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ASSESSING THE POTENTIAL BENEFIT OF ADAPTIVE HEADLIGHTING USING CRASH DATABASES

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16. Abstract

This report used 11 years of data from the Fatality Analysis Reporting System (FARS 1987-1997) to investigate the sensitivity to light level in three crash scenarios in which various forms of adaptive headlighting might have safety benefits. The scenarios included fatal pedestrian crashes at intersections, on dark roads, and single-vehicle run-off-road crashes on dark, curved roads.

Each scenario's sensitivity to light level was evaluated in two ways. In the first method, the seasonal pattern of crashes throughout the year was compared to the seasonal pattern of light level in three daily time periods (twilight, daylight, and nighttime), applying the same twilight-zone logic as Owens and Sivak (1993). Both of the fatal crash scenarios that involve pedestrians tracked the seasonal fluctuation in light level during this period, showing a decline in crashes during the twilight periods in the spring and summer, and an increase in crashes during the fall and winter. The daylight and nighttime control periods, in which light level is fixed, showed no similar trend. In contrast, the single-vehicle run-off-road scenario failed to show any influence of light level, and seems to be significantly associated with alcohol use. In the second method, the number of fatal crashes was compared across the changes to and from daylight savings time, within time periods in which an abrupt change in light level occurs relative to official clock time. Once again, scenarios involving pedestrians were most sensitive to light level, while single-vehicle run-off-road crashes showed little effect of light level.

The results suggest that adaptive lighting may produce the greatest measurable safety benefit when it addresses the problem of pedestrian vulnerability in darkness.

17. Key Words
daylight savings time, twilight zone, adaptive headlighting, fatal accidents, pedestrians

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1.0 Introduction

Over the last decade, vehicle lighting manufacturers have been steadily working to improve the effectiveness of headlighting systems through the development of technologies that will allow illumination to be distributed in flexible and dynamic ways not possible with conventional fixed headlighting. This work has come to be known variously as adaptive headlighting, intelligent lighting, or active headlighting. These solutions are typically applied to situations in which fixed headlighting is limited by design compromises made in order to produce a single acceptable lighting configuration for a variety of driving conditions. For example, fixed headlights mitigate glare to other drivers using a beam pattern designed to project light away from an oncoming vehicle. The solution is optimal for straight, level, and undivided roads. It is unlikely to be optimal on curved, graded, or divided roads. With adaptive headlighting, the pattern and aim of the beam can be modified to match the immediate situation. Low beam headlamps project light a fixed distance down the road. Depending on the speed of the vehicle, this distance may be inadequate to avoid obstacles in the road (Olson & Sivak, 1983). With adaptive headlighting, the projected distance of the beam might be adjusted with the speed of the vehicle. Other forms of adaptive lighting may adjust illumination to control the veiling luminance caused by atmospheric conditions (e.g., fog, snow); control variation in foreground luminance (a consequence of variation in road surface reflectivity); relevel beams to counteract effects of load distribution or acceleration forces; or adjust overall lighting characteristics to suit the driving context (e.g., rural, urban, motorway).

The deficiencies of fixed headlighting are not surprising. Low-beam headlighting patterns involve compromises between supplying sufficient illumination for a driver to control his/her vehicle and not crippling the vision of others who share the road. The two goals are often in conflict.

The fact that all motor vehicles come equipped with both high beams *and* low beams implicitly recognizes that a driver’s illumination needs vary, and that some level of dynamic control over forward illumination is needed. Adaptive headlighting solutions can be viewed as refinements of this older response to the problem of matching lighting to changing circumstances. They can substantially increase the variety of light distributions that are available for varying circumstances, and also provide automatic control.

Given these emerging possibilities in headlighting design, it might be useful to determine which fixed headlighting problems produce the most serious hazards to the public and to develop adaptive solutions to address these hazards with the highest priority. For this report, we select three types of adaptive headlighting countermeasures to investigate—cornering lamps, curve illumination, and speed-sensitive forward lighting. We identify types of vehicle crashes that each headlighting countermeasure might address and then look for evidence in various crash databases to assess both how commonplace such crashes are and how well the danger is reduced when adequate lighting is available.

To determine how effective lighting is in reducing crashes we apply the following rationale. If we assume that the best lighting an adaptive headlighting system could provide is comparable to daylight, we can compare the differences between daylight and dark crash rates to assess how sensitive the crash type is to lighting conditions. Of course, it would be incorrect to equate illumination by headlight to daylight. We are not suggesting that they are the same. We are merely determining the degree to which a crash type seems to be linked to variation in light level. If little relationship is found, it is unlikely that improved headlighting would affect crash rates significantly; if a strong relationship is found, it suggests proper headlighting may significantly reduce crashes.

It is also important to compare daylight and dark crashes under circumstances in which it is at least reasonable to assert that all factors other than light itself are equal. Such factors would include weather, traffic density, use of alcohol, driver fatigue, and many others. The issue of possible contaminating factors is a major limitation on the interpretation of crash statistics and will be addressed at some length in the remainder of this report.

Finally, we note that there are some possible benefits of adaptive headlighting that might not be reflected in crash statistics. For instance, adaptive headlighting may permit higher speeds on some roads without compromising safety. It may substantially reduce discomfort glare to other drivers. It may increase confidence in some segments of the driving population who currently avoid night driving (primarily older drivers). It may reduce fatigue, helping drivers maintain better alertness at night. None of these factors are assessed in the current analysis.

2.0 Previous Research

Assessment of the role of light in crash statistics has traditionally focused on determining the benefits (relative to cost) of fixed roadway illumination to help government agencies determine how much to invest in roadway upgrades (e.g., Box, 1989). Typically the focus has been on the aggregate changes in the crash count when illumination is introduced to a particular section of roadway (Stark, 1973; Box, 1972a, 1972b; CIE, 1992). Also typically, little detailed analysis has been made on whether different kinds of crashes are selectively reduced with lighting. Crashes are coarsely categorized as either pedestrian or nonpedestrian, or categorized by level of severity (property damage only, injury, and fatality). With this grouping, pedestrians are most often found to benefit from the introduction of fixed road lighting. CIE (1992) reports that pedestrian crashes are reduced by as much as 64% when illumination is introduced. Resisting the trend toward coarse categories, Box (1989) made a somewhat finer categorization of crashes and found the greatest reductions (with added road lighting) for sideswipe crashes (73%), fixed objects (61%), and pedestrians/bicycles (52%).

In fixed illumination, detailed analysis is often reserved for illumination characteristics—the input side of the lighting/crash equation (e.g., Scott, 1980; Janoff, Koth, McCunney, Berkovitz, & Freedman, 1978). Overall crash rate is correlated to quantified lighting characteristics like average road-surface luminance, longitudinal uniformity, horizontal illuminance, and discomfort glare. The result of much of this investigation is that road luminance appears to be a significant predictor of crash rate (Scott, 1980). Later work has investigated *visibility level* (VL), a measure of visual contrast, as a better way to quantify the effectiveness of lighting, although less work has been done to relate the measure to crash statistics. Thus it seems there has been a progression in the roadway lighting literature away from focusing solely on the light source (e.g., illuminance measures) to the illuminated environment (e.g., roadway luminance), and most recently to measures that consider both the environment *and* the perceiver (use of VL measures). Unfortunately, these measures are also progressively more difficult to record or estimate under the uncontrolled circumstances in which crashes occur, making it unlikely that studies can relate the latter measures back to crash data. One clear conclusion from the fixed-illumination research is that lighting reduces crash rates—in particular, pedestrian crash rates.

At least one analysis of fixed lighting examined the mixture of run-off-road crashes as a function of road geometry and lighting conditions. The ratio of fatal run-off-road crashes on straight roads versus curved roads was compared under conditions of daylight, night but lighted, and dark (Merrit, Helander, Abrams, & Miller, 1982; replicated in Perel, Olson, Sivak, & Medlin, 1983). Daylight and night (but lighted) proportions of curved-road to straight-road crashes were similar, but the night (dark) condition showed a markedly higher proportion of fatal crashes on curved roads. The authors concluded that the presence of fixed roadway lighting appears to reduce crashes on curves. Such an interpretation, however, is questionable. It implicitly equates conditions across many other dimensions, as if lighting "treatments" contained observations that were randomly sampled. In fact, the samples in each lighting condition probably differ in systematic ways. For example, it is likely that the nighttime crashes contain more drinking drivers, that the lighted roadways are situated in urban areas that are more heavily traveled, and that lighted roadways are better marked and better paved. Given this likelihood, it seems prudent to regard the conclusion with caution.

Another approach, explored by Owens and Sivak (1993) and discussed in more detail below, exploited the seasonal variation in the times of morning and evening twilight to investigate the role of light in fatal crash statistics. They reported that fatal pedestrian/pedalcycle crashes closely tracked the seasonal change in light level within a 6-hour time band called the *twilight-zone*. The time band included a 3-hour window each around the morning and evening hours of sunrise and sunset. Pedestrian/pedalcycle fatalities during this 6-hour time band appeared to decrease toward the summer solstice in response to the increases in the duration of daylight, and increase toward the winter solstice with the decrease in daylight. In addition, they found no significant correlation between illumination level and *nonpedestrian* accidents, suggesting that this broad class of crashes is unrelated to illumination levels. With respect to the emphasis on pedestrian vulnerability and light level, this conclusion is consistent with research on roadway illumination. However, roadway illumination studies also differ in that they have often revealed at least some effect of lighting on *nonpedestrian* crash data as well.

Pedestrians were also found to be especially vulnerable in studies that exploited the abrupt changes in light levels for certain time intervals across the annual transition to and from daylight savings time (DST) and British summer time (BST). Ferguson, Preusser, Lund, Zador, and Ulmer (1995) reported that the change from daylight to twilight in the fall return to standard time produced a 300% increase in fatal pedestrian crashes (or, expressed otherwise, a reduction of 75% between twilight and daylight fatalities). In contrast, only a 15% increase was found for fatal vehicle-occupant crashes. This was also consistent with a study by Tanner (1956) which made precisely the same estimate of the effect of darkness on adult pedestrians fatalities. Whittaker (1996) also examined the transition associated with BST among pedestrians, cyclists, and vehicle passengers. Although the results were not clear cut because of the limited geographical scope of the study (and consequent small sample size), suggestive trends were present in the data to implicate light level as a factor affecting crashes. In some cases, pedestrian casualties showed the greatest sensitivity to changing light conditions (in particular, the fall return to Greenwich Mean Time—GMT). However, in other cases little evidence was apparent that light level plays any role. For example, pedestrian casualties in the morning decline in the spring start of BST when the transition was from light to dark. Whittaker speculated that this was caused by diminished exposure of the population: Instead of walking, children were driven to school in the darker hours, reducing the numbers of pedestrians on the streets. As will be discussed later, the issue of population exposure such as this often complicates the interpretation of crash data.

In summary, most existing research on crash data converges on the conclusion that pedestrians are the road users who are most vulnerable to dark conditions. There is also general agreement that this vulnerability exists because, in the dark, pedestrians are not easily visible, lacking reflective material or marking lights to make their presence evident to a driver.

There is less evidence that lighting condition plays a role in other types of crashes. Only mild trends seem to exist for nonpedestrian crashes. It may be that light is truly less important in such crashes, but perhaps pooling vehicle crash statistics over many nonpedestrian crash types obscures effects of light that might otherwise be revealed if sampling were done in a more selective fashion. Vehicle crashes occur for many reasons. Drivers may be tired, inattentive, intoxicated, or have momentary lapses of judgement. Roadways may be icy, wet, covered in snow, or obscured by fog. Any of these conditions could precipitate a crash, independently of light level. In this report, we will specifically examine data for one particular nonpedestrian crash type (single-vehicle, run-off-road) in which we may be most likely to observe effects of light level and in which *curve illumination* adaptive lighting is likely to be useful.

3.0 Experimental Overview

This research indirectly measures the influence of light level on crash statistics by using two different methods for selecting data from the large databases available through the National Highway Traffic Safety Administration (NHTSA). One method, borrowed from Owens and Sivak (1993), investigates the match between the seasonal fluctuation in crash statistics and light level during morning and evening periods around twilight. The other method, similar to one used by Ferguson et al. (1995) examines whether the abrupt changes in light level associated with the changeovers to and from daylight savings time (DST) are reflected in changes in crash statistics. Each method provides a way of comparing crash frequencies during dark periods with those during light periods, allowing a determination of the significance of light level in contributing to a crash.

The crash data used in these studies include 11 years (1987-1997) of NHTSA's Fatality Analysis Reporting System (FARS), and 10 years (1988-1997) from the National Automotive Sampling System (NASS) General Estimates System (GES). The FARS data are essentially a detailed census of all fatal crashes that have occurred in the United States. They contain only crashes in which at least one of the persons involved died within 30 days of the crash.

The GES database is an estimation database, providing a means to statistically approximate frequencies of specific types of crashes. It is limited in its ability to resolve highly detailed questions; as the number of sampled cases becomes small, the sampling error increases. Here, its use is limited to investigating the possible role of severity level in nonpedestrian accidents.

3.1 Determining the Role of Light in Crash Data.

Comparing Night and Day. In the U.S., the total number of fatal crashes during all nighttime hours is about the same as the total for the daytime hours (see Figure 1), despite smaller traffic volumes at night. Thus, road conditions appear to be significantly more dangerous at night. Although it may seem obvious that darkness is a key factor, determining how darkness, by itself, contributes to this danger is not straightforward. At night, there are fewer drivers on the road, the incidence of driver fatigue or intoxication is higher, and the driver demographics are different. In 1997, for example, there were 18,414 fatal crashes between the hours of 6 P.M. and

6 A.M.; 59% of them were alcohol-related. In contrast, during the daytime, between the hours of 6 A.M. and 6 P.M., there were 18,530 fatal crashes; only 17% were alcohol related (National Highway Traffic Safety Administration, 1998c, p. 56). Without some effort to control these factors, drawing any inferences about light level and crash rates from day/night comparisons is precarious.

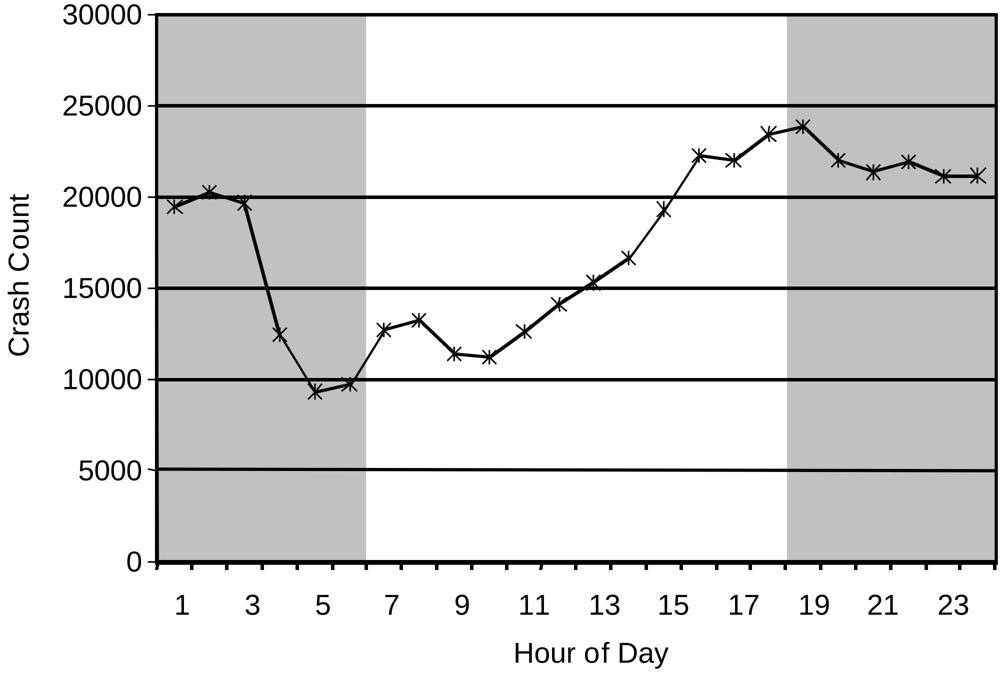

Figure 1. Overall number of fatal crashes by time of day. Compiled over an 11-year period from FARS, 1987 through 1997.

Using Seasonal Changes in Light. To help control factors unrelated to light level, Owens and Sivak (1993) looked at restricted time windows in which it was assumed that, throughout the year, factors like fatigue, alcohol use, traffic density, etc. would either remain fixed or not systematically vary with light level. One pair of time intervals was chosen to include that part of the day in which the start and end of civil twilight fluctuated throughout the year. Civil twilight starts and ends when the sun is 6 degrees below the horizon in the morning (ending at sunrise) and evening (starting at sunset). At this time, ambient illumination under good weather conditions is sufficient to distinguish the horizon and other objects. The two time intervals were collectively referred to as the *twilight zone* (see Figure 2). Other intervals, which were light all year or dark all year, were chosen to straddle the twilight zone, to be used as controls for factors other than light level.

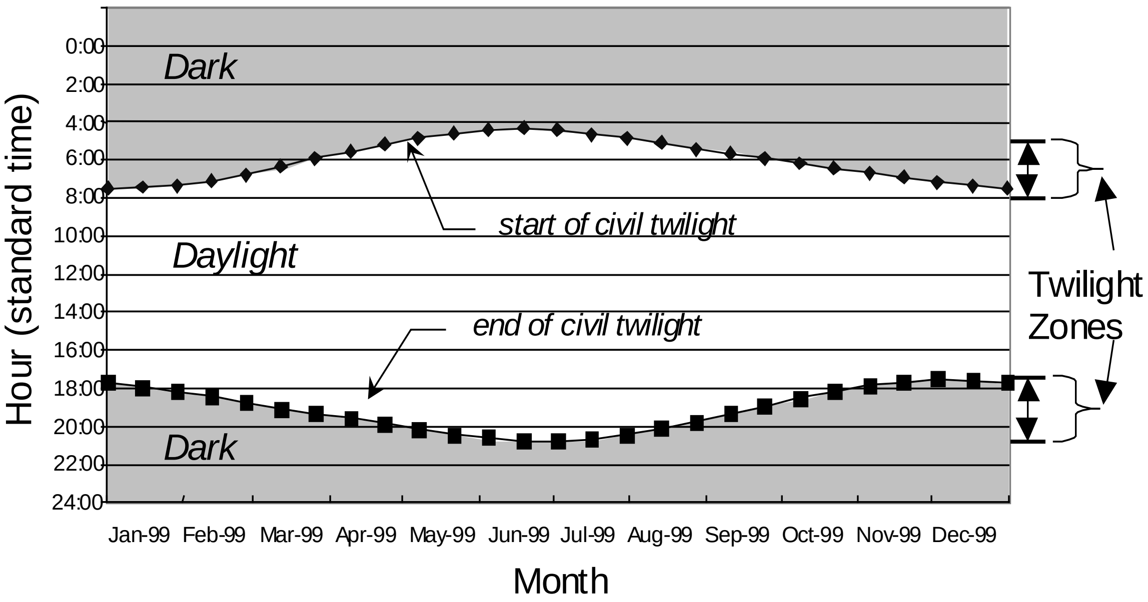

Figure 2. Example solar cycle for start and end of civil twilight for 83W longitude, 43 latitude, in standard time.

As Figure 2 shows, at the summer solstice (late June), these intervals are mostly in daylight. In the winter, as the length of the day shortens, the intervals are mostly in darkness. Using the twilight zone bands, Owens and Sivak examined pedestrian/pedalcycle and all other types of crashes month-by-month throughout the year. They found that proportions of pedestrian/ pedalcycle crashes fluctuated with the sun's seasonal cycle: Rates were smaller in the summer when there is more daylight, and higher in the winter when there is more darkness. No such effect was found for the other types of crashes, suggesting that light level selectively affected pedestrians.

As noted earlier, that study attempted to control confounding factors by selecting a narrow time window—the twilight zone—in which it was assumed that there was little or no systematic variation in (possibly confounding) factors related to season. While this may be effective in controlling the day/night confounds like fatigue level, alcohol use, and driver demographics, it also introduces other possible confounds like weather conditions and pedestrian exposure levels that are known to vary seasonally. As always, one should be cautious interpreting the results, and acknowledge the possible effects of such confounding factors.

