-way highways that are not physically divided, or divided only by a median strip with no barrier. Pedestrians also occasionally rely on medians to cross multi-lane traffic in stages. Standing in the median places pedestrians to the left of oncoming traffic in both directions, where at night the low-beam light distribution is weakest. On the other hand, pedestrian exposure is likely to be lower around roadways separated by medians (e.g., interstates). Such restriction may easily overshadow any observable dark/light differences in the distribution of crashes. The actual breakdown of crashes is shown in Table 6. In both dark and light conditions, approximately 70% of pedestrian crashes occur on undivided two-way trafficways. No difference was observed between the dark and light pedestrian crash distributions (χ^2 (4, N = 1,240) = 6.7, p = 0.15).

The distribution of pedestrian crashes by number of roadway lanes was examined by dividing the sample into freeway and nonfreeway lanes. Separate consideration of the number of lanes by road type is important because the number of lanes alone indicates only the width of a trafficway. Thus two lanes on a freeway (separated by a median) will generally carry traffic traveling in a single direction and likely involve little glare from opposing traffic; two lanes on a nonfreeway roadway will generally carry two-way traffic and is more likely to involve glare from opposing traffic. Table 7 shows the breakdown of pedestrian crashes by lane number and light condition, excluding nonroadway crashes and unknown or uncoded data. The small amount of freeway data limits any definitive statement about the interaction of number of lanes with light conditions. In the case of the nonfreeway data, most pedestrian crashes occur on two-lane roadways, which likely mirror the high exposure level to two-lane roads. The distribution of nonfreeway pedestrian crashes over number of lanes was also found to be different across light conditions (χ^2 (8, N = 1,127) = 15.5, $p < 0.05$). The largest dark/light difference in expected values occurred in the 3- and 5-lane crash distributions: in darkness, there were proportionally fewer 3-lane crashes and proportionally more 5-lane crashes than in daylight. On explanation might be as follows. Roadways with odd numbers of lanes generally have a center turn lane which, because it is situated on the driver's side of the vehicle is less brightly illuminated than the right side of the roadway. If pedestrians are inclined to use the center lane as a "safety" zone where they might pause while crossing a wide street in stages, we might expect that pedestrian occupancy of the center lane on 5-lane roads would be higher than it is on 3-lane roadways. If this is the case, then we would expect a relatively higher proportion of nighttime pedestrian crashes involving 5-lane roads than 3-lane roads. Coupled with the likely higher speed of 5-lane roads (and the strong effect of speed on pedestrian crash risk in the dark), it is likely that 5-lane roads with center turn lanes result in a higher pedestrian crash risk in darkness.

Table 4
The distribution of single-pedestrian single-vehicle crashes by roadway area during dark and light conditions.

Category	Category detail	Light Conditions	
		Dark	Light
Freeway			
	Enter/Exit ramp	1.6%	0.9%
	Median crossing	0.2%	0.1%
	Transition area	0.5%	0.4%
	Rest area	-	0.3%
	Other	2.4%	1.3%
Subtotal		4.2%	3.1%
Nonfreeway Intersection			
	In intersection	18.4%	25.6%
	In driveway (near intersection)	4.0%	4.5%
	Intersection related	11.5%	14.3%
Subtotal		33.8%	44.4%
Nonfreeway Nonintersection			
	Straight roadway	52.0%	37.6%
	Curved roadway	1.5%	1.2%
	Driveway (not near intersection)	1.8%	4.4%
	Parking related	-	0.7%
	Transition area	0.5%	0.3%
	Median	0.5%	0.3%
	Railroad	0.4%	-
Subtotal		56.7%	44.4%
Nontraffic/Other/Unknown			
Subtotal		5.3%	8.2
Total percent		100.0%	100%
Total crashes		553	687

Table 5
The distribution of single-pedestrian single-vehicle crashes by highway class during dark and light conditions.

Category	Light Conditions: Dark	Light
Interstate	2.9%	1.9%
U.S. Route	4.5%	3.9%
Michigan Route	22.1%	19.9%
Business Route—Interstate	1.8%	2.8%
Business Route—US Route	1.8%	2.2%
Business Route—Michigan	-	-
Connector	0.2%	0.2%
Service Drive	2.0%	3.1%
Country Road, city street, or unknown	64.7%	66.1%
Total percent	100.0%	100.0%
Total crashes	553	687

Table 6
The distribution of single-pedestrian single-vehicle crashes by trafficway configuration during dark and light conditions.

Category	Light Conditions: Dark	Light
Not physically divided (two-way trafficway)	72.7	69.9
Divided highway, median strip, no barrier	4.0	3.9
Divided highway, median strip, barrier	2.2	1.8
One-way trafficway	2.5	5.4
Uncoded/Error	18.6	19.1
Total percent	100.0	100.0
Total crashes	553	687

Table 7
The distribution of single-pedestrian single-vehicle crashes by freeway and number of lanes during dark and light conditions.

		Light Conditions	
Category	Number of lanes	Dark	Light
Freeway			
	1	3.8%	23.8%
	2	30.8%	28.6%
	3	34.6%	14.3%
	4	19.2%	19.1%
	5	-	9.5%
	6	7.7%	4.8%
	7	-	-
	8	-	-
	9	3.9%	-
Total percent		100%	100%
Total crashes		26	21
Nonfreeway			
	1	3.8%	4.6%
	2	45.5%	48.6%
	3	7.0%	10.5%
	4	18.2%	16.7%
	5	18.6%	14.2%
	6	2.8%	2.2%
	7	3.2%	2.1%
	8	-	0.8%
	9	0.8%	0.3%
Total percent		100%	100%
Total crashes		499	628

Weather-related conditions. In this analysis, weather conditions and road surface conditions in which a pedestrian crash occurs are examined for prevalence and differences in the dark/light distribution. Road surface could affect pedestrian risk in darkness in several ways. On a wet roadway in darkness, surface water reduces the retro-reflectivity of lane markings, making it difficult for drivers to monitor their lane position. In addition, the reflectivity of the wet road surface increases, producing a mirror-like image of the visual scene. At night, this mirror image effectively doubles the number of light sources projected into a driver's eyes, increasing both the complexity of the visual scene and the total glare light. It is also probable that driver expectation plays a role such that during inclement weather conditions, drivers may not be as prepared to see a pedestrian along the roadway as they would in clear weather or in daylight conditions. As shown in Table 8, pedestrian crashes generally occur when the roadway surface is dry. This is likely most of the time. However, consistent with the earlier suggestion that wet roadways at night create a special visibility problem, the number of pedestrian-vehicle collisions is disproportionately higher in darkness on wet roadways than during daylight, χ^2 (6, N = 1,240) = 54.97, $p < 0.0001$). A similar pattern, not surprisingly, is seen in the dark/light breakdown of weather conditions (Table 9). In darkness, pedestrian crashes in the rain are proportionally much higher than in daylight (18% versus 5%; χ^2 (8, N = 1,240) = 87.1, $p < 0.0001$).

Table 8
The distribution of single-pedestrian single-vehicle crashes by roadway surface condition during dark and light conditions.

	Light Conditions	
Road Conditions	Dark	Light
Dry	62.0%	78.3%
Wet	28.8%	12.4%
Icy	1.8%	2.0%
Snowy	5.2%	4.5%
Muddy	-	-
Slushy	0.5%	1.2%
Debris	-	-
Other/Unknown	0.7%	.7%
Unencoded	0.9%	.9%
Total percent	100%	100%
Total count	553	687

Table 9
The distribution of single-pedestrian single-vehicle crashes by weather condition during dark and light conditions.