To apply this analytic technique, we apply the procedures used by Owens and Sivak to 11 years of FARS crash data from 1987 to 1997 for 47 of the continental states, excluding Arizona. (Owens and Sivak's study included data from 1980 to 1990.) The same twilight-zone time intervals (based on the mean solar cycle for the middle latitudes of each United States time zone) defined by Owens and Sivak were used in this study along with the Daylight and Nighttime intervals. Each crash record was grouped into an A.M. and a P.M. time period of Twilight, Daylight, and Nighttime as shown in Table 1. All data from within periods of daylight savings time (DST) observance used clock times one hour later than standard time, effectively converting times back to standard time. For example, the Twilight times of 4:00 to 6:59 A.M. under standard time was grouped with the times 5:00 to 7:59 A.M. under DST. The exact dates of the changeover to DST for each year were adjusted.

Table 1. Definition of test periods of Twilight, Daylight, and Nighttime for standard time and daylight savings time in Owens & Sivak (1993).

Period	Clock Times Included	
	Standard Time	Daylight Savings Time
Twilight	0400-0659 hr 1700-1959 hr	0500-0759 hr 1800-2059 hr
Daylight Control	0700-0959 hr 1400-1659 hr	0800-1059 hr 1500-1759 hr
Nighttime Control	2000-2259 hr 0100-0359 hr	2100-2359 hr 0200-0459 hr

Daytime and Nighttime periods were defined so that they would contain the same number of hours as the Twilight period, and could serve as control conditions containing periods of total light and total darkness. Selection was constrained to the 3-hour intervals straddling the Twilight zones (depicted in Figure 3). Thus, each time interval spanned 6 hours, or 25% of the day; and the combined set of three time intervals (Twilight, Daylight, and Nighttime) represent 75% of the day. If crashes were equally probable throughout the day, we would expect to see 25% of the total number of crashes appear in each time period. The residual interval, labeled "Other," contains 2 hours of darkness and 4 hours of light.

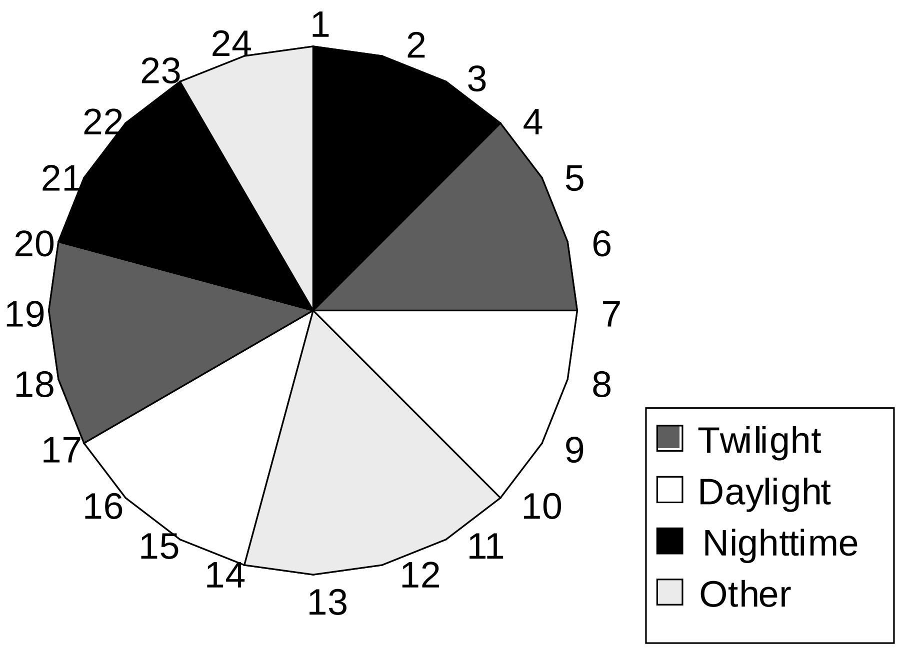

Figure 3. Distribution of Twilight, Daylight, Nighttime, and Other time intervals throughout a twenty-four hour day. Hours are given in standard time.

The Daylight and Nighttime periods provide control conditions to permit detection of seasonal variation in crash rates that are unrelated to light conditions. Owens and Sivak make the further assumption that such factors (like severe weather) probably exert the same influence on all intervals. Thus, many of their results are reported as relative proportions in order to factor out these influences from the analysis. Use of this technique will be reviewed in Quasi-Experiment I.

Using this analysis method, various crash characteristics can be selected from FARS over the 11-year period, and compiled for each month for the Twilight, Daylight, and Nighttime intervals. Patterns in the data for a particular type of crash that coincide with the changing pattern of light, as a function of the months of the year, would suggest that such a crash is influenced by light level. The amplitude of the seasonal variation could then be used as an estimate of how sensitive that type of crash was to light level.

Comparing Daylight Savings Time Changeovers. As indicated above, to control for seasonal variation in exposure levels and weather, several researchers have exploited daylight savings time (DST) or British summer time (BST) (Ferguson et al., 1995; Tanner, 1956; Whittaker, 1996). In the springtime, many jurisdictions change their official clock time ahead by one hour. In the fall, clocks are reset back to standard time. This action has the effect of extending the summer P.M. daylight an additional hour, and creating abrupt changes in light level within particular intervals around the start and end of civil twilight (Figure 4). This is an ideal condition for viewing the effect of light level while, at the same time, limiting the potential for seasonal confounds like those described earlier.

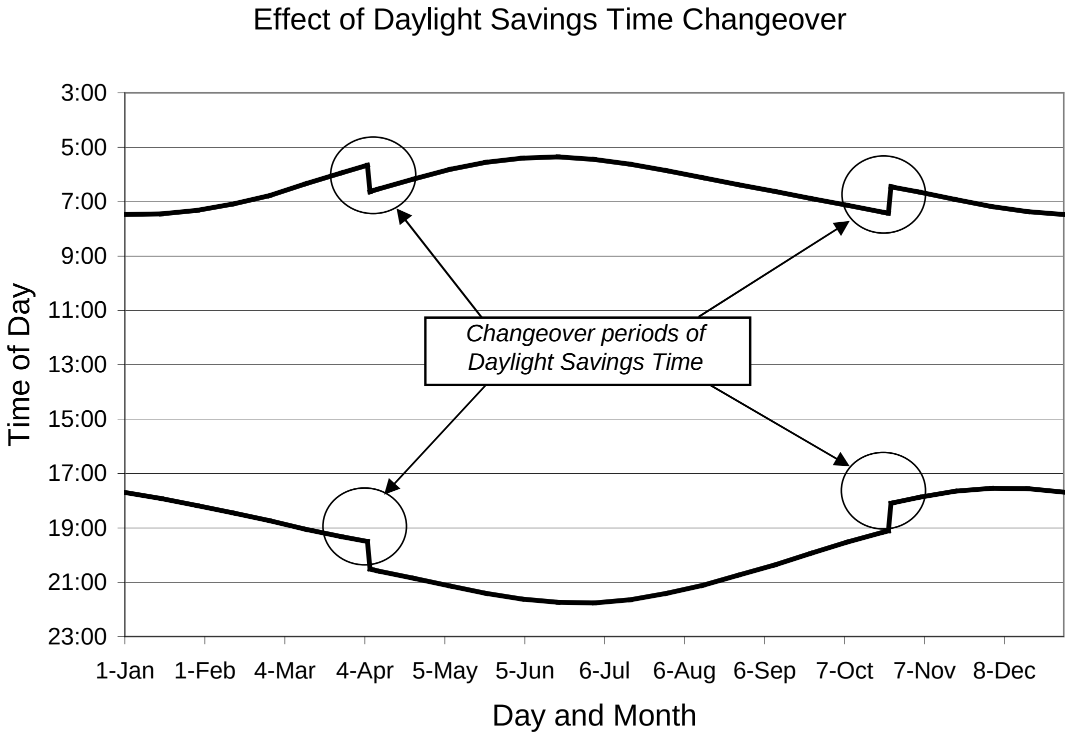

Figure 4. Daylight savings time transition points superimposed on the solar cycle. The morning transition patterns produce a saw-tooth transition. For example, in the spring dark gradually becomes light and abruptly changes to dark and again gradually changes to light. In the evening, there is a step change from dark to light (and light to dark).

The procedure involves comparing crash frequencies before and after the transitions during time intervals in which the lighting change is most dramatic. For example, there is a morning time period in the spring, which, prior to DST, is in twilight and changes to darkness. In the evening, there is a period that was dark in standard time and abruptly transitions to light. Comparable changes in the crash statistics would strongly implicate light level as a critical factor.

Like the investigation of seasonal variation in light level, this method will also be used to investigate specific kinds of crashes in order to assess how sensitive they are to light levels. It is hoped that both methods converge on a similar estimate of the degree of influence light has on crash statistics.

3.2 Selection of Crash Database Records

This investigation is primarily concerned with the kinds of crashes that might be either reduced or eliminated with the use of an adaptive lighting system. Here we identify three crash scenarios that we associate with different kinds of adaptive lighting solutions, and provide a rationale for their selection.

Scenario 1: Pedestrian Crashes at Intersections. This scenario was chosen to evaluate the potential effectiveness of various specific forms of adaptive headlighting that might make pedestrians more clearly visible at intersections, by providing, for example, side or corner lamps. Conflicts occur when vehicles make turns into pedestrian crosswalks while attempting left or right turns. Side/corner lamps are typically activated by the turn signal, and illuminate a wide near area, at a 45 degree angle to the side in the direction of the turn (e.g., Kobayashi, Takahashi, & Yagi, 1997). Of all the fatal pedestrian crashes covered during the 11-year period (61,243), 21% (12,831) of them happened at intersections. Furthermore, 57% of the pedestrian intersection crashes occur when the light levels are low, suggesting that low light levels may add to the problem.

To assess this possible benefit, FARS crash records will be examined for pedestrian fatalities occurring at roadway intersections.

Scenario 2: Pedestrian Crashes on Dark, Straight, High-Speed Roads. This scenario is intended to quantify the potential effectiveness of adaptive headlamps that tailor their forward illumination power to vehicle speed so that at higher speeds, the driver will be able to see further down the road than is possible with conventional low beams. One solution, for example, tapers the high beam using lenses so that it narrows to a longer forward range at high speed and widens at lower speed (Groh, 1997). Other systems add supplemental illumination as a function of vehicle speed (e.g., a low beam with a hot spot, Hogrefe & Neuman, 1997). These solutions address two problems. At night, drivers typically drive at speeds well in excess of their ability to see and react to an obstacle in the roadway (Johansson & Rumar, 1968; Olson & Sivak, 1983;

Leibowitz, Owens, & Tyrrell, 1998). The other problem is that drivers apparently under-use their high beams (Hare & Hemion, 1968)[1]. As a consequence, nighttime forward visibility is habitually less than is needed to properly react to a pedestrian in the middle of the road. This is especially a problem with high-speed driving.

To investigate the potential utility of this adaptive lighting solution, we looked to rural roads, which are predominantly unlit at night. We further restricted the selection to posted speed limits above 40 mph (64 kph), to increase the likelihood that drivers would be exceeding their ability to respond to roadway obstacles in darkness; and to include only straight sections of roadway where actual high speed is likely. Pedestrian crashes are singled out because pedestrians are often unlit, unexpected, and (most likely) unseen on dark roads. Although pedestrians are not the only objects drivers are likely to collide with—animals, fixed objects, and parked cars are commonly found at the impact end of a crash—they *are* most likely to result in a fatality and thus be recorded in the FARS crash census.

Scenario 3: Single-Vehicle, Run-Off-Road Crashes. One commonly cited shortcoming of conventional, fixed headlamps is their poor ability to properly illuminate a curved stretch of roadway. Depending on the turn direction, fixed headlighting either directs excessive light into the shoulder or into the lane of oncoming traffic, creating a glare hazard. At the same time, insufficient light is cast in the direction of travel. Curved sections of road are reported to be more hazardous than straight lengths of roadway especially at night (Aoki et al., 1997; Merrit et al., 1982; Perel et al., 1983). Table 2 summarizes 11 years of FARS data looking at road alignment by lighting condition. Within the dark lighting condition, curved roads appear to be more risky than the other lighting conditions; the difference is 10% above the daylight condition. Of course, this analysis relies on the assumption that the roadways in each category are comparable in all respects other than light level. In fact, it may not be safe to make this assumption. For example, roadways with lighting are often located in urban areas; unlighted roads are more common in rural areas. As will be seen, the analyses to be reported avoid this problem.

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[1] Some also have suggested that a narrow forward beam also helps to properly direct a driver's attention forward, where the car is heading, avoiding foreground distractions. If so, this is not an effect that can be assessed using daylight.

If we assume that the best an adaptive headlighting solution might do is to duplicate the daytime levels, this would mean that about 13,540 fatal crashes (over 11 years) could have been avoided (or 1,231 per year). Adaptive headlighting systems addressing this problem typically take information from steering wheel angle, vehicle speed, and sometimes roadway databases, to either activate additional light sources or pivot existing light sources to illuminate the direction of travel.

Table 2. Fatal crashes by lighting condition and road alignment 1987 to 1997.

	Road Alignment	
Lighting Condition	Straight	Curved
Light	152,131 (77%)	44,370 (23%)
Dark	89,413 (67%)	44,292 (33%)
Dark w. Road Lighting	57,243 (82%)	12,619 (18%)
Dawn	5,694 (76%)	1,801 (24%)
Dusk	7,381 (75%)	2,411 (25%)
Unknown	646 (60%)	434 (40%)

This crash scenario was investigated by choosing records for rural (and most likely unlighted), curved roadways, that involve single vehicles, and whose final relation to the roadway is not *on roadway* (i.e., the vehicle has run off the road). Admittedly, the benefit of this form of headlighting probably extends beyond this restrictive sample—poorly illuminated objects like pedestrians or animals are probably made more visible with it, but these cases are excluded from the sample. Nevertheless it seems worthwhile taking a look at these crashes because of the possible importance of illumination in fatal, single-vehicle, run-off-road crashes.

Crash Data Limitations. It should be generally recognized that crash databases provide a less than perfect means to examine the causal connection between a factor and a crash outcome. The researcher is largely at the mercy of naturally occurring events and cannot impose any direct control whatever on the data. Thus the effects of lighting conditions cannot be determined simply by comparing night to day. Many other factors covary with day and night. There is more traffic in the daytime than at night; because of this, crashes are more likely to occur in daylight. Fewer drivers in general, and fewer older drivers in particular, choose to drive at night. The locations where crashes take place are different between night and day. For example, 74% of fatal nighttime crashes occur on rural roads, whereas 60% of fatal daytime crashes occur on rural roads (FARS 1987-1997). To be sure, this statistic might be attributed to the general absence of fixed lighting on rural roads. However it should be noted that rural roads often have less favorable road geometry, are unlikely to include barriers separating traffic flow, and probably exhibit different daily traffic patterns than urban roads. Each of these factors may contribute to the fatality statistics. Alcohol involvement also increases at night. Between 1987 and 1997, during daylight hours, alcohol was involved in 19% of fatal crashes; at night, it was involved in 56% of fatal crashes. Clearly, light level is not the only factor influencing crash rates at night.

Researchers have found ways to untangle some of these factors by normalizing the data, or applying selection criteria to the crash records. For example, crash data are normalized against measures of traffic volume so that crash statistics are given in terms of crashes per 1,000 miles of vehicle travel. This corrects for the amount of exposure. One method, described previously, attempts to control confounding factors by fixing the time of day and comparing seasonal variation in crash rates as a function of light level. If one assumes that alcohol consumption, and other factors, are relatively the same throughout the year within the twilight-zone time band (and are independent of light level) this is an effective control. Another method compares changes during DST changeover time periods to control seasonal factors (like weather conditions) unrelated to light level.

Beyond controlling for contamination by other factors, there are some limitations that even canny data-analysis techniques cannot overcome. Sometimes the data of interest are not explicitly available. For example, ambient light levels are unknown in FARS beyond the categories of light, dark, dark with lights, dusk, and dawn. Thus, we cannot know with precision what the exact light levels are. Another example is that we cannot restrict our analysis to investigate only unlit roadways. The availability of roadway lighting is only given when the crash occurs at night. The lighting condition variable identifies roads with lights if the crash occurs in the dark; but in daylight, we have no information on whether the roadway has lights. Such information could be valuable because the presence or absence of light is probably correlated to other road characteristics— that are important in the day as well as at night—such as traffic volume, curve geometry, and type of traffic control devices.

In the FARS database, only fatal crashes are recorded. No information on less severe crashes can be gleaned from the database. In contrast, crash-severity information is available in the General Estimates System (GES), but because it is an estimation database, precise information about locale and time of crash are not available, making it difficult to impose selection criteria requiring precise knowledge of time and place. Because GES is an estimation system, there is proportionately larger error associated with the smaller counts, making crash counts using restrictive selection criteria subject to large estimation errors.

4.0 Quasi-Experiment I: Replication of Owens and Sivak (1993)

This experiment replicates Experiment II of Owens and Sivak (1993) both to update their results to include more recent data and to examine in more detail the characteristics of both pedestrian and pedalcyclist vulnerability as a function of light levels. These two victim classes differ in ways that suggest differences may exist in their pattern of vulnerability. For example, the pedalcyclist population is probably more reactive to seasonal weather variation than pedestrians. In 1997, most pedalcycle fatalities occurred during the months of June, July, and August (35%; NHTSA, 1998a). This is likely a consequence of seasonal exposure differences: more pedalcycles are on the road during the summer months when school is in recess and the weather is agreeable. Coupled to this problem is the fact that school-aged children dominate the population of pedalcycle victims. Forty percent of the victims in 1997 were between the ages of 5 and 20. In contrast, this age range makes up only 15% of pedestrian victims (NHTSA, 1998b).

Seasonal changes in exposure level could be normalized against other times of day if the seasonal changes were independent of time of day. For example, if a 10% increase in pedalcyclist exposure in summer afternoons is accompanied by the same increases at other times of the day, normalization using crash proportions during the day intervals could factor out changing exposure. Unfortunately, when school is in recess during the summer months, school-aged children become more exposed during the daytime hours when they would otherwise be attending school. If looked at as proportions, a disproportionate *increase* in the daytime fatalities might appear as a *decrease* in other time-interval proportions.

Differences in the conspicuity of pedalcycles and pedestrians may also influence vulnerability. Since 1976, the Consumer Product Safety Commission bicycle regulations have required reflectors on the front and rear of the bicycle, and on the pedals and wheels; likewise bicycle helmets, although not yet strictly regulated, are often fitted with reflectors. In contrast, pedestrians do not normally wear any reflective material. Thus, pedalcycles may actually be more visible than pedestrians at night and therefore be less subject to the effect of light level.

Thus, this experiment investigates the seasonal effects of light level and the advisability of grouping pedestrians with pedalcyclists. Each group's seasonal pattern of fatal crashes is examined separately.

4.1 Method

This experiment used crash data from FARS selected from the 11-year period from 1987 to 1997. As previously described, each crash record was grouped into one of three time-interval categories based on the time of day when the crash occurred—Twilight, Daylight, and Nighttime (as shown in Table 1). Data from 47 of the continental United States were included in the analysis (as mentioned earlier, Arizona was omitted). The central hypothesis of Owens and Sivak (1993)—that light level affects pedestrian crashes—was investigated by examining the pattern of crashes throughout the year. It was predicted that the pattern of fatalities in the Twilight time period should follow the period's pattern of light level. In the winter, when the period is mostly dark, pedestrian crashes should crest; in summer, when the period is mostly in light, pedestrian crashes should plunge.

First, the overall frequency of fatal crashes throughout the year is examined for the selected time intervals and compared against the overall crash rate to assure that the sampled intervals collectively contain a representative proportion of the crash data. Since the time intervals represent 75% of the day, we expect they will collectively contain approximately 75% of the crash records. Next, we replicate Owens and Sivak, but we select only pedestrian crash data and compare this result with nonpedestrian crash data. Finally, pedalcycle data are examined separately to assess whether pedalcycle crash patterns are substantially different from pedestrian patterns. Both crash *count* and crash *proportions* are reported for each data summary.

4.2 Results

Over the 11-year period investigated, there were a total of 419,994 fatal crashes resulting in 471,047 fatalities; 313,525 (74.6%) of these occurred during the combined test periods, approximating the 75% portion of the time in a day contained in the combined test periods; 49,557 (11.8%) fatal crashes involved pedestrians during the combined periods.