	Light Conditions	
Weather Conditions	Dark	Light
Clear	45.6%	61.1%
Cloudy	27.1%	30.0%
Fog/Smoke	1.1%	-
Rain	17.9%	4.5%
Snow/Blowing Snow	4.0%	2.9%
Severe Wind	2.9%	0.7%
Sleet/Hail	0.4%	0.2%
Other/Unknown	1.1%	0.4%
Error	-	0.2%
Total percent	100%	100%
Total crashes	553	687

Pedestrian crash risk and roadway crossing geometry. In this analysis, pedestrian crossing trajectory is examined in the context of the precrash vehicle maneuver—turning left, turning right, and traveling straight. As described earlier, these analyses were conducted on a sample of 400 cases randomly selected from the set of all single-pedestrian, single-vehicle collisions in the 2004 MDOT crash dataset, with 200 of the sampled crashes occurring in darkness, and 200 occurring in daylight. A breakdown of the prior crash maneuvers is shown in Table 10. Although the sampled distribution resembles the larger distribution with respect to dark/light breakdown of prior maneuver, it should be noted that the *intended* prior vehicle maneuver was determined from the crash diagram and narrative provided in the crash report form and may not always agree with the coded maneuver. For example, in some circumstances the intended precrash maneuver may be identified as a turn while the coded precrash maneuver identifies it as "not a turn." As noted earlier, there are proportionally more turning crashes in daylight than in darkness, especially right turns (χ^2 (2, N=389) = 25.6, $p < 0.0001$). This could be a consequence of traffic density: with more vehicles on the road, finding a gap in traffic that would allow a turn may require greater lookout effort than at night, resulting in failures to notice crossing pedestrians.

Table 10
Distribution of intended prior vehicle maneuvers in sampled crashes.

	Light Conditions	
Intended vehicle maneuver	Dark	Light
Left turn	15.5%	20.2%
Right turn	5.5%	21.5%
Not a turn	75.5%	56.5%
Unknown/Other	3.5%	2.0%
Total percent	100%	100%
Total crashes	200	200

In examining pedestrian crossing trajectories, about 37% of the cases were classified either as unknown/indeterminate or not engaged in crossing a street at all. This portion of the data contained 43% (85) of the cases in darkness and 32% (63) of the cases in daylight, with 252 cases remaining for analysis. For example, in some instances a pedestrian was standing in or walking along the roadway; in others, the police report only describes where a pedestrian was struck, not what the pedestrian was doing at the time; and in hit-and-run collisions, too little information is available to determine what happened.

Pedestrian crossing trajectory during left turns. There are four possible crossing paths that could result in a pedestrian-vehicle collision while a vehicle is executing a left turn (see Figure 2): two crossing paths are perpendicular to the turning vehicle's starting position (A-B, B-A), before the turn is begun; and two are perpendicular to the turn *after* the turn is executed (A-D, D-A). Based on the likely distribution of light as a left turn is executed, a pedestrian is more likely to be illuminated and thus be more visible in some crossing paths than in others. For example, path of the headlamp beam is more likely to sweep across location D during a left turn, and unlikely to sweep across location A. Consequently, a pedestrian crossing from D to A (the far left) would more likely be seen than one crossing from A to D (the near left).

For left-turning vehicles, there were 56 pedestrian cases which fell into one of the four crossing path categories (or 22% of the pool of 256 cases): 25 cases in the dark and 30 in daylight. Only four cases involved pedestrians crossing in the A-B, B-A path. The remaining cases are shown in Figure 3, distributed by light condition and crossing direction. An interaction between light condition and crossing trajectory was observed (χ^2 (1, N = 52) = 4.7, $p < 0.05$), suggesting that, in darkness the risk is higher in the near-left crossing trajectory.