Looking at the subpopulation of pedestrians, overall 61,243 (14.6% of all fatal crashes) fatal crashes involved pedestrians, and 81% of these cases fell within the combined time periods. This suggests that pedestrian fatalities may not be distributed quite the same way as the pooled accidents. Owens and Sivak found a similar pattern. Their test intervals contained 74.9% of all crash data, and when restricted to pedestrians and pedalcycle crashes, the test intervals included 79.6% of the data. Figure 5 shows how the makeup of the sampled time interval fluctuated annually. It reached a minimum of 76% in July and a maximum of 84% in December. The drop in the proportion at midyear appears to be related to increasing numbers of pedestrian crashes around the midday and midnight hours (which comprise the *non-experimental* time period), as suggested by the contour map of pedestrian crashes in Figure 6.

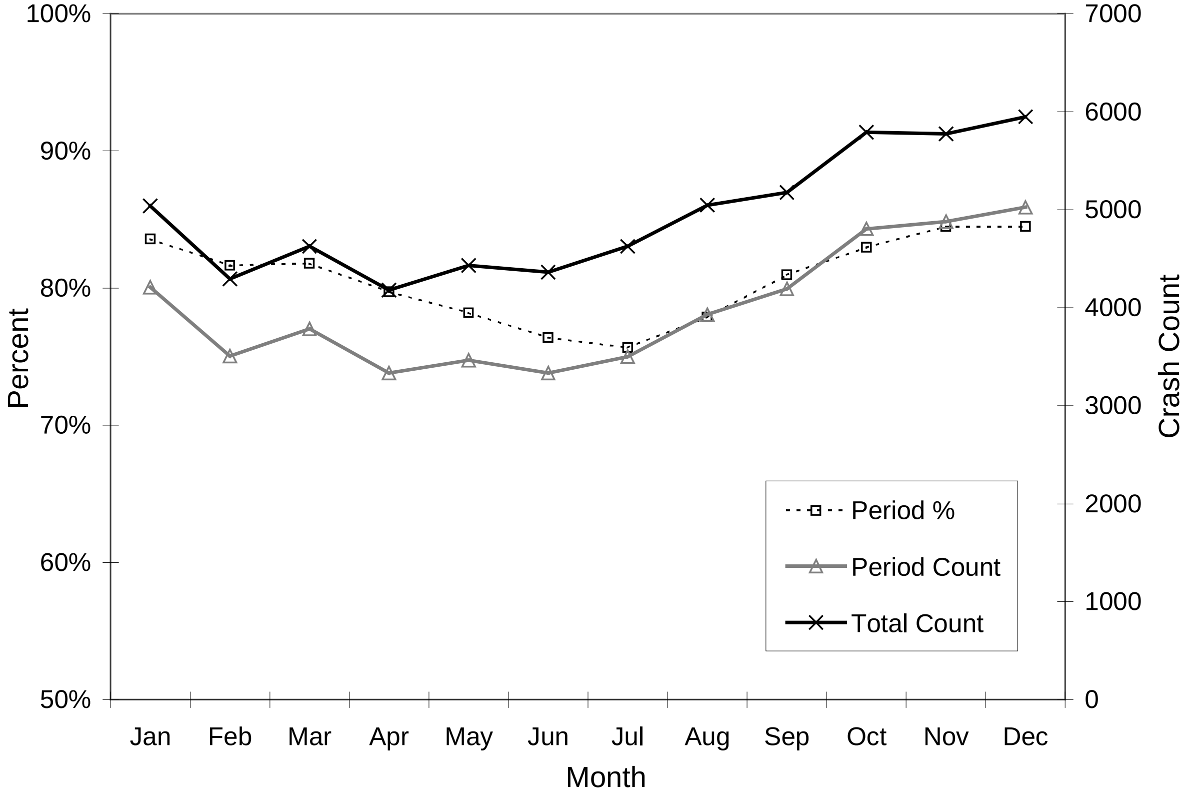

Figure 5. The distribution of all pedestrian crashes by month, within the combined Twilight, Daylight, and Nighttime periods. Percent variation is between 74% and 86%.

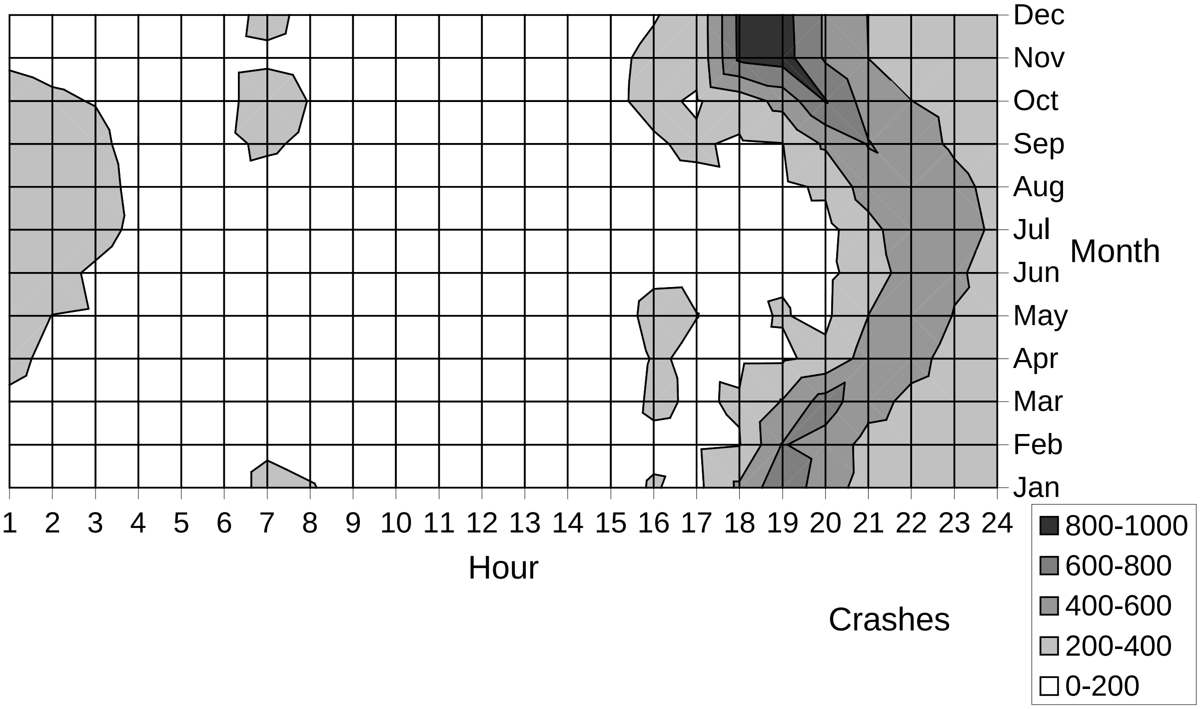

Figure 6. Contour map of fatal pedestrian crashes. Crash counts are compiled for each hour of each month for an 11-year period from 1987 to 1997.

In contrast to the broad pattern of pedestrian crashes, nonpedestrian crashes seem to *escalate* during the summer months and reach their peak in August (34,019; see Figure 7). They are at a minimum in February (22,273). The overall proportion of crashes falling within the test intervals ranges from a minimum of 72.0% (23,861) in August to a maximum of 75.2% (24,503) in February (overall mean of 73.2%). This is lower than the proportions observed with pedestrians, and the trend is opposite to the overall count totals, suggesting that slightly disproportionate increases in crashes occur during the time period outside of the test intervals.

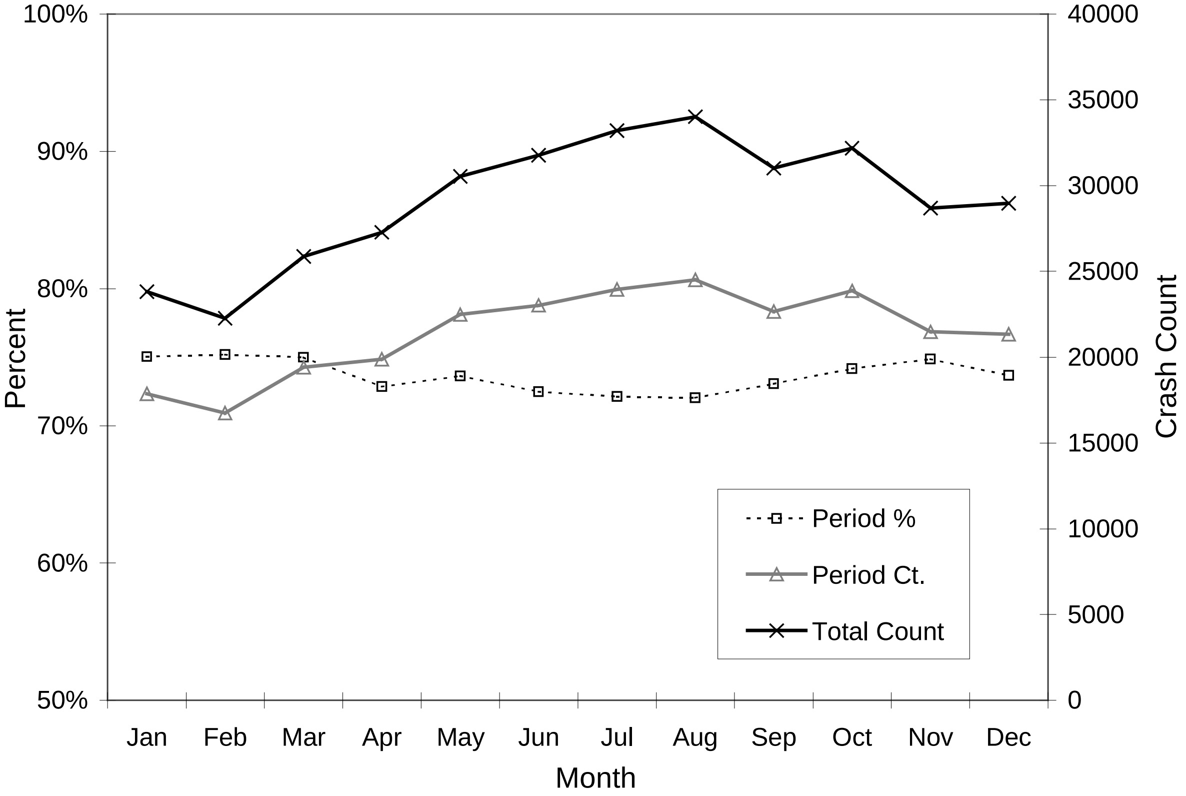

Figure 7. The distribution of all nonpedestrian crashes by month within the test periods Twilight, Daylight, and Nighttime (1987-1997). Percent variation is between 72% and 73 %.

Turning to the breakdown of nonpedestrian crashes into the test time periods, Figure 8 and Figure 9 show the monthly crash counts and percentages, respectively. Depicted as percentages (Figure 9), little seasonal trend is apparent in the data. The proportion of fatal crashes in the Twilight zone ranged from 22.1% in June to 23.8% in October, with a mean of 23.0%; those in the Daylight Control period ranged from 24.3% in August to 26.4% in January, with a mean of 25.1%; and those in the Nighttime Control period ranged from 24.9% in October to 26.8% in March, with a mean of 25.5%. Unlike Owens and Sivak (1993), the Nighttime Control period was indistinguishable from the Daylight Control period. The result appears to be related to the difference in sampling periods used in each study. Owens and Sivak report results for the years 1980 to 1990; here we report on 1987 to 1997. As Figure 10 shows, prior to 1989, nighttime crashes exceeded daytime crashes. However, there has been a general decline in the overall number of nighttime fatal crashes since 1988, while there has been an increase in the number of daytime fatal crashes. This likely accounts for the difference.

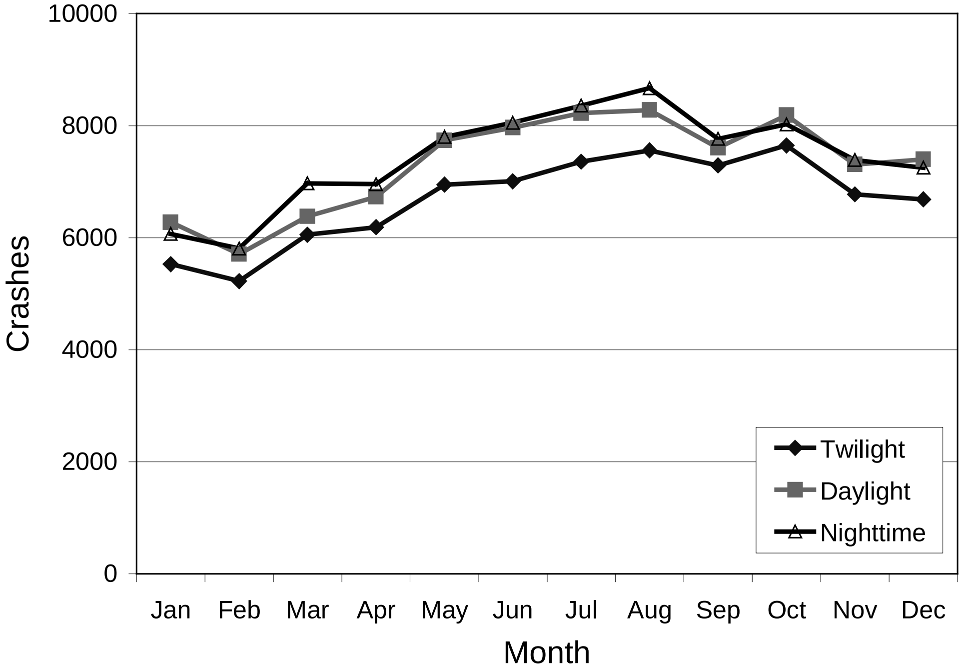

Figure 8. Cumulative fatal nonpedestrian crashes by month for the Twilight, Daylight, and Nighttime periods, from 1987 to 1997.

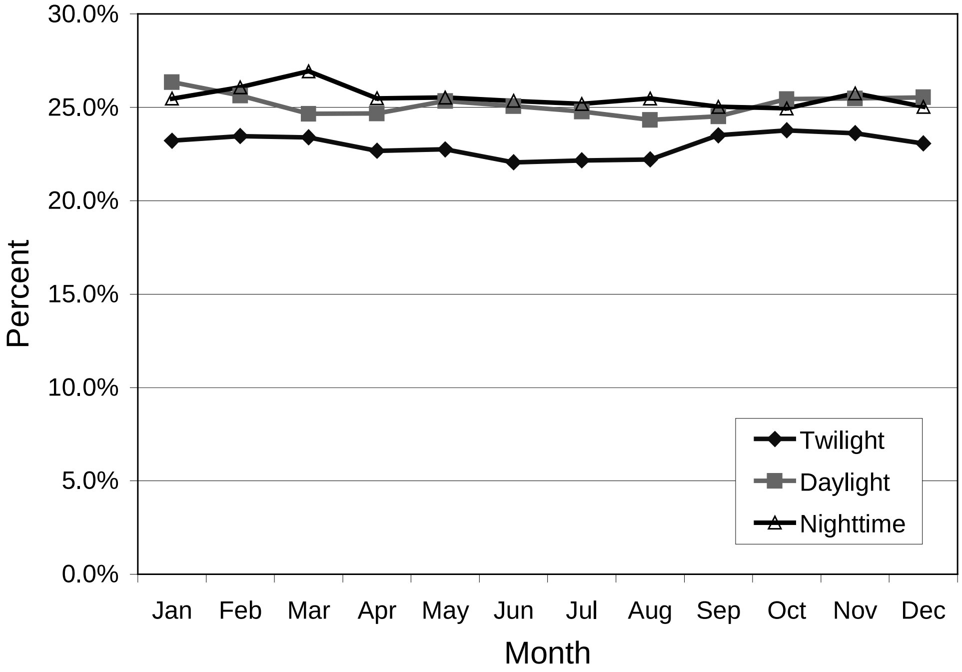

Figure 9. Proportions of fatal nonpedestrian crashes by month during the Twilight, Daylight and Nighttime periods from 1987 to 1997.

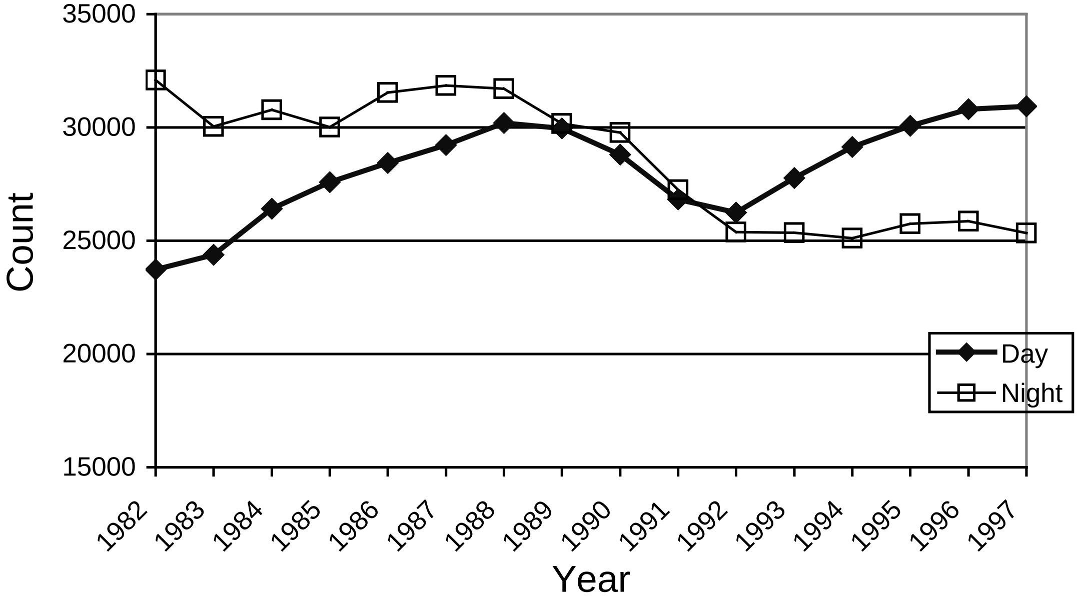

Figure 10. Annual fatal crash totals for daytime and nighttime periods, from 1982 to 1997 (NHTSA, 1997c).

Pedestrian crashes are shown in Figure 11 (counts) and Figure 12 (proportions). Unlike the nonpedestrian data, a strong trend is apparent during the Twilight period, which follows a pattern that tracks the seasonal changes in light levels within this period. The proportion of fatal crashes in the Twilight zone ranged from 18.4% (852 crashes) in July to 44.9% (2,671) in December with a mean of 32.9%. The proportion of crashes in the Daylight Control period, over which illumination is uniformly light, show little seasonal variation. They range from 16.0% in December to 19.6% in June with a mean of 17.4%. The proportions in the Nighttime Control, which is uniformly dark, show the opposite pattern to the Twilight period—proportions of fatal crashes are generally higher in the summer, and lower in the winter. They ranged from 23.3% in November to 40.8% in July with a mean of 30.7%. Owens and Sivak found the same pattern, suggesting it is a consequence of heightened pedestrian exposure in the summer, and reduced exposure in the winter. Thus it seems that omission of pedalcyclist data from the sample changes little in the results.

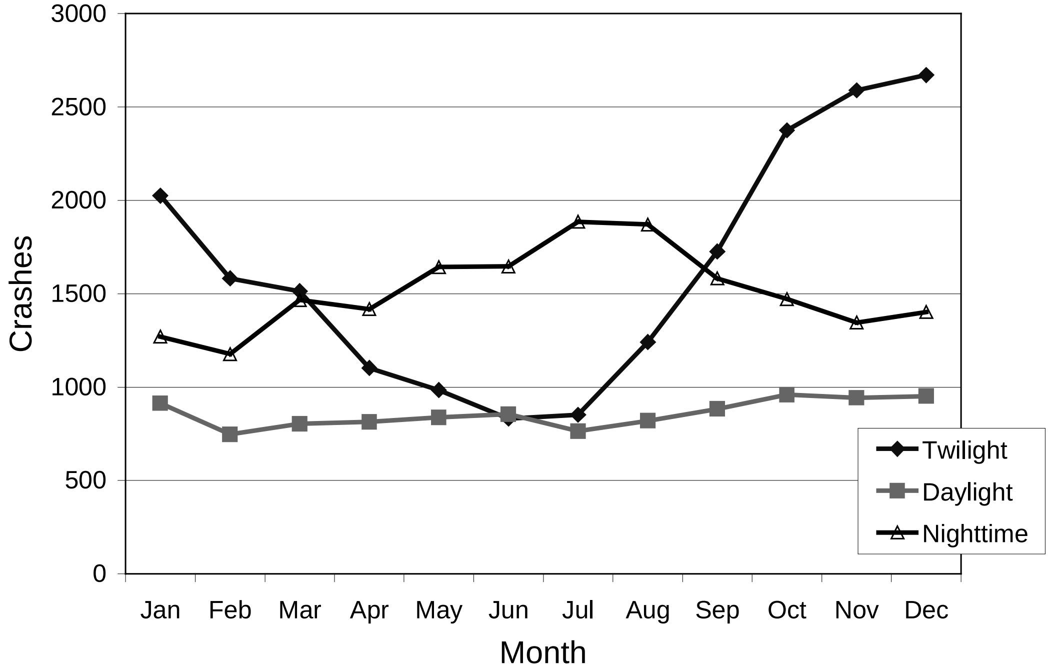

Figure 11. Cumulative fatal pedestrian crashes by month for the Twilight, Daylight and Nighttime periods from 1987 to 1997.

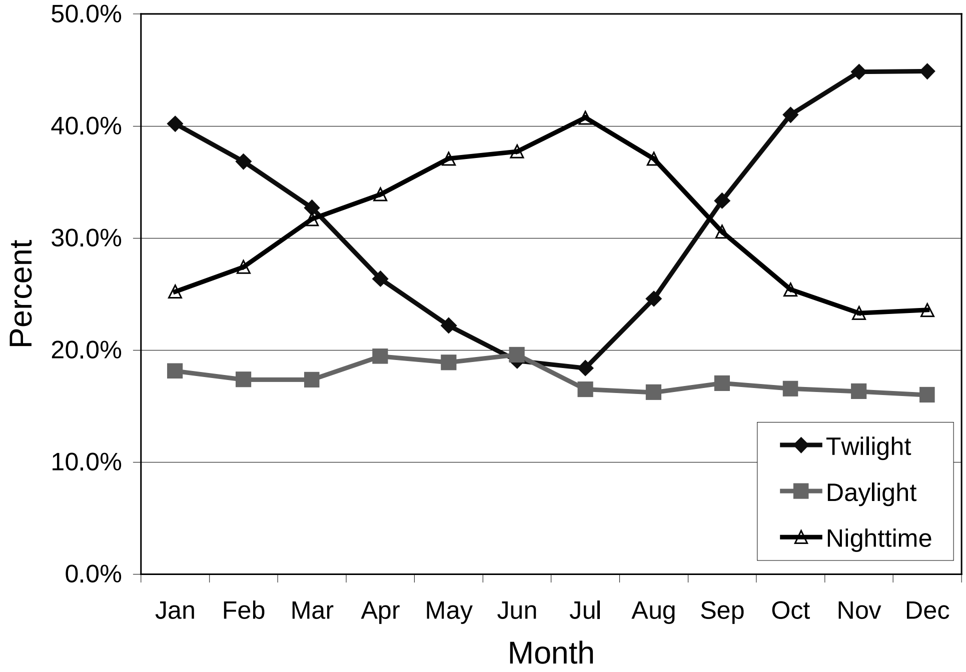

Figure 12. Proportions of fatal pedestrian crashes by month during the Twilight, Daylight and Nighttime periods from 1987 to 1997.

Next, we turn to pedalcyclist data shown in Figure 13 (counts) and Figure 14 (percentages). The percentage plot (Figure 14) appears to show a similar twilight pattern as that observed with pedestrians; a minimum is reached in the summer (June) when it is light, and a peak occurs in winter (January) when it is mostly dark. However, unlike the pedestrian data, the raw counts of fatal pedalcyclist crashes (Figure 13) increase in the Daytime Control period over the summer months, and are consistently higher in the daytime than at night. Perhaps during the spring and summer, when the weather is temperate, more pedalcyclists take to the road, thereby increasing their exposure to traffic hazards. It is also likely that there are more pedalcyclists on the streets during the daytime than at night, creating more opportunity for daytime fatalities.

Of course, the same could be said for pedestrians. Nice weather is bound to bring more of them out onto the streets; and more are likely to be out in the daytime than at night. Yet, despite this, we see that fatal pedestrian crashes defy the probable exposure trend and *decline* as weather improves and remain consistently *lower* during the daytime than at night. Perhaps pedestrian fatalities are more strongly influenced by lighting conditions than pedalcycle fatalities. Bicycles are routinely fitted with reflectors, making them somewhat more conspicuous in the dark than pedestrians, and therefore less affected by lighting conditions. Weather conditions may also have a much greater influence on pedalcycle exposure than pedestrian exposure. Few but the hardiest of pedalcyclists would venture out in a snowstorm, yet pedestrians will routinely brave severe weather to get around town. Finally, as mentioned earlier, the makeup of the pedestrian and pedalcycle victims differs. For example, in 1997 the age range 5 to 20 years represented about 15% of the fatal pedestrian crashes; the same age range represents 41% of the pedalcyclists. Because school-aged children represent a significant part of the pedalcyclist data, it is likely that whether school is in session or in recess also matters.

Given that pedestrian and pedalcyclist populations apparently differ in their sensitivity to lighting conditions, and given that fatal pedestrian crashes are sufficient to illustrate the seasonal effect of light levels, it seems reasonable to exclude pedalcyclists from further analysis. Doing so may help reduce spurious seasonal variation associated with the school calendar and perhaps heighten the contrast between daylight and dark crash levels.

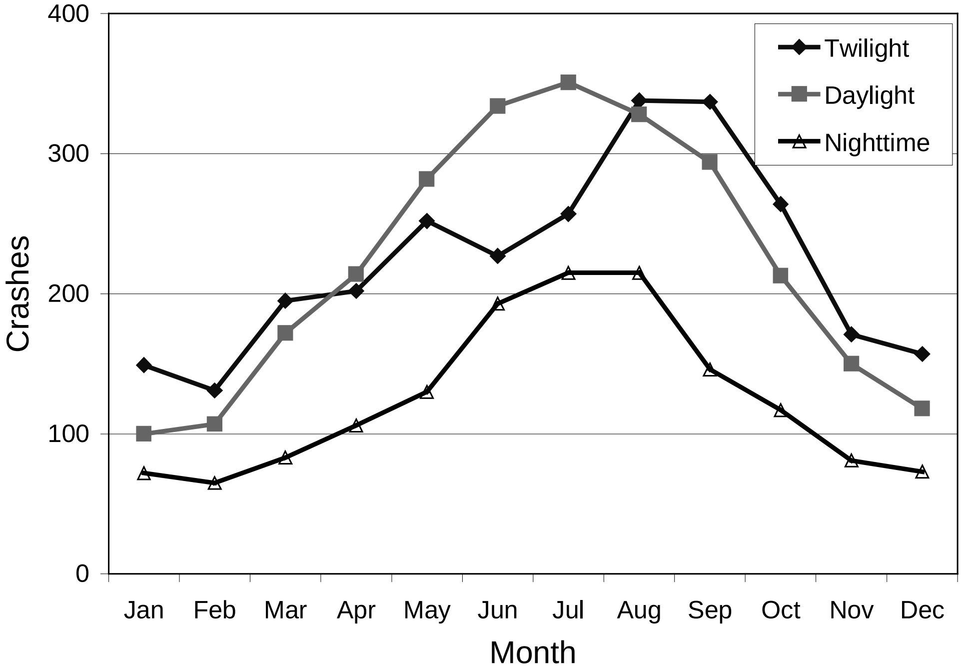

Figure 13. Cumulative fatal pedalcycle crashes by month for the Twilight, Daylight, and Nighttime periods, from 1987 to 1997.

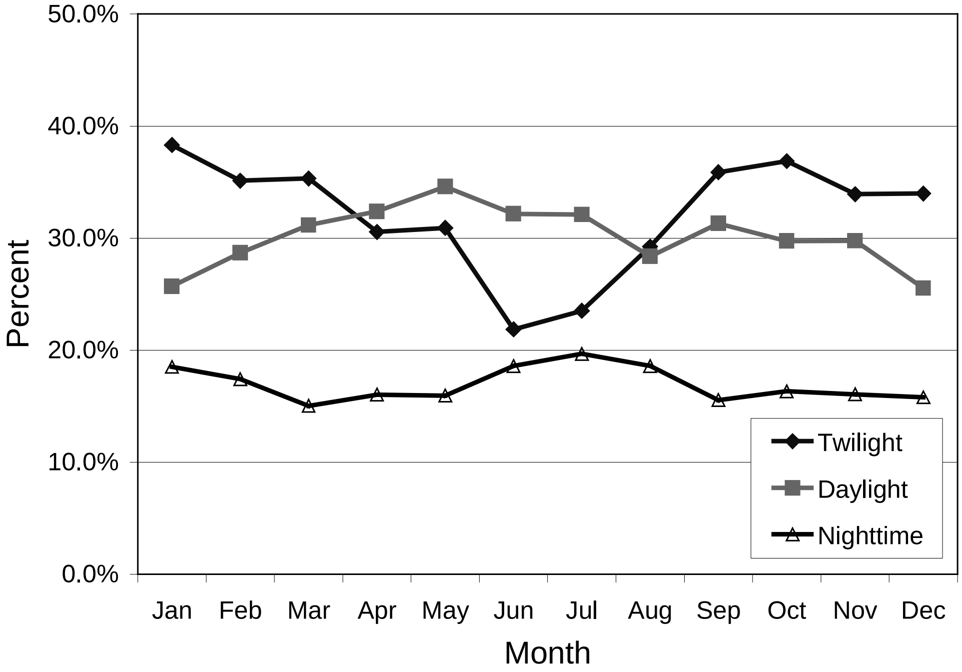

Figure 14. Proportions of fatal pedalcycle crashes by month during the Twilight, Daylight and Nighttime periods from 1987 to 1997.

4.3 Discussion

This study, using only fatal pedestrian crashes, effectively replicated and updated Owens and Sivak (1993), further supporting their finding that fatal pedestrian crashes appear to be strongly influenced by light level. This result was extended to cover 11 years of FARS data from 1987-1997. Consistent with Owens and Sivak’s previous research, the analysis of nonpedestrian crashes revealed no clear seasonal trends.

Fatal pedalcyclist crashes were also separately analyzed to assess the advisability of pooling those data with the pedestrian data. A somewhat different pattern of results was obtained, suggesting that exposure effects played a more dominant role in affecting absolute numbers of fatal pedalcyclist crashes. Whereas pedestrian crashes decline during the summer months, despite the likely rise in exposure levels, pedalcycle crashes increase during this period, suggesting a greater influence of exposure or a lesser influence of light level.

Since the twilight-zone effect is readily producible without inclusion of pedalcyclist data, and since the pattern of results from the pedalcyclist crash data departs from the pattern observed in the pedestrian crash data, all further analyses of twilight-zone effects will omit the pedalcyclist data.

5.0 Quasi-Experiment II: Adaptive Headlighting Scenarios in the Twilight Zone

Having replicated Owens and Sivak, we now focus on applying a similar analysis to the specific crash scenarios that were associated with different adaptive headlighting solutions in section 3.2. In each case, crash data will be filtered to contain only the records matched to a particular crash scenario, and plotted as a monthly frequency and percentage for each of the test time intervals: Twilight, Daylight Control, and Nighttime Control. Both the relative frequency of the problem and the magnitude of the Twilight Zone effect will be reported for each scenario.

5.1 Scenario 1: Pedestrian Crashes at Intersections

Cornering lamps are a solution particularly suited to illuminating pedestrians at intersections. Accordingly, records were selected from the FARS databases to include *first harmful events* to be pedestrian crashes and their *relation to junction* was either *intersection* or *intersection related*.[2] As before, data from the continental United States were selected, excluding Arizona.

5.5.1 Results

There were 12,416 fatal pedestrian crashes occurring at intersections over the 11-year sample period. This comprised about 20.3% of all pedestrian crashes. Approximately 80.4% of these crashes occurred in the Twilight, Daylight, and Nighttime time intervals.

Pedestrian crashes at intersections are shown in Figure 15 (raw count) and Figure 16 (proportions). There seems to be a clear indication that variation in light level during the Twilight period produces a significant effect on crash levels. Neither the Daylight Control nor the Nighttime Control periods, in which light-levels are uniform, display as much variation in crash count as the Twilight period. During the Twilight period, the crash level reaches a minimum in June of 161, and a maximum in December of 596—an increase of 3.7 times. In contrast, the Daylight Control period crashes range from 197 in July to 328 in October—an increase of 1.66; and the Nighttime Control period crashes range from 187 in February to 290 in July—an increase of 1.55.

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[2] In 1991 and later, a distinction is made in FARS between intersections within noninterchange areas and those within interchange areas. For the purpose of this analysis, no distinction is made—both types of crashes are used.

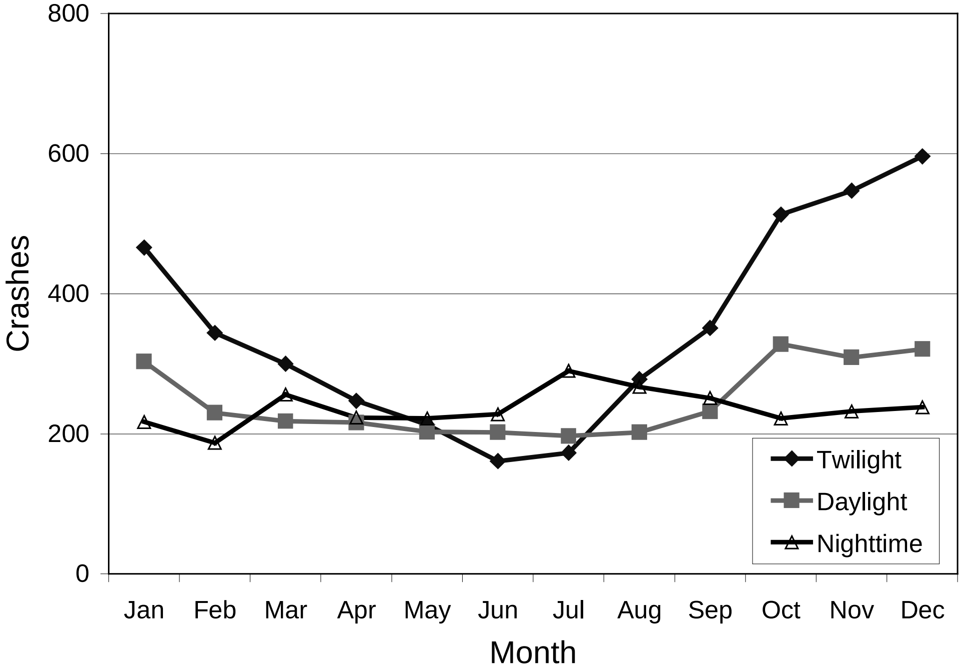

Figure 15. Cumulative fatal pedestrian crashes at intersections by month for the Twilight, Daylight, and Nighttime periods from 1987 to 1997.

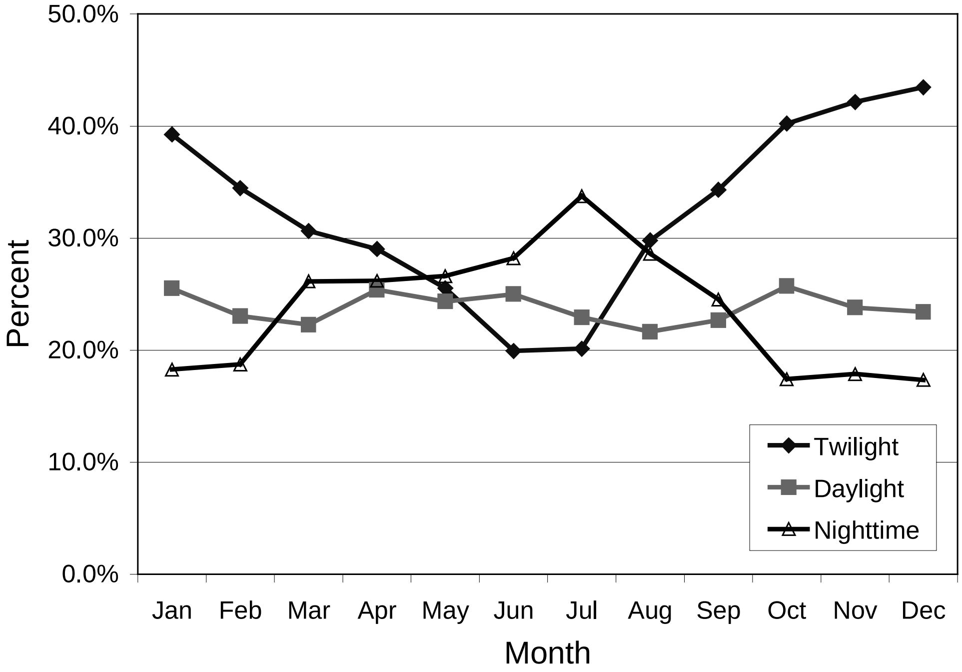

Figure 16. Proportions of fatal pedestrian crashes at intersections by month within Twilight, Daylight, and Nighttime periods from 1987 to 1997.

When plotted in terms of percentages (Figure 16), the drop in the Twilight period crashes tends to make it appear that Nighttime crashes are more on the rise during the summer months than they appear to be from the raw numbers. This is something of a distortion. Any unilateral drop in frequency within one time window, if reported proportionally, would make other perfectly flat distributions appear to bow upwards. It becomes unclear which quantities have changed to produce an observed effect. Because of this, raw counts should always be reported.

It should also be noted that during November and December, the crash count is higher than it is in January, despite the fact that the twilight-zone light levels are comparable. The effect is even more apparent on the pedestrian crash contour map (Figure 6). It seems obvious that this is not an effect of illumination. Perhaps it is an exposure effect produced by holiday shopping or more moderate temperatures in December than January. It suggests that estimation of lighting effect magnitudes using this analysis technique should be done with some caution, since seasonal variation in exposure is confounded with seasonal variation in light level.

5.2 Scenario 2: Pedestrian Crashes on Rural Roads

This experiment investigates a crash scenario that could be remedied with the use of low-beam headlights that extend the driver's forward view as a function of vehicle speed. To investigate this, we have selected pedestrian crashes on straight sections of rural roads (which are likely to be dark at night), with posted speed limits equal to or above 40 mph (64 kph). Accordingly, records were selected from the FARS databases to include pedestrian crashes as the *first harmful event*, along with the described roadway restrictions.

5.2.1 Results

There were 12,818 fatal pedestrian crashes occurring on rural, high-speed, straight sections of roadway. This comprised about 20.9% of all pedestrian crashes. Approximately 81.7% of these crashes occurred in the Twilight, Daylight, and Nighttime time intervals used in this analysis.

Pedestrian crashes on high-speed, straight, rural roads are shown in Figure 17 (raw count) and Figure 18 (proportions). Like pedestrian crashes at intersections, there also seems to be an effect of light level during the Twilight period. Unlike pedestrian crashes, there also appears to be marked seasonal variation in the Nighttime Control period crash levels. During the Twilight period, the crash level reaches a minimum of 158 in June and a maximum of 605 in December—

an increase of 3.8 times. In contrast, the Daylight Control period ranges from 117 crashes in February, to 160 in May (a difference of 1.3 times); the Nighttime Control period ranges from 268 crashes in January, to 548 in July (a difference of 2 times)[3].

It is unclear why we see such a pronounced climb in Nighttime crashes in this scenario. One possibility involves the interaction of pedestrian exposure with fixed roadway illumination and perhaps driver expectation. That is, in the first scenario, intersections are probably illuminated by fixed street lighting, especially in urban areas and drivers look to intersections as probable sources of conflict. This makes pedestrians more visible, expected, generally avoidable, and possibly reduces the influence of exposure level on crash rates. It is noteworthy that daylight conditions appear not to be particularly sensitive to exposure level. Crash rates are flat throughout the year despite the fact that there are surely more pedestrians on the street when the weather is agreeable. Thus, the presence of fixed overhead lighting makes the Nighttime Control look more like the Daylight Control (see Figure 15). Light appears to *gate* the effect of exposure.