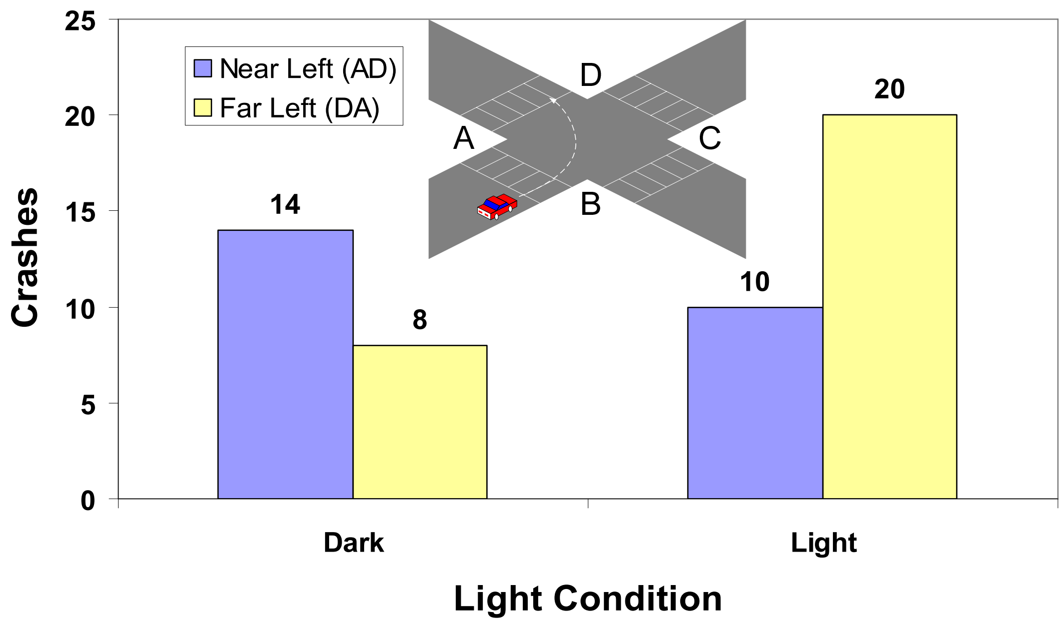


Figure 3. Pedestrian collisions during intended left-turn maneuvers by crossing trajectory.

Pedestrian crossing trajectory during right turns. There are four possible crossing paths that could result in a pedestrian-vehicle collision while a vehicle is executing a right turn (see Figure 2): as described earlier for left turns, crossing paths are perpendicular to the turning vehicle's starting position (A-B, B-A) before the turn is begun; and two are perpendicular to the turn *after* the turn is executed (B-C, C-B). Based on the likely distribution of light as a right turn is approached and executed, a pedestrian is likely to be illuminated on the right side of the road (locations B and C) and thus be more visible in crossing paths originating from the passenger side of the roadway (locations B or C). However, we should also consider where a driver is inclined to look when initiating a right turn. That would be toward the origin of the crossing traffic—to the driver's left. Thus, in the case of a right turn, while visibility may be better on the right side, attention may be habitually directed to the left.

For right-turning vehicles, there were 50 pedestrian cases which fell into one of the four crossing path categories (20% of the pool of 256 cases): 10 cases occurred in the dark and 40 in daylight. Paths originating on the right side of the roadway (B-A, B-C and C-B) were grouped together for comparison with those originating from the left side of the roadway (A-B). These cases are shown in Figure 4. No interaction between light level and crossing direction was observed (χ^2 (1, N = 50) = 0.35, p = 0.55).