In the case of *rural* roads used in this scenario, the roadways are most likely *not* lighted, making pedestrians relatively invisible to drivers. Consequently, as the number of poorly visible pedestrians increase on the roadway at night during the summer months, we see a direct increase in the nighttime pedestrian fatalities.

The reason the twilight-zone effects appear to be the same between the two conditions is unclear. Even in areas with road illumination, the effectiveness of that illumination in making pedestrians conspicuous is limited. It suggests that the factors creating the differences in each scenario's Nighttime crashes are irrelevant in the Twilight interval.

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[3] These data overlapped the Scenario 1 data. That is, 3967 records included here were also included in the Scenario 1 analysis—pedestrian crashes occurred on straight rural roads that were *also* situated at an intersection. Because there is nearly the same number of cases in each sample, the overlap had a proportionately equivalent effect—32% for Scenario 1, 31% for Scenario 2. When these cases were removed from each sample, few systematic differences were found between this analysis and the original one that included the overlap. For example, with the overlapping records omitted, there were about 3.9 times the number of fatal pedestrian crashes during the Twilight period in November as there were in June (605 versus 156). This is comparable to the result found here.

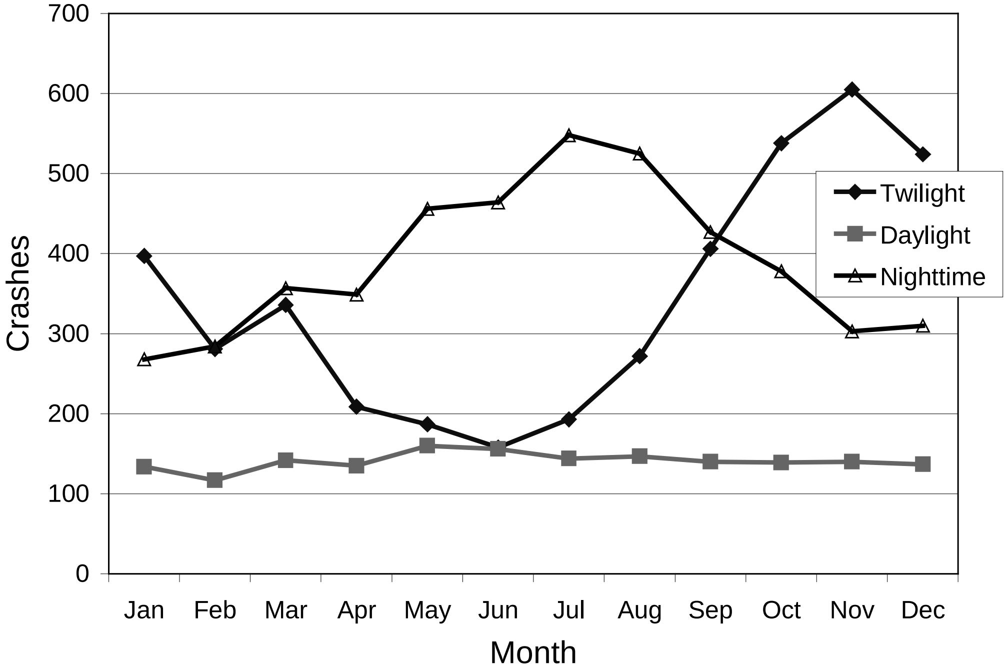

Figure 17. Cumulative fatal pedestrian crashes on straight, rural roads with posted limits greater than or equal to 40 mph. Data compiled by month during the Twilight, Daylight and Nighttime periods from 1987 to 1997.

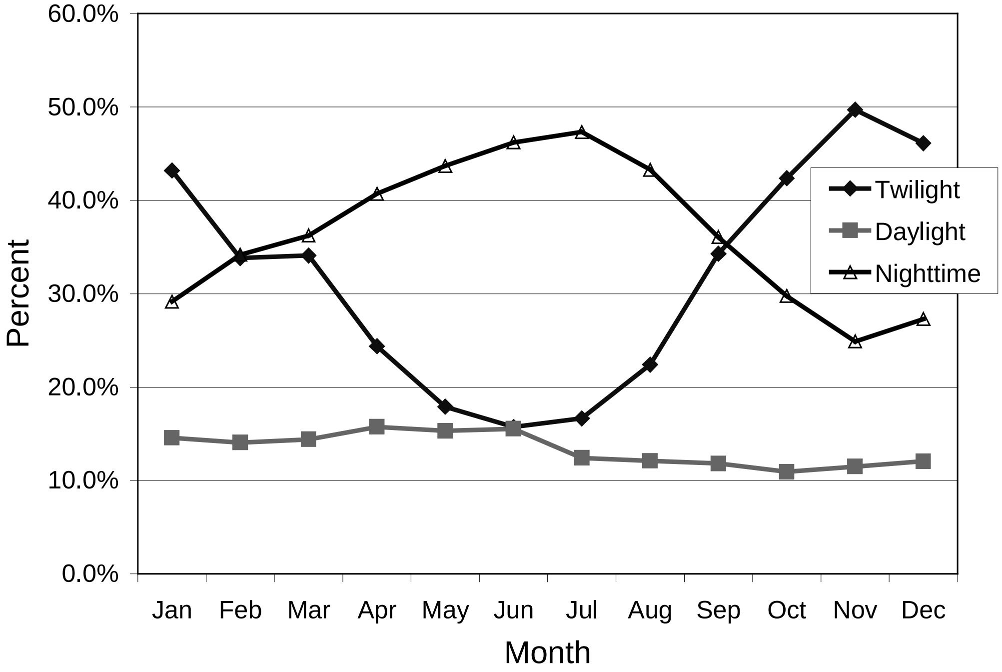

Figure 18. Proportions of fatal pedestrian crashes on straight, rural roads with posted limits greater than or equal to 40 mph for each time period. Data compiled by month during the Twilight, Daylight and Nighttime periods from 1987 to 1997.

5.3 Scenario 3: Single-Vehicle Road Departure on Curved Rural Roads

This experiment investigates the degree to which light level influences the risk of driving off a curved section of a dark, rural (and unlit) roadway. We investigate this by looking at crash records in FARS that involve single vehicles (i.e., in FARS, the field *manner of collision* is defined as “Not Collision with Motor Vehicle in Transport”), running off the roadway (*relation to road* is not “On Roadway”), on curved (*roadway alignment* is “Curved”), rural (*roadway function class* is one of the rural categories) roadways.

5.3.1 Results

This crash scenario included 47,609 crash records over the 11-year span of data. This represents approximately 11% of all crashes and 13% of all nonpedestrian crashes. Approximately 73.2% of the crashes in the sample occurred within the three experimental time periods.

For this crash scenario, the results appear to show little influence of the changes in light level in the Twilight period. All periods (Daylight, Twilight, and Nighttime) show a rise in crashes toward the middle of the year (Figure 19), possibly because of increasing numbers of motorists in the summertime when the weather is favorable. If we try to factor out the effect of weather by computing proportions, even less seasonal variation is apparent (Figure 20). This is in rather sharp contrast to the results obtained with pedestrians. Although their exposure levels are *also* likely to increase in the summer months, this risk appears to be more than offset by the benefit of increased daylight. Thus, despite the increased exposure in the summertime, pedestrian fatalities seem to be reduced by the presence of additional daylight. It would seem that light level is less relevant in single-vehicle road departures than in pedestrian crashes.

Several factors might make lighting conditions more influential in the pedestrian crash scenario. For example, pedestrian detection does not have the same degree of redundancy as roadway markings. If one fails to detect a lane marker, others will surely follow, and navigation can even proceed with reasonable accuracy based on the *last seen* marker. Failure to detect a pedestrian in the roadway is, by comparison, catastrophic because there is little redundancy. With such a low tolerance for detection error, anything that enhances pedestrian detection probability is likely to have a significant effect on crash numbers.

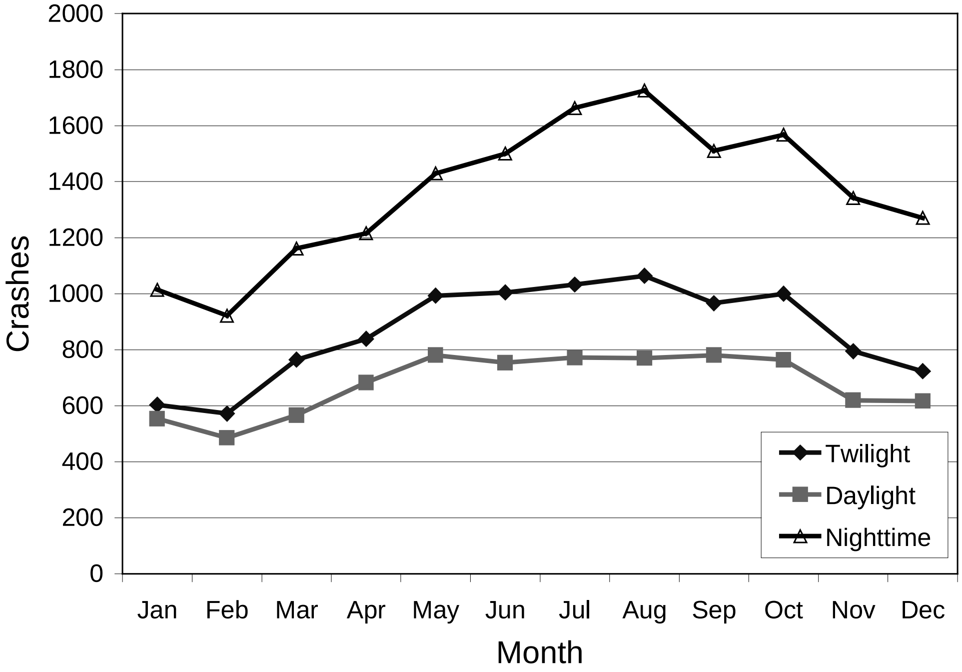

Figure 19. Cumulative fatal single-vehicle road departure crashes on rural, curved roads with posted speed limits greater than or equal to 40 miles per hour. Data compiled by month during the Twilight, Daylight and Nighttime periods from 1987 to 1997.

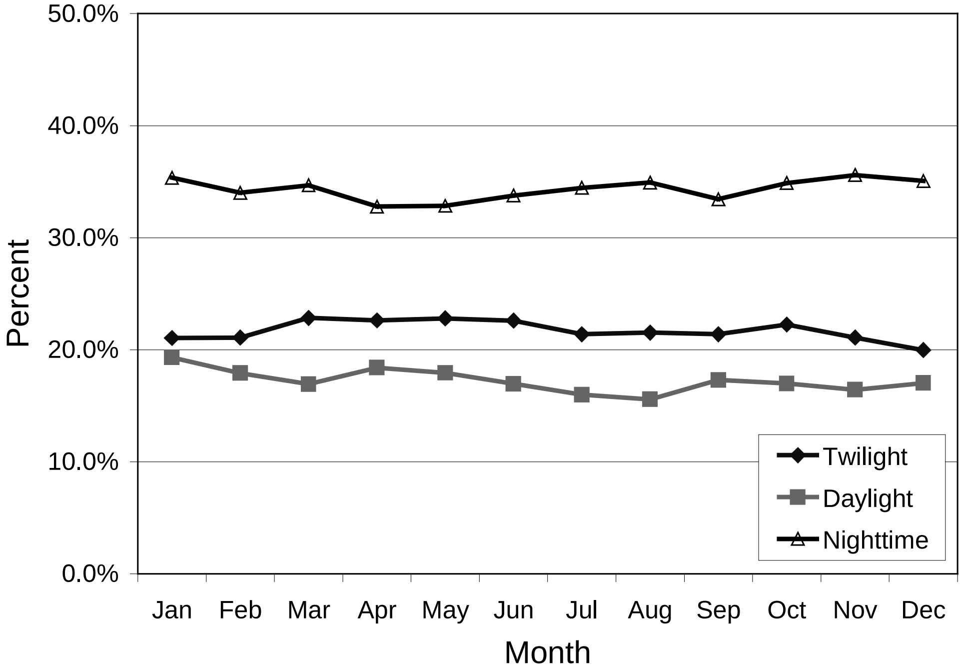

Figure 20. Proportion of single-vehicle road departure crashes on curved rural roads with posted speeds greater than or equal to 40 mph. Data compiled by month during the Twilight, Daylight and Nighttime periods from 1987 to 1997.

The time margins to recognize a pedestrian and take evasive action are likely shorter than the response time to recognize that one is leaving the roadway. Warning signs, speed limit reductions, and arrows normally precede curved roads; pedestrians appear in the roadway without warning. Consequently, anything that allows earlier detection of a pedestrian is likely to reduce fatal pedestrian crashes.

Maintenance of roadway position is an activity that involves continuous monitoring. Even on the poorest roads, lane markings and reflective material are normally available to assist. Drivers might also regulate their speed to reduce their risk of a crash. Compared to avoiding a pedestrian crash, veering off the road is relatively gradual and unlikely to catch one completely by surprise unless asleep—and, in that case, road lighting would matter little.

Pedestrian crashes are a likely consequence of failing to detect a pedestrian in the roadway; single-vehicle road departures are perhaps a consequence of a lapse in road monitoring or a lapse in proper vehicle control. While it seems obvious that better illumination could improve detection of pedestrians, it may do little to improve the monitoring and control performance of drivers. Perhaps other factors, unrelated to light level, are most responsible for run-off-road types of crashes.

Impaired Judgement? To further investigate the properties of single-vehicle road departures, we determine the extent to which impaired judgement or motor performance might be involved by looking at alcohol involvement. If a significant portion of the run-off-road crashes involve alcohol, it is possible that poor judgement, motor control, drowsiness, and inattention are the dominant factors contributing to the crash. Any effect of light level may be overshadowed by these other factors. Perhaps an effect of light level may be more clearly seen with the nondrinking drivers.

Figure 21 shows the portion of the data reported earlier in which drinking was a factor. Drinking drivers appear to dominate these crashes, especially at night. Overall, 60% of these types of crashes involved drinking (76% at Nighttime, 58% during Twilight, and 37% during Daylight). In contrast, about 37% of all fatal crashes are identified as involving drinking, and only 12% of pedestrian fatalities involve drinking. This evidence suggests that fatal, single-vehicle road departure crashes are related to drinking. This may overshadow any effect of light level.

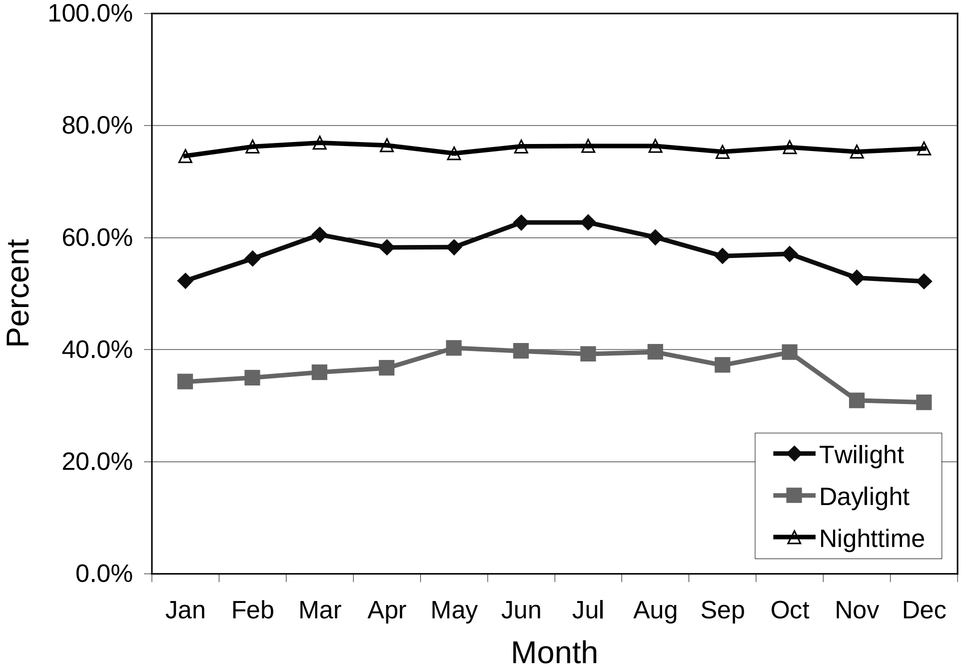

Figure 21. Proportion of drinking drivers in single-vehicle road departures on curved roads. Data compiled by month during the Twilight, Daylight and Nighttime periods from 1987 to 1997.

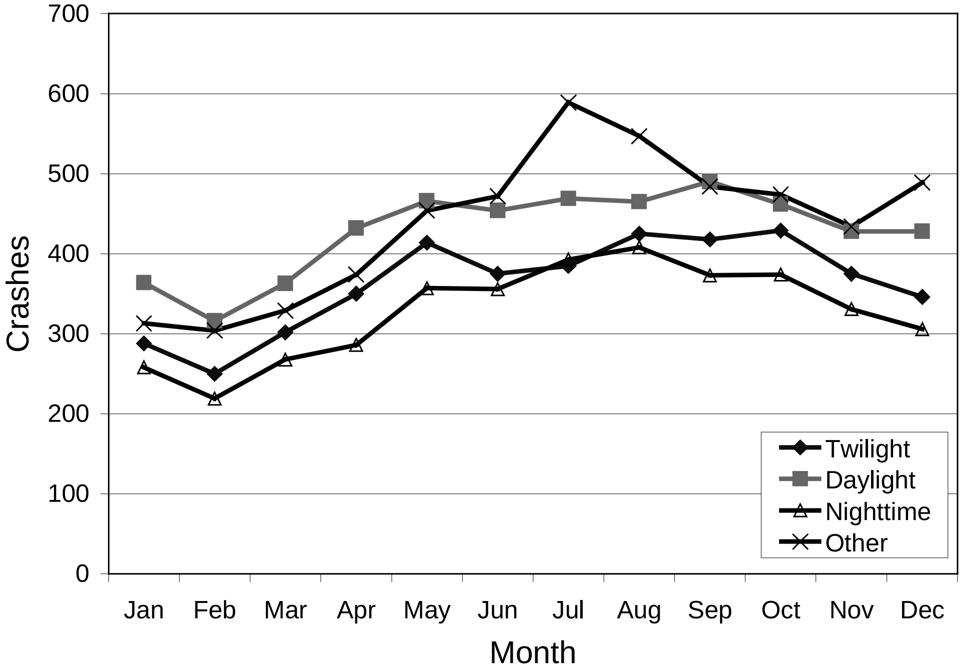

Figure 22. Cumulative nondrinking drivers in fatal single-vehicle road departure crashes by month and time period. Data include the “Other” time interval, showing a disproportionately higher number of cases in July and August. The figure includes data from 1987 to 1997.

Perhaps light level influences nondrinking drivers. In Figure 22, we see that among nondrinking drivers, single-vehicle road departures occur more often in the daytime, than at night, suggesting a possible exposure difference related to this subset of driver. On the other hand, perhaps nondrinking drivers are moderating their driving at night (by driving at slower speeds) to reduce their risk of running off the road. Lower speed is likely to reduce the potential for fatality. The lack of independent exposure data on nondrinking drivers makes it difficult to distinguish between these two possibilities.

In any case, the elevated crash levels during the spring and summer months also suggest seasonal exposure effects. If we try to factor out exposure by looking at the data as proportions, we find a mild dip in the proportion of crashes occurring in the Twilight period during the summer months (Figure 23), suggesting that light level may be proportionately reducing the number of crashes. However, a similar dip in the Daylight condition (where light level is unchanged) suggests something else is responsible. In fact, there is a disproportionate *increase* in fatalities during the summer months in the “Other” nonexperimental time period. (This period includes 2 nighttime hours [between 11 P.M. and 1 A.M.], and 4 daytime hours [between 10

A.M. and 2 P.M.].) Thus, the proportionate decline appears to be a consequence of the increase in the "Other" time interval and not an effect of light level.