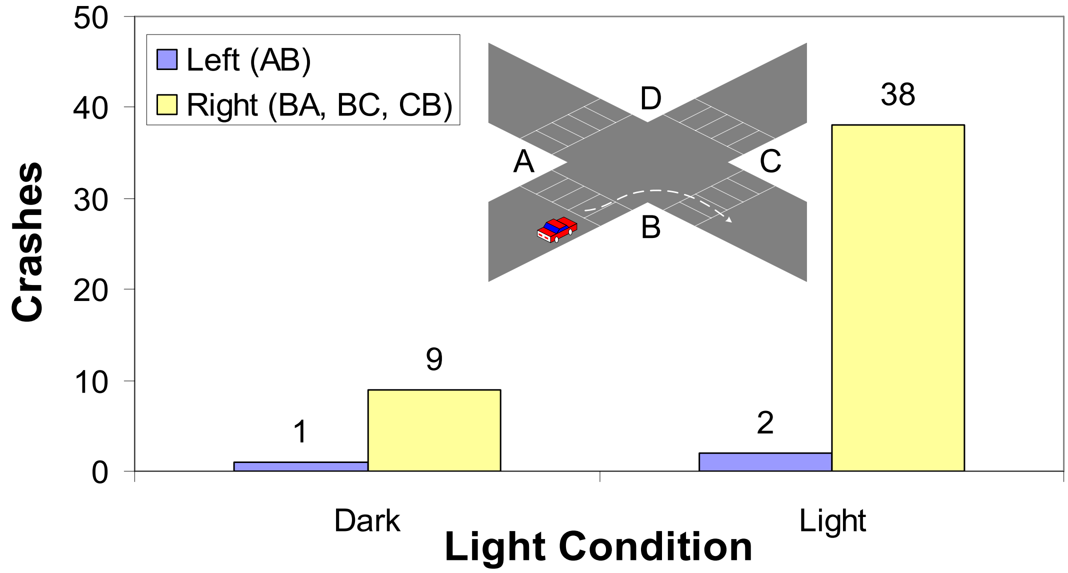


Figure 4. Pedestrian collisions during intended right-turn maneuvers by crossing trajectory.

Pedestrian crossing trajectory during nonturns. There were a total of 146 pedestrian collisions involving nonturning vehicles. These involved collisions while crossing at intersections (28 cases), and at nonintersections (88 cases), and other pedestrian crossing behavior (29 cases) coded variously as: unknown, other, in roadway with traffic, and working in roadway. Pedestrian crossing paths were characterized as originating from either the left or right side of the roadway. Because intersections are frequently fitted with fixed overhead illumination, they were separately analyzed from the other cases. The intersection-related pedestrian crash breakdown is shown in Figure 5. In this small sample, there is little evidence of an interaction between lighting condition and pedestrian travel direction.

The nonintersection cases are shown in Figure 6. In this figure, there appears to be proportionally more crashes approaching from the left in the dark. However, the size of the effect is not statistically significant, χ^2 (1, N = 88) = 1.14, p = 0.29.

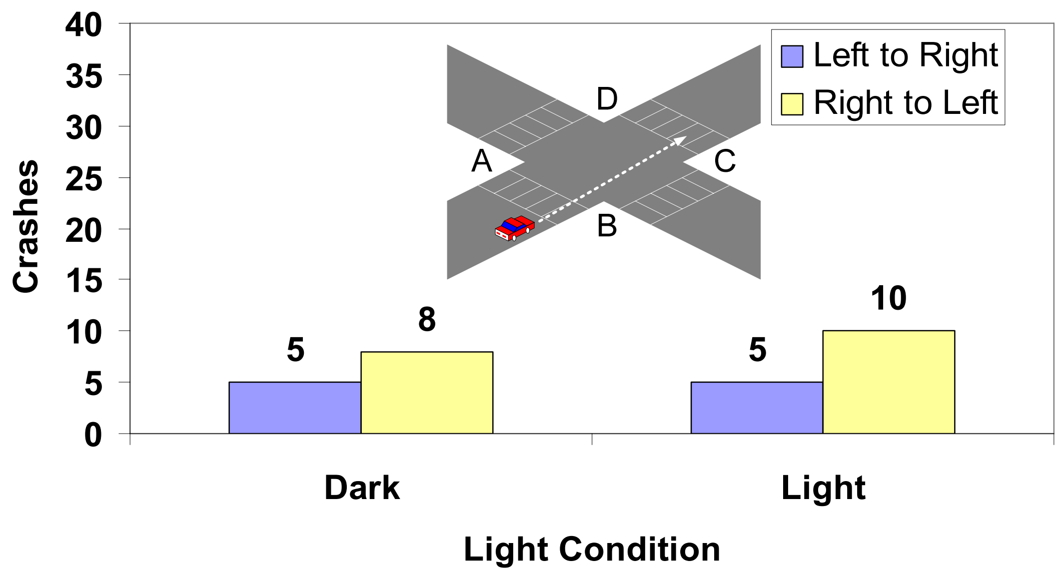


Figure 5. Intersection-related pedestrian crashes by light condition and crossing direction.

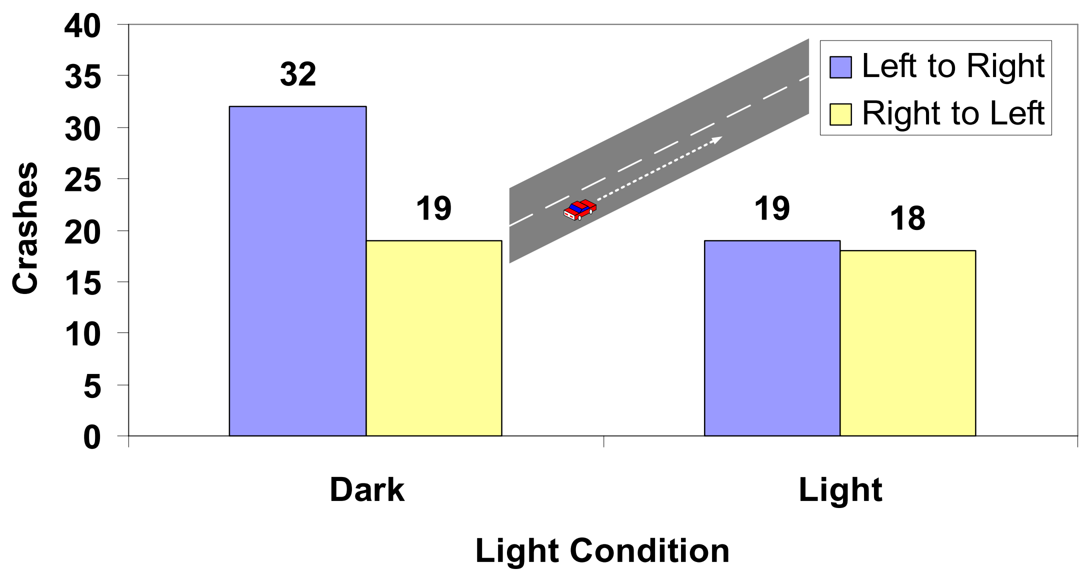


Figure 6. Nonintersection-related pedestrian crashes by light condition and crossing direction.

Conclusions

From the analysis of the 2003 MDOT crash dataset of single-pedestrian, single-vehicle collisions, prior pedestrian actions involving road crossings either at intersections or at nonintersections make up the majority of crashes, with the highest proportion of crashes in darkness occurring at nonintersections (30.7%), while in daylight the highest proportion of pedestrian crashes occurred at intersections (36.2%). There are also proportionally more crashes in darkness involving pedestrians walking in the roadway in the direction of traffic (9.6% versus 4.7% in light). With respect to the prior vehicle actions, most pedestrian collisions occur with a vehicle going straight, both in darkness (68.5%) and in daylight (50.8%), with darkness having a proportionally higher share of these crashes. The higher outcome in darkness is likely related to the fact that vehicles traveling straight may also, on average, be traveling at a higher speed than turning vehicles. With the limited forward preview provided by low-beam headlamps, any travel condition that permits a higher travel speed is also likely to increase crash risk in the dark.

In daylight, turning maneuvers were found to account for proportionally more crashes than in darkness. One explanation for this is that turning to merge into traffic is more challenging in daylight, when there are more vehicles on the road and gaps in traffic are less abundant. A driver's attention may be drawn away from monitoring the whereabouts of pedestrians, increasing the potential of a pedestrian collision.

With respect to the roadway environment, most pedestrian crashes occurred on straight roadways both in daylight and darkness. This is not surprising—straight roadways are plentiful and exposure is likely to be high. However it was also found that there are proportionally more pedestrian crashes in darkness than in daylight on straight roadways. In as much as straight roadways are conducive to high speed, as mentioned earlier, risk in darkness is likely to be elevated.