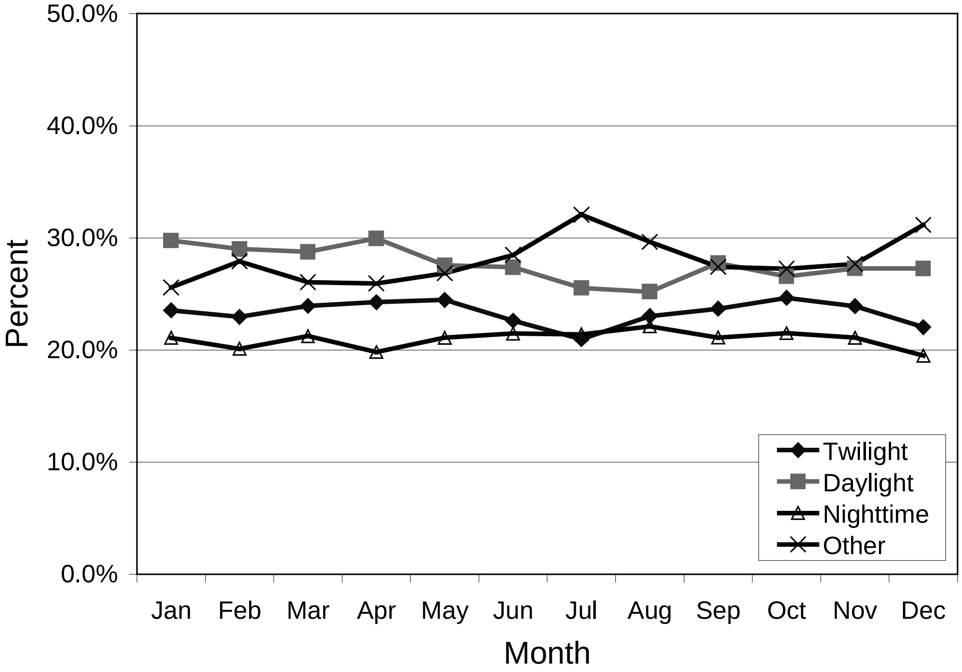

Figure 23. Proportion of fatal non-drinking single-vehicle road departures on curved rural roads with posted speeds greater than or equal to 40 mph. Data compiled by month during the Twilight, Daylight, Nighttime, and Other time periods from 1987 to 1997.

Does "Fatality Threshold" Affect the Pattern? A pedestrian is more likely to be killed when struck by a vehicle than is the vehicle's driver. In a single-vehicle, run-off-road accident, drivers and passengers are cocooned inside the vehicle's steel passenger compartment, designed to absorb some degree of impact. Thus, more energy (i.e., higher speed) is required to produce a single-vehicle fatality than a pedestrian fatality. Bearing this in mind, it might be the case that the single-vehicle fatality records only show exceptionally reckless instances of driving. In contrast, pedestrian fatality data may include a more typical cross section of driving behavior, and with it, a population of drivers that may be more responsive to external conditions like light level. Perhaps instead of looking at fatal run-off-road crashes, we should examine less severe crashes of this type, in order to observe an effect of light level.

As noted earlier, FARS contains only fatal crash data; however, severity-level data is available in the NASS GES databases. If we select a similar crash scenario from the GES databases and consider only crashes that produce either "No Injury" or "Possible" injury, we may find a trend for vehicle occupants similar to that which was found with the pedestrian fatality data.

Because NHTSA's GES database is an estimation database and not a census like FARS, the time resolution of the dataset is comparatively coarse, resolving time only to the month. (Although hour-of-day is also provided.) In addition, the state where a crash occurred is not available, so this analysis cannot select data for specific locales. Thus, precise correction for daylight savings time changeovers and exclusion of certain states from the analysis is not possible. With these limitations, an approximate analysis, comparable to the one performed with the FARS database was done using the GES databases from over a 10-year period (1988 to 1997) for crashes which involved "No Injury" or "Possible Injury" severity levels. This is shown in Figure 24. No clear trend is evident from the data. Neither time-interval nor season seems to reveal any particular trend.

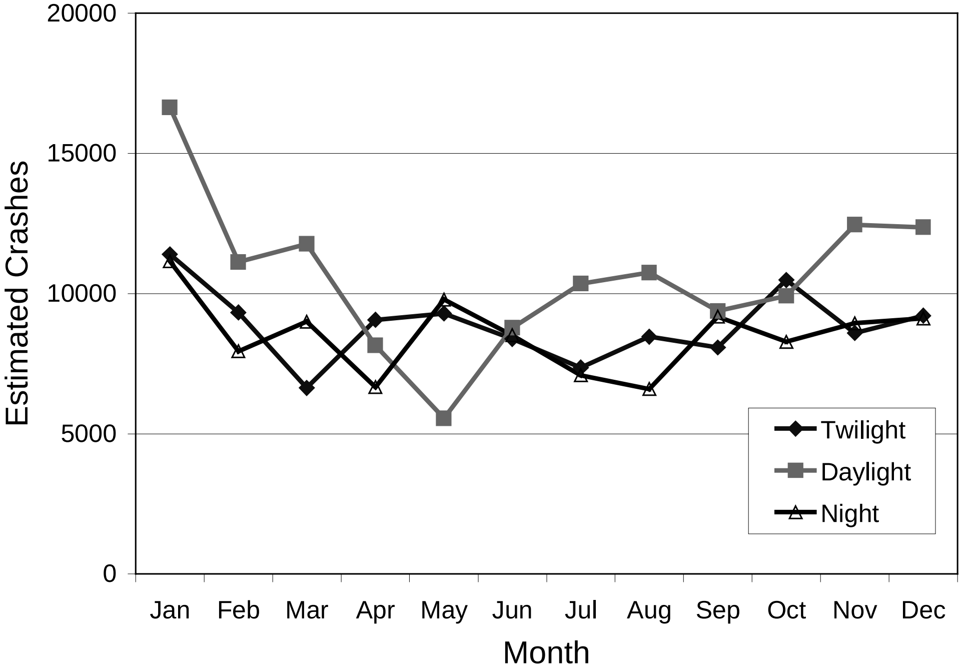

Figure 24. Cumulative estimates of single-vehicle, run-off-road crashes on curved roads for mild injury crashes (no or possible injury). Compiled from GES data, 1988 to 1997.

5.3.2 Summary and Discussion

Road Departures and Pedestrian Crashes. It seems clear from this series of experiments that pedestrian crashes are more strongly influenced by light level than are the single-vehicle road-departure crashes investigated as Scenario 3. We have suggested that the reason for this difference is directly related to differences between the tasks of avoiding pedestrians and of maintaining position on a roadway. Avoiding a pedestrian crash first requires detection of the pedestrian with sufficient advanced notice that effective action can be taken. The earlier a pedestrian is detected, the more time is available to take action. It is likely that good illumination supports early detection.

In contrast, maintenance of lane position is a task that is more continuously controllable by a driver. As mentioned earlier, road markings are redundant and make the task somewhat more predictable than pedestrian collision avoidance. The task is also, in some sense, *self-paced.* By regulating their speed, drivers can make the task of staying on the road more or less difficult. (The same might be said for pedestrian avoidance: that it is also self-paced. However, pedestrian encounters in the roadway are rare and afford limited opportunity for feedback. Drivers are likely to be unaware that their speed is above a limit for safe avoidance of a pedestrian.) Thus run-off-road crashes may result more from poor judgement than poor lighting. If lighting has any effect, it may be that it permits drivers to take curves at higher speeds than they would normally deem safe.

The Problem of Exposure. We have repeatedly noted different kinds of seasonal exposure effects that seem to be entangled in much of the data presented here. While it seems clear that more pedestrians are out on the streets in the summertime, we nevertheless see a sharp decline in pedestrian crashes during the summer months. One suggestion is that light level *gates* exposure effects: when light level is high, exposure effects are sharply attenuated; when light level is low, exposure effects become strongly apparent in the crash statistics.

This suggests that the lighting effects observed in this series of experiments may underestimate the degree to which illumination level influences fatal crash levels. That is, if we assess light-level influence by comparing the peak crash frequency in the winter with the dip in the summer, we neglect to consider the fact that pedestrian exposure trends are 180 deg out of phase with this. There are more pedestrians out and about in the summer than there are in the winter. As a consequence, the dip in the summer may be shallower, and the peak in winter more stunted than we would obtain if exposure could be better controlled.

The next series of experiments attempts to control seasonal fluctuation in exposure levels by looking at weekly time windows containing sudden changes in light levels associated with changeover to daylight savings time.

6.0 Quasi-Experiment III: Assessing the Influence of Light Level with Daylight Savings Time

6.1 General Method

Twice a year, in most of the United States, clocks are reset. In the spring, clocks are set one hour ahead, making sunrise and sunset one hour later than in standard time. In the fall, clocks are set back to standard time, effectively making sunrise and sunset earlier. If we assume that daily traffic patterns are governed by clock time, we can use this manipulation to assess the relative effect of light level on crash statistics while traffic patterns (we expect) remain relatively unchanged. For example, suppose that it is dark at 6:00 P.M. the day before the change to daylight savings time (DST). After the change, it is light at 6:00 P.M. If we assume traffic volume, pedestrian exposure, and weather do not substantially change shortly before and shortly after the time change, we could compare the crash rates during the lighted period before, with the crash rates during the dark period after, to assess the role of light in affecting crashes. This comparison would be relatively free of the seasonal sources of contamination since the time window is short.

To perform this analysis, the exact start and end of civil twilight was computed for the dates of the spring and fall adjustments for daylight savings time. This was done for each of the 11 years (1987-1997) covered in this analysis and for each county in the United States. U.S. Census Bureau data were used to identify the latitude and longitude of each county center to make the estimates. Arizona, Hawaii, and Puerto Rico were excluded from the analysis because they do not use daylight savings time. Indiana was excluded from the analysis because 77 of its 95 counties do not use daylight savings time. Finally, Alaska was excluded because at its extreme northern latitudes the solar cycle substantially deviates from that found in the lower 48 states. For example, in Nome, the June 21st sunset occurs at 12:48 A.M. on June 22 (standard time; it is 1:48 A.M. DST). Since time zones cut across several state boundaries, each county's time zone was also independently identified so that the local clock time of civil twilight could be accurately computed.

Once each county's time of start and end of civil twilight was determined (in standard time), crash-record clock times were grouped into 1-hour intervals before and after this time point. This was done for each of the four transitions: spring A.M. and P.M., and fall A.M. and

P.M. The interval TW (twilight interval in Table 3) designated the 1-hour interval just after the start of civil twilight in the A.M., and the one-hour interval just *before* the end of civil twilight in the P.M. Thus, this interval defines a clock time during the transition from darkness to daylight or from daylight to darkness. In the A.M., 1-hour intervals prior to TW were identified as N0, N1 (night) for each hour further from the interval; likewise, hours following TW were designated D0, D1 (day) for each hour after the TW interval. In the P.M., the categorization was reversed. Intervals preceding TW were identified as D0 and D1 for each hour earlier than TW, and N0 and N1 for each hour later than the interval. As shown in Table 3 and Table 4, the characteristics of the light transitions are different depending on whether it is morning or evening, spring or fall. This can be seen more clearly in Figure 25 (spring A.M.), Figure 27 (spring P.M.), Figure 29 (fall A.M.), and Figure 31 (fall P.M.). Tables 3 and 4 also highlight time windows in which light level effects should be most observable and which are plotted in the figures that follow.

Table 3. Descriptions of transition characteristics within the spring A.M. and P.M. time periods. Crashes are plotted in the following figures for the cells highlighted in gray.

	Spring	
Period	A.M. Transition	P.M. Transition
N1	Night to Night	Night to Night to Twilight
N0	Night to Night	Night to Twilight to Daylight
TW	Twilight to Night to Twilight (6 weeks)	Twilight to Daylight
D0	Daylight to Twilight	Daylight to Daylight
D1	Daylight to Daylight	Daylight to Daylight

Table 4. Descriptions of transition characteristics within the fall A.M. and P.M. time periods. Crashes are plotted in the following figures for the cells highlighted in gray.

	Fall	
Period	A.M. Transition	P.M. Transition
N1	Night to Night	Twilight (-5 weeks) to Night to Night
N0	Night to Night	Twilight to Night
TW	Night to Twilight to Night (8 weeks)	Daylight to Twilight
D0	Twilight to Daylight	Daylight to Daylight
D1	Daylight to Daylight	Daylight to Daylight

The following series of studies will first look at fatal pedestrian crashes in general to obtain estimates that can be compared to the fatal pedestrian crashes in the Owens and Sivak replication. Following this, each scenario examined in the previous section will be examined using this method.

6.2 Fatal Pedestrian Crashes During DST Changeover Periods

Spring A.M. Figure 26 shows the cumulative fatal pedestrian crashes before and after the spring A.M. change to DST. Relative to the previous analyses, the number of crashes in this data set is quite small (1,100 cases, averaging 61 cases per week). Nevertheless, some trends consistent with light level are readily apparent. For example, TW shows a decline in crashes starting at week -8 (39 crashes) until week -1 (8 crashes); at the changeover, when the period is returned to darkness, the crash level rises again (coincidentally, to 39). This pattern mimics the gradual increase in light level in the weeks leading up to the changeover, the abrupt changeover to darkness, and the repetition of the gradual increase in light level (Figure 25). Crash numbers appear to be inversely related to light level—the darker it is, the more fatal crashes are observed. The D0 time interval also shows a trend consistent with this increasing light levels during this time window, but is omitted for clarity of presentation.

This analysis suggests that pedestrian fatalities are about five times more likely in darkness than in daylight.

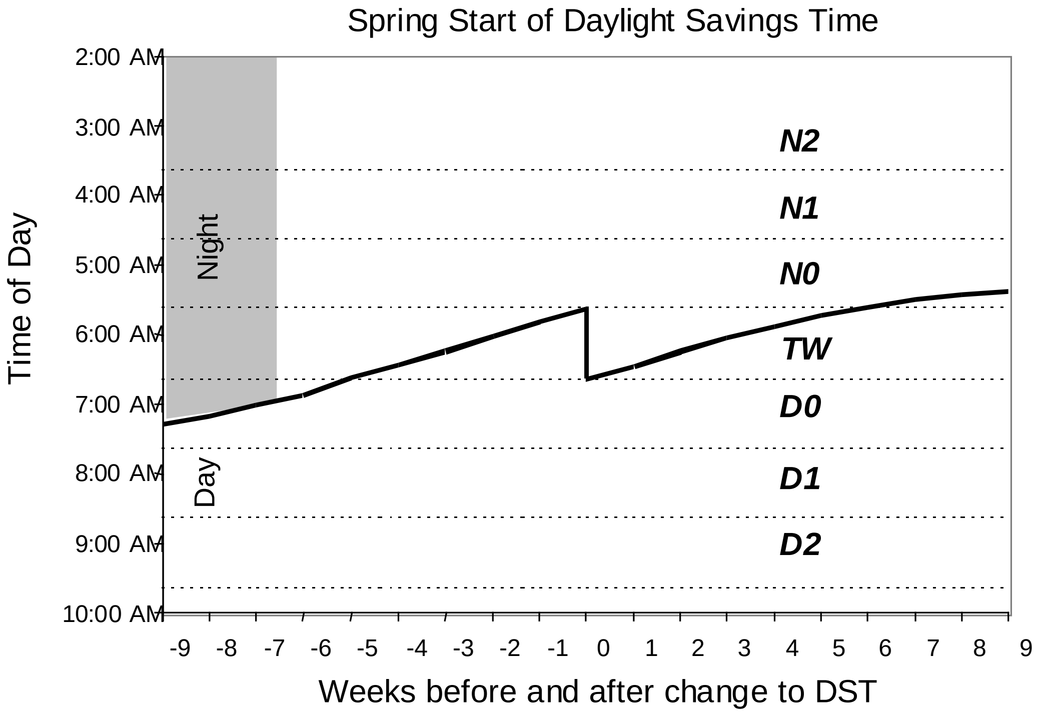

Figure 25. Spring A.M. transition to DST illustrating changes within each time period category. The figure plots the morning start of civil twilight in local time for the 9 weeks preceding, and the 9 weeks following DST.

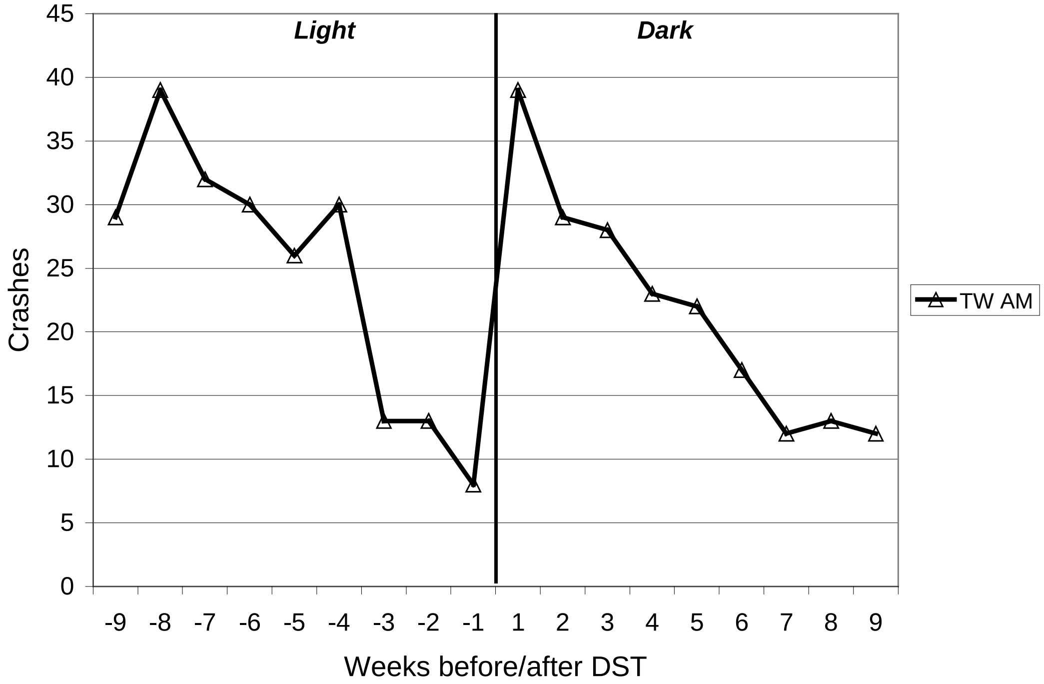

Figure 26. Cumulative spring A.M. crashes before and after DST changeover during the morning TW time interval. Data span 11-years, 1987 to 1997.

Spring P.M. Figure 28 shows the cumulative fatal pedestrian crashes before and after the evening change to DST. This data set included 4,700 crashes, averaging about 261 cases per week. Here, the time period N0 undergoes the greatest lighting change, transitioning from night to twilight (and on to daylight). Consistent with this, the crash frequency peaks at 168 in the dark period just before the DST changeover, and drops to 54, the week after the changeover and declines more the following week to 32 (as the days grow longer). The before-and-after difference suggests that pedestrian fatalities are perhaps three to five times more likely in darkness than in light.

It is also notable that the TW interval (not shown) also displays a steady decline that levels off at around the changeover (182 at week -9, to 38 at week 1), closely tracking the increasing light levels as the length of day increases.

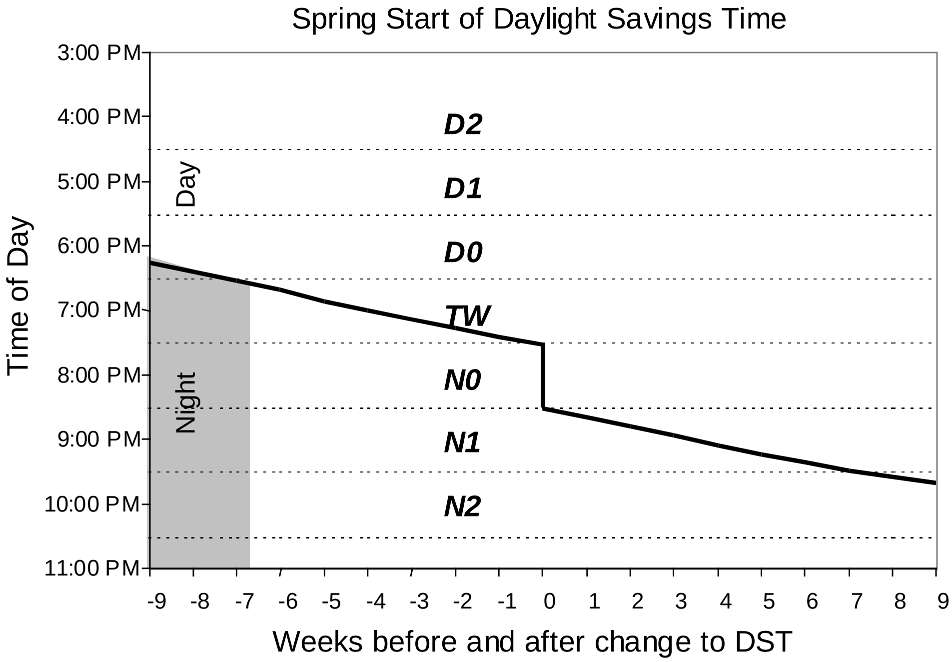

Figure 27. Spring P.M. transition to DST, illustrating changes within time period categories. The figure plots the evening end of civil twilight in local time for the 9 weeks preceding, and the 9 weeks following DST.