Neither road class nor trafficway configuration interacted with ambient light level. The latter result is especially surprising given that glare from oncoming traffic can be expected to be worse on roadways with limited two-way traffic separation in darkness.

Perhaps reduced traffic density during periods of darkness also reduces the amount of glare from opposing traffic, offsetting any effect of road class or configuration.

In the lane analysis presented in Table 7, it was found that nearly half of all pedestrian-vehicle crashes occur on 2-lane roadways, regardless of light condition. However, it also appears that 5-lane roadways present a special problem in darkness that may be related both to travel speed and insufficient illumination of the center lane.

Finally, it was found that wet road conditions and rain involved proportionally more pedestrian crashes in darkness than in daylight. This may be caused by a variety of factors that affect visibility (roadway surface reflectance multiplies the number of potential glare sources, negative contrast is lost and lane markings disappear on a wet roadway, and water droplets on windshields may obscure the forward view) as well as reduced driver expectation to see pedestrians on the roadway during bad weather.

Results derived from the examination of geometric details recovered from the diagrams and narrative content contained in police reports suggest that there is valuable supplemental information in these reports that can go beyond the information captured in the conventional crash data tables. For example, from the perspective of whether an approaching driver may have seen a pedestrian before a collision, it may be less important to identify whether the collision occurred *while* a turn was being executed than to identify whether a turn was executed any time in the several seconds preceding the collision. It is similarly important, from the perspective of vehicle lighting, to establish geometric relationships between pedestrians and vehicles using a vehicle-centric reference basis. Thus, it is more important to know that a pedestrian is crossing in front of a vehicle from the left or right direction than to know each party's absolute heading. When pedestrian location was recast in this manner, a consistent pattern was found in the left-turn pedestrian-vehicle collisions that suggests the visibility of pedestrians is poorer on the left side of the roadway, consistent with low-beam light distribution. A similar, although not statistically significant, pattern was also observed for pedestrians crossing in front of vehicles traveling straight. No such pattern was apparent for right-turning vehicles, perhaps because driver attention is normally directed to the left, regardless of light condition, when attempting to merge with oncoming traffic. In this case, pedestrians approaching from the right side of the roadway are the principal victims.

Implications for Headlighting

The analyses of pedestrian crashes in which the striking vehicle was turning left (Figure 3) showed a marked increase in relative risk at night for pedestrians who were illuminated only by the left side of headlamp beam patterns. Although this pattern is not surprising, the results reported here, together with previous analyses (Sullivan & Flannagan, 2006), provide an estimate of the size of the potential problem based on actual crash data. These results suggest that some form of supplemental cornering light may have substantial safety benefits.

The data for nonintersection crashes in which the striking vehicle was not turning (Figure 6) showed a similar trend toward greater risk on the left at night, but even though the observed difference was large, it was not statistically significant. This suggests that it might be useful to extend the method used here to a larger set of crashes in order to provide better information about this potentially important effect. However, a further difficulty in interpreting any such effect is that it is difficult to disentangle the possible effects of insufficient light emitted by the striking vehicle from glare effects of light emitted by possible oncoming vehicles. Because the striking vehicle was not turning, there is a simple spatial correspondence between the leftward region in which low-beam light is intentionally limited and the likely locations of any oncoming vehicles. Although glare was not noted as a factor in any of the crashes analyzed here, it is difficult to rule out an influence of glare. If the pattern that appears in Figure 6 can be statistically supported, it would also be valuable to determine the relative contributions of lack of light and glare.

The results reported here provide examples of how asymmetries in headlamp photometry may affect real-world outcomes. They may therefore provide an important opportunity for validation of quantitative models of headlamp performance (e.g., Bhise et al., 1977; Kosmatka, 2003). Although headlamps vary, standards insure that they are all reasonably similar at the relatively coarse level of the right/left asymmetry of low beams (e.g., Sivak, Schoettle, & Flannagan, 2006). Headlamp visibility models have been validated against field visibility data, but testing the agreement of model predictions with the right/left differences in crash outcomes observed here could provide a closer tie to the actual effects of headlighting on safety.

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