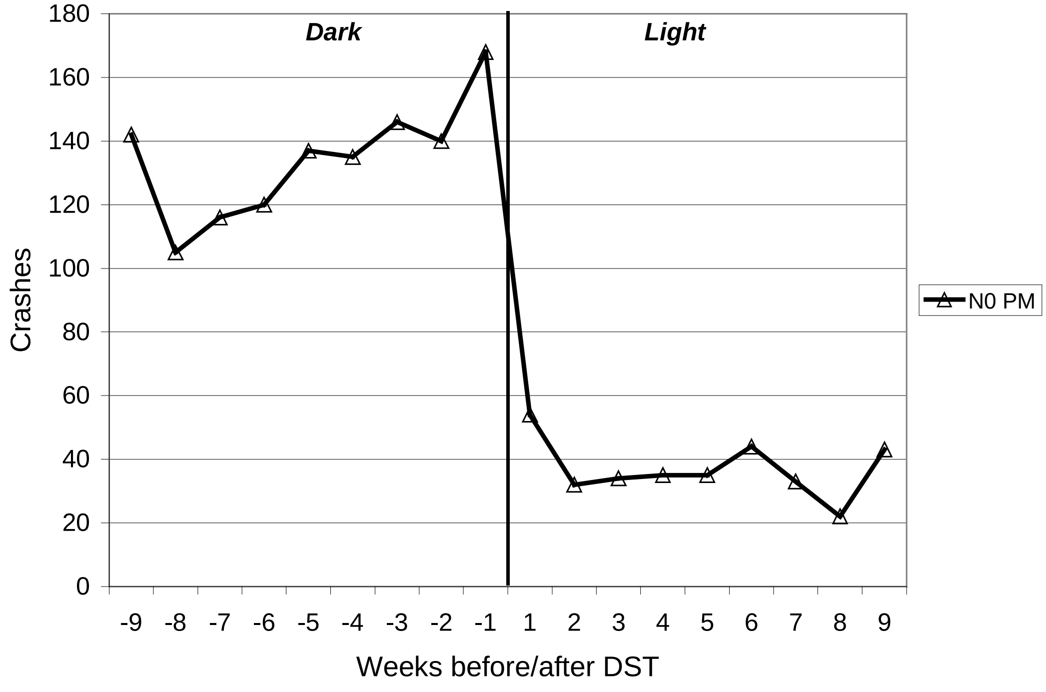

Figure 28. Cumulative spring P.M. crashes before and after the DST changeover in the evening for the N0 time interval. Data span 11 years, 1987 to 1997.

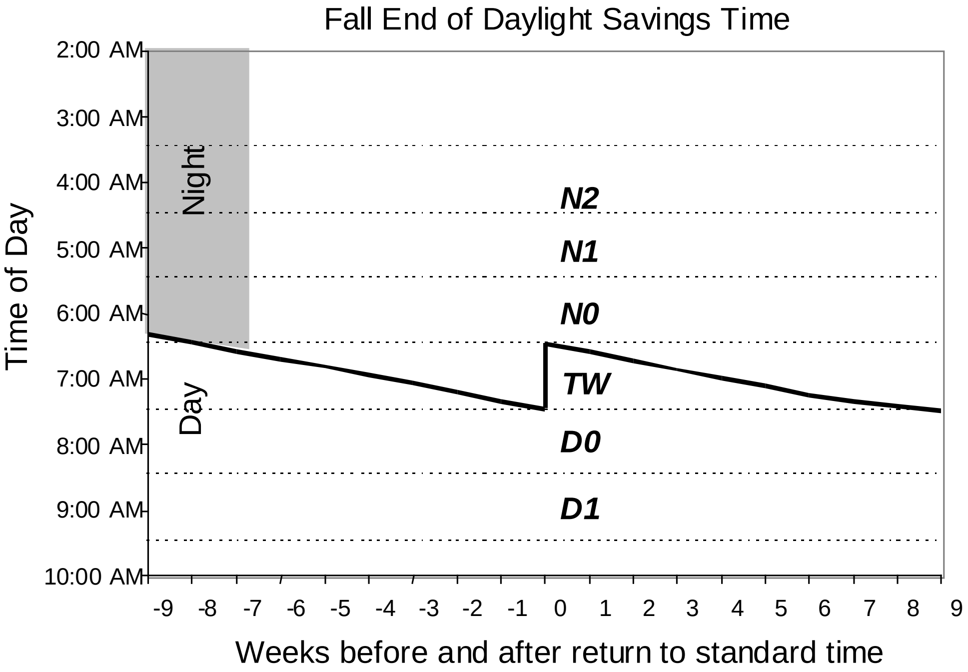

Figure 29. Fall A.M. transition back to standard time, illustrating changes within each time period category. The figure plots the morning start of civil twilight in local time for the 9 weeks preceding, and the 9 weeks following the return to standard time.

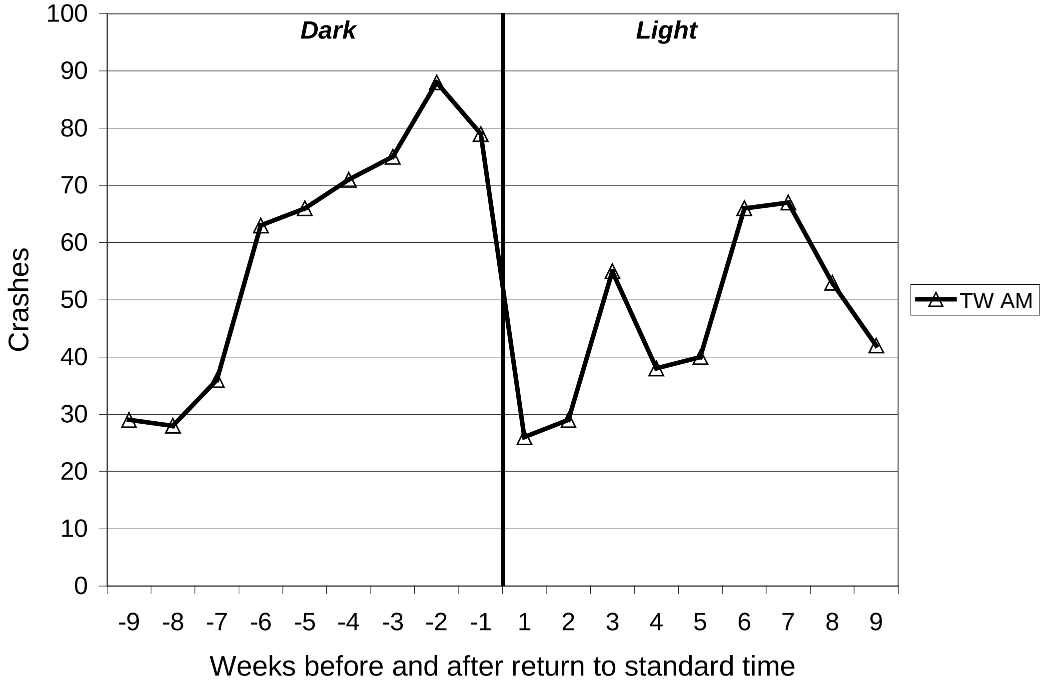

Figure 30. Cumulative fall A.M. crashes before and after return to standard time during the morning TW time interval. Data span 11 years, 1987 to 1997.

Fall A.M. Figure 30 shows the morning fatal pedestrian crashes before and after the fall return to standard time. This data set included 2,149 crashes, averaging about 119 cases per week. In this transition, the TW interval contains the greatest lighting change (Figure 29), changing from night to twilight. Consistent with the light-level explanation, we see there are 79 crashes before the transition and 29 after, and that as light level declines with the shortening day, the crash numbers rise in the weeks following the return to standard time. The before-and-after difference in crash count suggests it is three times riskier for pedestrians in the dark.

Fall P.M. Figure 32 shows the evening fatal pedestrian crashes before and after the fall return to standard time. This data set included 6,403 crashes, averaging about 356 cases/week. In this time period, the N0 interval transitions from twilight to night (Figure 31). Consistent with the light-level effects observed in the other time periods, we see a sharp rise in fatal crashes over the transition from light to dark. In the week before the transition there were 65 crashes, in the following week there were 227, an increase of 3.5 times.

Figure 33 summarizes the changes in crash counts for the 2 weeks before and 2 weeks after the transition between dark and light. Although light level fluctuates to some degree in the other time intervals, this graph summarizes only data during changeover between night to twilight and twilight to night. This is the TW period in the spring and fall morning (A.M.), and the N0 periods in the spring and fall evenings (P.M.). From this graph, it is clear that more crashes occur in the evening, and more occur in the fall. Table 5 lists the ratio of crashes in the dark to light conditions.

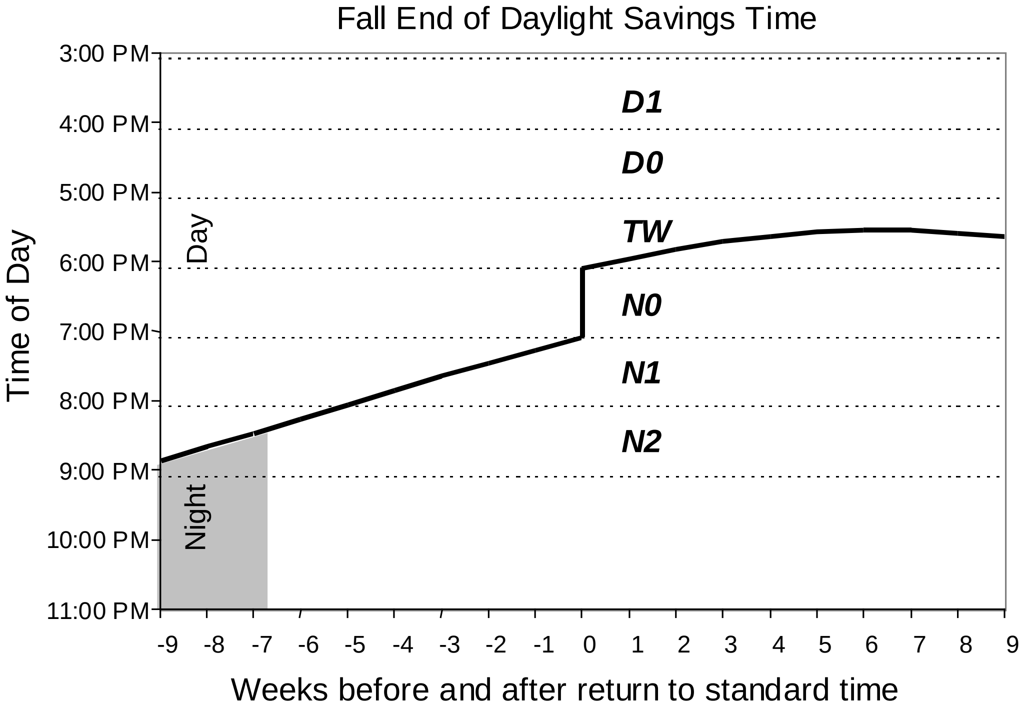

Figure 31. Fall P.M. transition to standard time, illustrating changes within time period categories. The figure plots the evening end of civil twilight in local time for the 9 weeks preceding, and the 9 weeks following return to standard time.

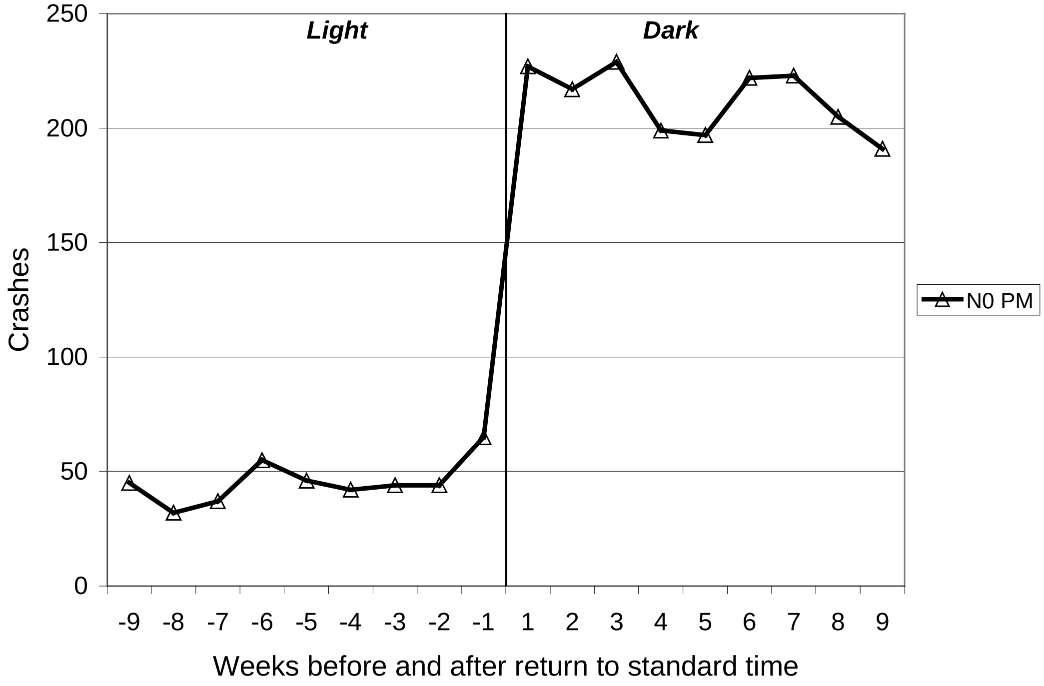

Figure 32. Cumulative fall P.M. fatal pedestrian crashes before and after return to standard time during the evening N0 time interval. Data span 11 years, 1987 to 1997

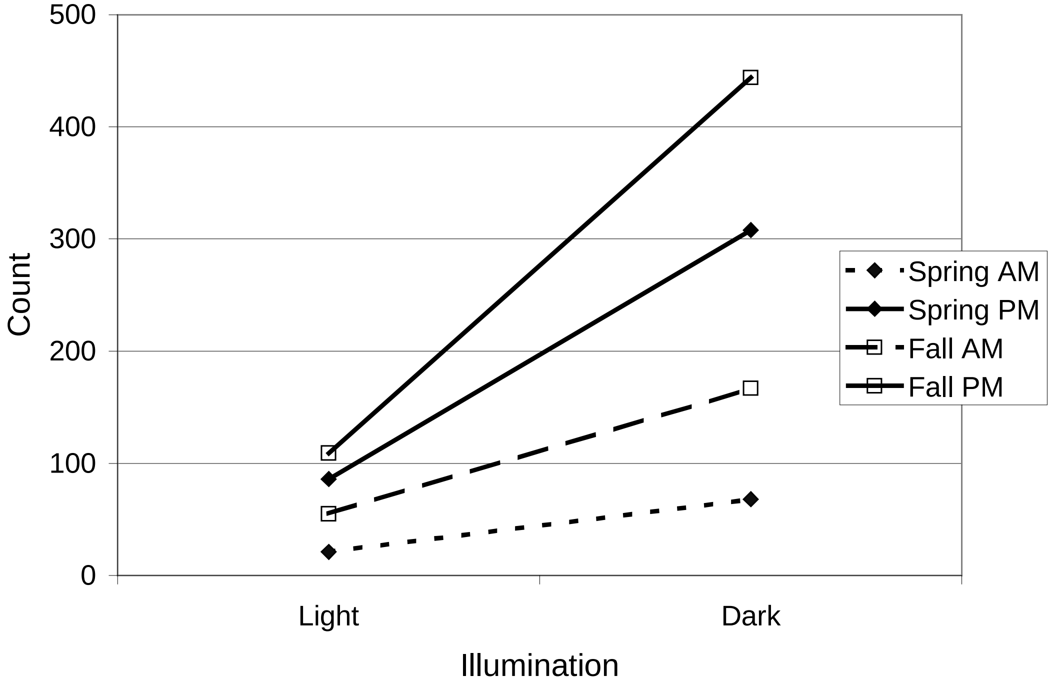

Figure 33. The change in crash counts as a function of illumination condition in the 2 weeks before and 2 weeks after DST changeovers. Transition intervals used TW for morning and N0 for evening.

Table 5. Darkness to Light conditions crash proportions for pedestrians: season by time of day.

All Fatal Pedestrian Crashes		
	A.M.	P.M.
Spring	3.23	3.58
Fall	3.04	4.07

6.3 Scenario 1: Pedestrian Crashes at Intersections

For this and the other two scenarios, data will be summarized using data from 2 weeks before and after each changeover scenario, as reported in Section 6.2, Figure 33 and Table 5. The detailed plots of the fall and spring, morning and evening crash patterns are included in Appendix A.

Overall, the results show a pattern that is similar to the combined pedestrian data (albeit weaker). Once again, it appears that the fall and evening time of day show particularly strong effects of lighting.

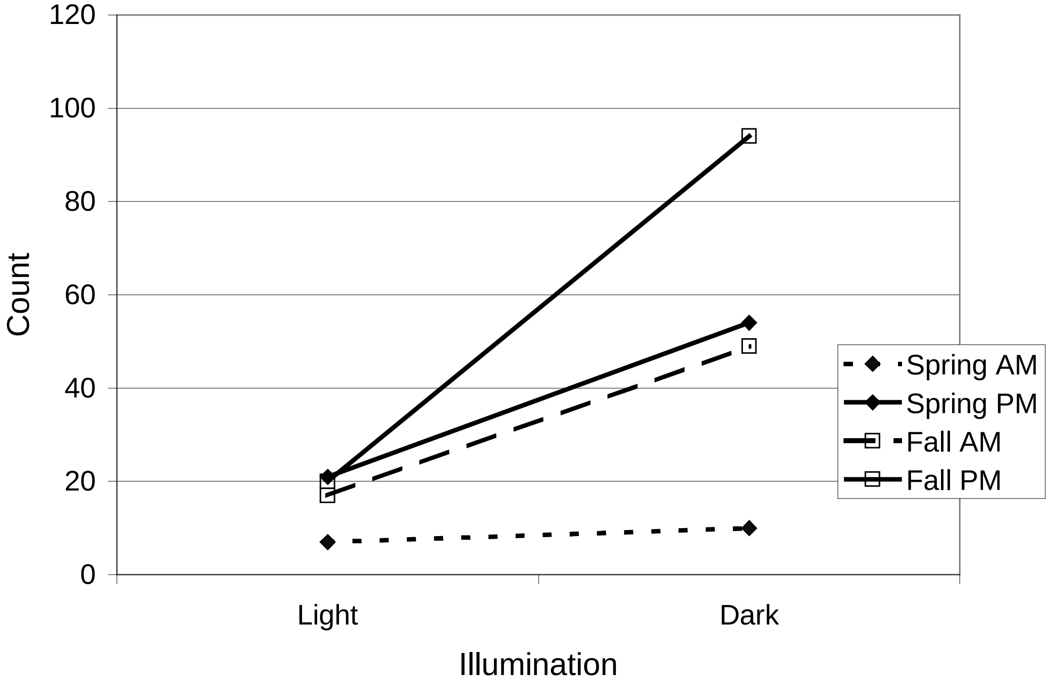

Figure 34. Cumulative fatal pedestrian crashes at intersections during transitions from light to dark and dark to light in the 2 weeks before and after DST changeover.

Table 6. Proportions of dark to light fatal pedestrian crashes at intersections by season and time of day.

Pedestrian crashes at intersections		
	A.M.	P.M.
Spring	1.43	2.57
Fall	2.88	4.70

6.4 Scenario 2: Pedestrian Crashes on Rural Roads

These results seem to indicate a much stronger influence of light level in this crash scenario than in the intersection scenario (Scenario 1). As Table 7 indicates, the number of crashes in dark conditions ranges from between three to nearly seven times the number in lighted conditions. Perhaps, as suggested earlier, the presence of fixed roadway illumination at intersections attenuated the impact of light level on the number of crashes.

Once again, the number of crashes is highest in the fall and in the evening time periods. Perhaps this is an adaptation effect. In the spring, the evening transition is from dark to light. Consequently, drivers may be relatively acclimated to driving in the darkness. Perhaps they drive more carefully or expect their commutes to take a longer time. In the fall, the transition is from light to dark. If drivers make little accommodation for the change in light level, one might expect a significant rise in fall P.M. crashes. This hypothesis, however, is not well supported by the A.M. crash data—the spring A.M. light-to-dark transition shows lower crash levels than the fall A.M. dark-to-light transitions, opposite to the adaptation prediction.

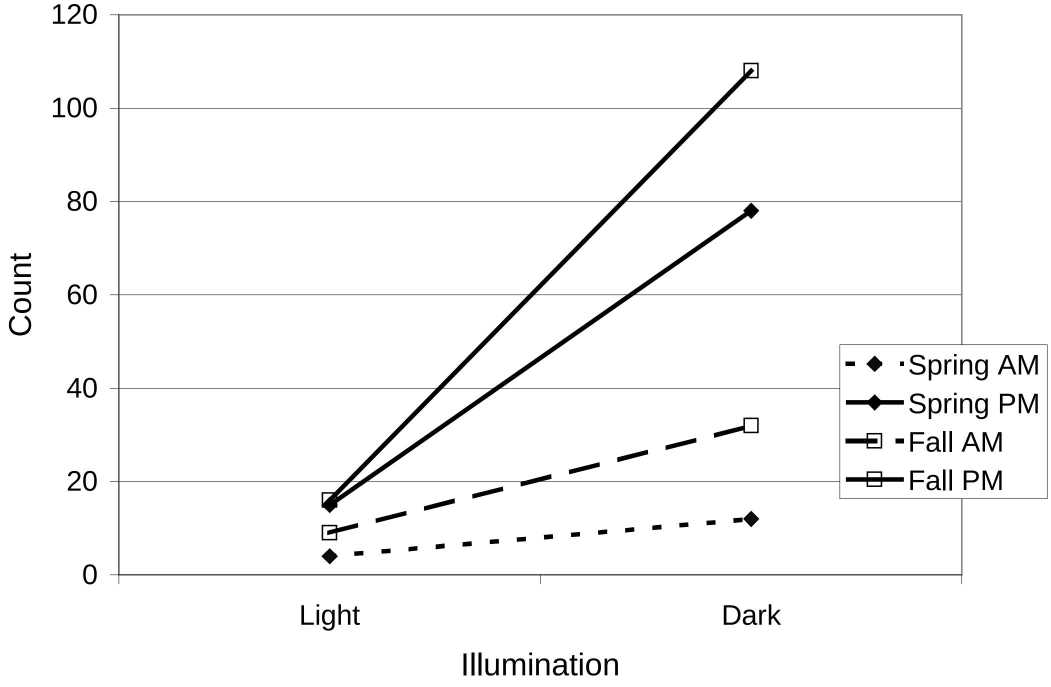

Figure 35. Cumulative fatal pedestrian crashes on straight, high-speed, rural roads two weeks before and after DST changeover. Data span 11 years, 1987 to 1997.

Table 7. Proportions of dark to light fatal pedestrian crashes on straight, high-speed, rural roads by season and time of day.

Pedestrians on rural, high-speed, straight roads		
	A.M.	P.M.
Spring	3.00	5.20
Fall	3.55	6.75

6.5 Scenario 3: Single-vehicle Road Departures on Curved Rural Roads

This scenario shows much smaller effects of light level than those observed in the previous two pedestrian crash scenarios. In the spring P.M. changeover from dark to light, crashes actually increase. In all other cases, there are more crashes in the dark than in the light, as in the pedestrian scenarios. However the range of differences is much smaller: between 0.76 and 1.48 (see Figure 36 and Table 8).

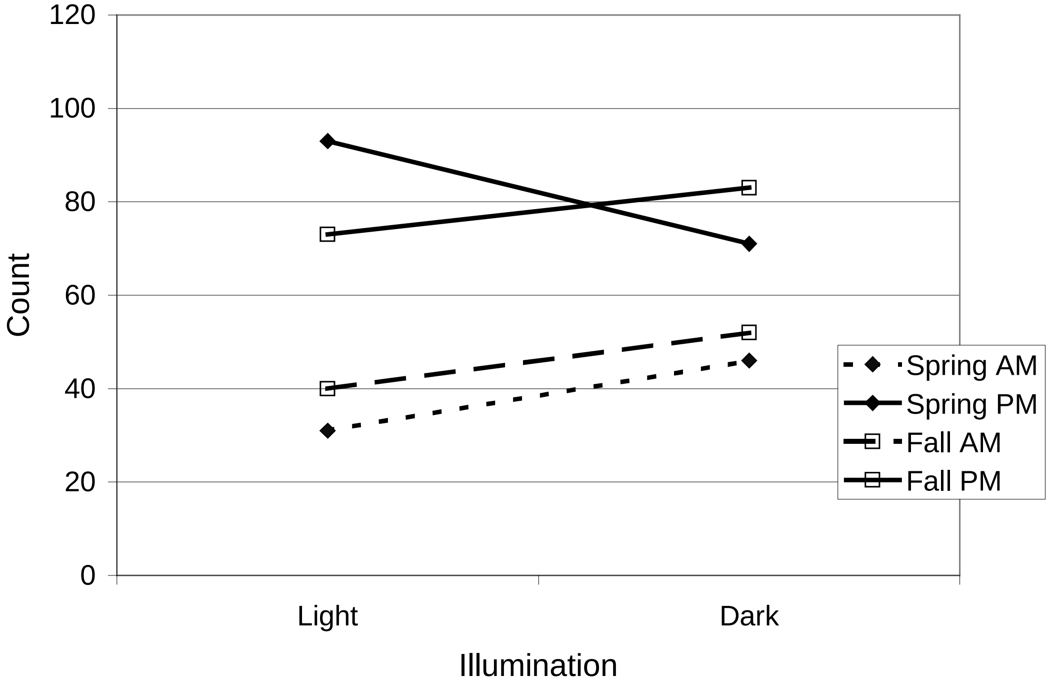

Figure 36. Cumulative fatal crashes at transition periods between dark to light and light to dark during the two weeks before and after the DST changeover.

Table 8. Proportions of dark to light fatal single-vehicle crashes on curved, high-speed, rural roads by season and time of day.

Single-vehicle road departure on curved, high-speed, rural roads		
	A.M.	P.M.
Spring	1.48	0.76
Fall	1.30	1.14

6.6 Results and Discussion

The frequency data from each scenario were pooled to model some of the relationships between scenario, season, time of day, and light level using a log-linear analysis. A model that treats each of the factors as independent is clearly not supported by the present data (χ^2= 164.62, df=18, p<0.00001), strongly suggesting an interaction between some of the factors.

When the interaction of scenario and light level was introduced in the model, a significantly better fit was produced (χ^2=66.00, *df*=16, $p < 0.00001$; difference χ^2=98.6, *df*=2, $p < 0.00001$), although the model still fails to fully account for the observed data. The scenario by light level interaction is plotted in Figure 37 which shows that the influence of light level is practically absent from Scenario 3, present in Scenario 1, and strongest in Scenario 2.

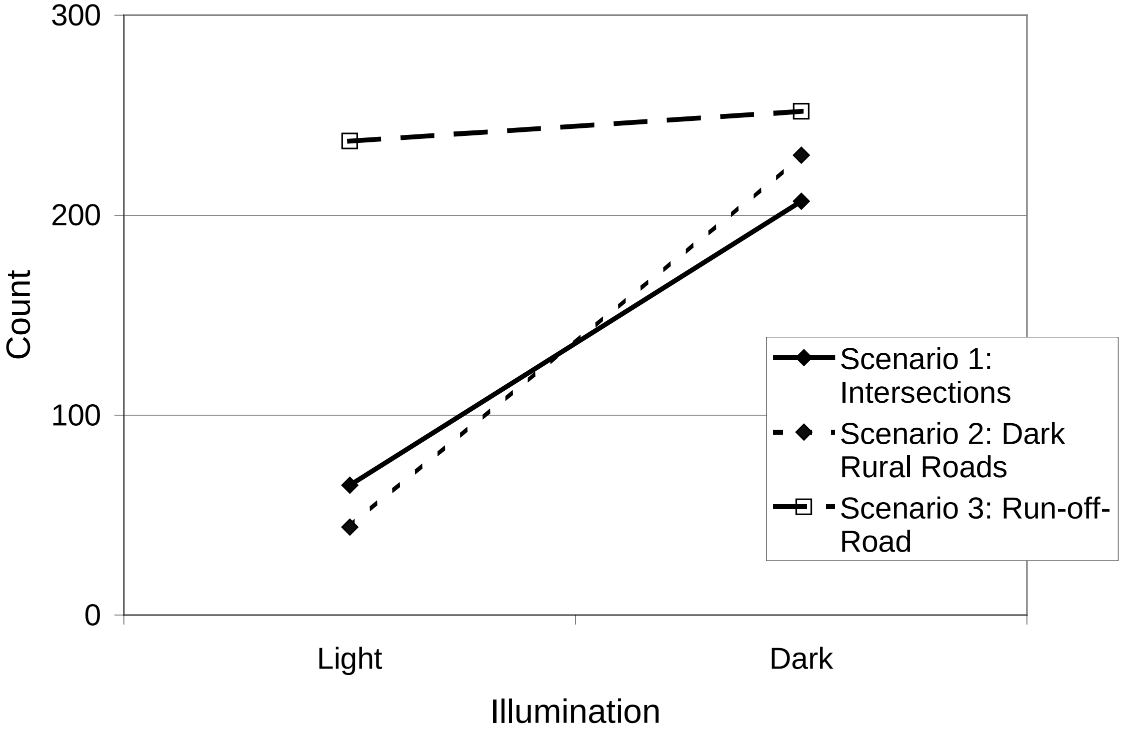

Figure 37. Light level by scenario interaction effects. The plot shows smaller effects of light level on run-off-road crashes than fatal pedestrian crashes on rural roads or intersections.

Scenarios were individually compared to each other to evaluate the relative size of the scenario by light level interactions. This was done to assess whether the scenario by light level interaction is entirely attributable to the difference between the run-off-road scenario and the pedestrian scenarios, or whether the pedestrian scenarios differ in their sensitivity to light level.

Table 9 shows the degree of reduction in χ^2 as the scenario by light level interaction is introduced. As expected, when pedestrian scenarios are compared to the run-off-road scenario, there is a clear interaction between these factors. When this interaction is taken into account in the model, a substantially better fit is made to the data. It is important to note that there is also evidence that the pedestrian scenarios also differ from each other with respect to their sensitivity to light level. The effect is less pronounced than it is in the run-off-road comparison (Table 9), but it suggests that pedestrian crashes at intersections may be less sensitive to light level than pedestrian crashes on rural roads.

Table 9. Pairwise comparisons of scenarios for magnitude of light level by scenario interactions.

Comparison	**Model**	χ^2	***df***	***p***
Pedestrians: Intersection versus Dark Rural Roads	Independent	36.65	11	0.00003
	Scenario by Light Level	31.53	10	0.00048
	Difference	5.12	1	0.02365
Pedestrians on Dark Roads versus Run-off-Road	Independent	121.7	11	>0.00001
	Scenario by Light Level	38.35	10	0.00003
	Difference	83.35	1	>0.00001
Pedestrians at Intersections versus Run-off-Road	Independent	87.66	11	>0.00001
	Scenario by Light Level	42.81	10	0.00001
	Difference	44.86	1	>0.00001

These results generally complement the seasonal twilight zone results. The estimate of the increase in Scenario 1 (fatal pedestrian crashes at intersections) in darkness was 3.7 times in the twilight-zone study, and here it is about 3.1 times (65 in light, 207 in dark). The increase in Scenario 2 (fatal pedestrian crashes on dark, straight roads) was 3.8 times, and here it is about 5.2 times (44 in light, 230 in dark). The effect in Scenario 3 (single-vehicle, road departure) appeared relatively flat in the twilight-zone study. No effect was estimated because probable patterns of exposure appeared to dominate the frequency data, and proportional estimation produced no obvious effects. In this study, the combined light to dark effect over the DST changeovers was estimated to be 1.06 times (237 in light, 252 in dark).

7.0 Conclusions

7.1 Pedestrian Crashes Show the Greatest Sensitivity to Light

This research provides evidence of the strong effect of light on fatal pedestrian crashes. The effect can be clearly seen in both the seasonal twilight-zone crash rates and in the daylight savings time changeover crash rates. Estimates drawn from these studies suggest that pedestrians may be 3 to 6.75 times more vulnerable in the dark than in daylight, depending on the circumstances. In the two pedestrian scenarios investigated, sensitivity to light level was greatest in crash data associated with straight rural high speed roads, where there is less likely to be supplemental lighting at night. Fatal pedestrian crashes at intersections show a smaller effect, possibly because fixed lighting illuminates many intersections at night.

In contrast, single-vehicle run-off-road crashes on dark curved roads do not appear as sensitive to light level as pedestrian crashes. This trend was found by Owens and Sivak (1993) with respect to all nonpedestrian/pedalcycle fatal crashes, and is supported here in the more restricted context of run-off-road fatalities. Further analysis of this type of crash suggests that alcohol is a significant factor, playing a role in as many as 76% of the Nighttime, 58% of the Twilight, and 37% of the Daylight fatal crashes. This is much greater than the reported involvement of drinking in pedestrian crashes for the same time periods: 18% of Nighttime, 9% of Twilight, and 5% of the Daylight crashes. The difference suggests that run-off-road crashes may be more a consequence of impaired judgement or reflexes than a consequence of inadequate lighting.

If we consider what is required to avoid running off the road compared to avoiding a collision with a pedestrian, it seems evident that the two tasks make different requirements of the driver. Maintenance of road position is a continuous task usually performed (even in the dark) with continuous visual error feedback from roadway markings. If roadway tracking becomes unacceptably erratic, the driver can opt to decrease vehicle speed and thus regulate the difficulty of the task.

To avoid a collision with a pedestrian in the dark, a driver must detect a pedestrian in a previously empty (or dark) area of the visual field and take evasive action immediately. The more time available in that time-to-collision interval, the more likely a collision will be avoided. This time can be extended by driving more slowly or by extending the distance at which a pedestrian is detected (at night with enhanced illumination). In general, a driver is likely to adjust vehicle speed based on visual feedback about the quality of his vehicle control. However, at night there is relatively little available feedback that the vehicle is moving too fast to avoid a collision with a pedestrian—pedestrians are sparsely distributed about the roadway. There is, however, ample feedback about lane position from roadway markings. If the speed at which the driver can maintain an acceptable lane position is higher than the speed at which a pedestrian collision can be successfully avoided, we might expect the driver to adjust his/her vehicle speed in accord with the most *available* feedback—i.e., lane position. Consistent with this, drivers appear to use this feedback and increase their speed as a consequence of improved pavement markings (Cottrell, 1998; Rumar & Marsh, 1998).

Owens and Tyrell (1999) have also suggested that lane guidance is mediated by visual mechanisms that are less adversely affected by lower light levels, providing drivers with a false sense of their own visual competence. This suggests that not only is the driver's lane guidance performance a prominent source of driving feedback, but that it also happens to be a task that is visually less demanding. As a consequence, drivers routinely overdrive their headlights because all available feedback tells them they are driving at a safe speed.

Perhaps drivers can be encouraged to drive more slowly by introducing continuous feedback on their stopping capability, although it is difficult to conceive what form this feedback might take. At the moment, the most practical means to extend the available time to avoid a pedestrian collision seems to be to improve lighting to illuminate objects further ahead of the vehicle to extend the available time to react.

7.2 What Does This Mean for Adaptive Headlighting?

The results of the reported analyses seem to suggest that the adaptive lighting that mitigates pedestrian vulnerability in darkness is most likely to provide the greatest measurable reduction in fatal crashes. There is also a suggestion that the effect is likely to be greatest wherever any other visual enhancements are absent. Existing roadway markings, fixed roadway illumination, and light sources on other vehicles appear to provide substantial assistance to drivers. When these aids are present, additional reduction in fatalities with better lighting appears smaller than when they are not.

This is not to suggest it is not worthwhile to pursue adaptive headlighting solutions that do not involve pedestrian safety. This study only sought evidence that light level affected particular kinds of *fatal* crashes. No firm conclusions can be drawn about the role of light level in other fatal crash scenarios, nor in any *nonfatal* crashes. Furthermore benefits from better illumination likely exist beyond simple reduction in fatal crashes—discomfort from headlight glare, driver anxiety, and fatigue may all be substantially reduced, while travel efficiency may be substantially increased.

It appears unlikely that adaptive headlighting solutions that enhance curve illumination (examined in Scenario 3) will significantly reduce single-vehicle run-off-road crashes. Programs to reduce the incidence of drunk driving may be better able to reduce the incidence of this type of crash. Better curve illumination may, however, provide a measurable benefit in the reduction of glare to oncoming vehicles and in extending the distance at which pedestrians are detected in curved sections of roadway. Neither of these associated benefits was examined in this series of studies.

In sum, if it were desirable to maximize the safety benefit afforded by an adaptive lighting system, such a system would realize the greatest safety benefit by specifically addressing the problem of pedestrian visibility on dark roadways.

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Appendix A – Supplemental Plots

A.1 Scenario 1: DST Changeover Effects on Fatal Pedestrian Crashes at Intersections.

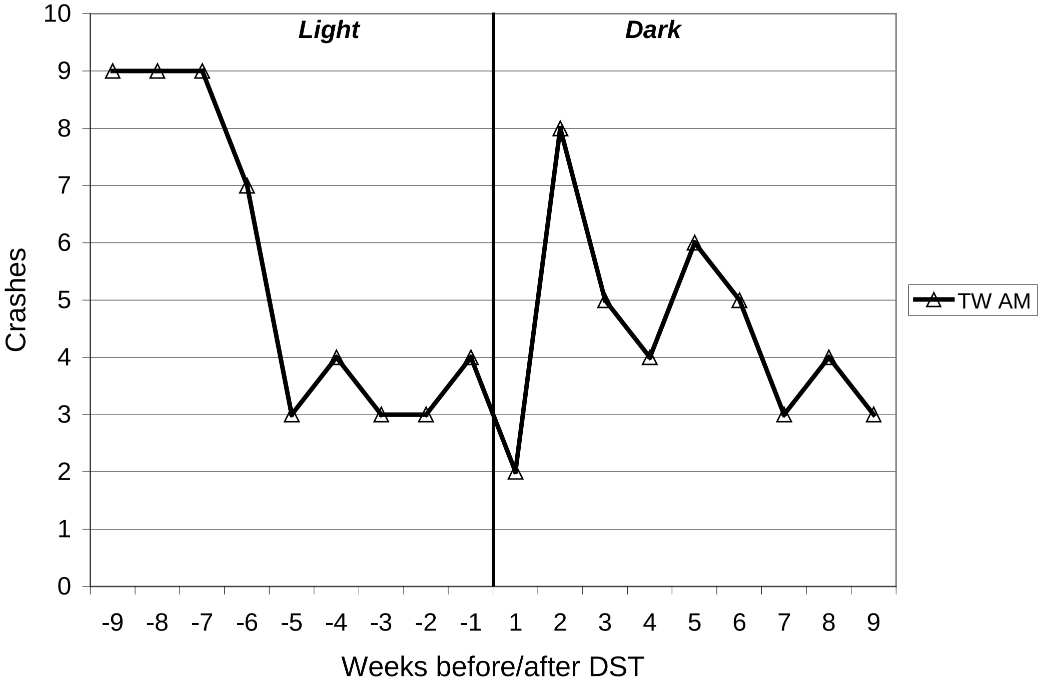

Figure 38. Cumulative spring A.M. crashes before and after DST changeover during the morning TW time interval for fatal pedestrian crashes at intersections. Data span 11 years, 1987 to 1997.

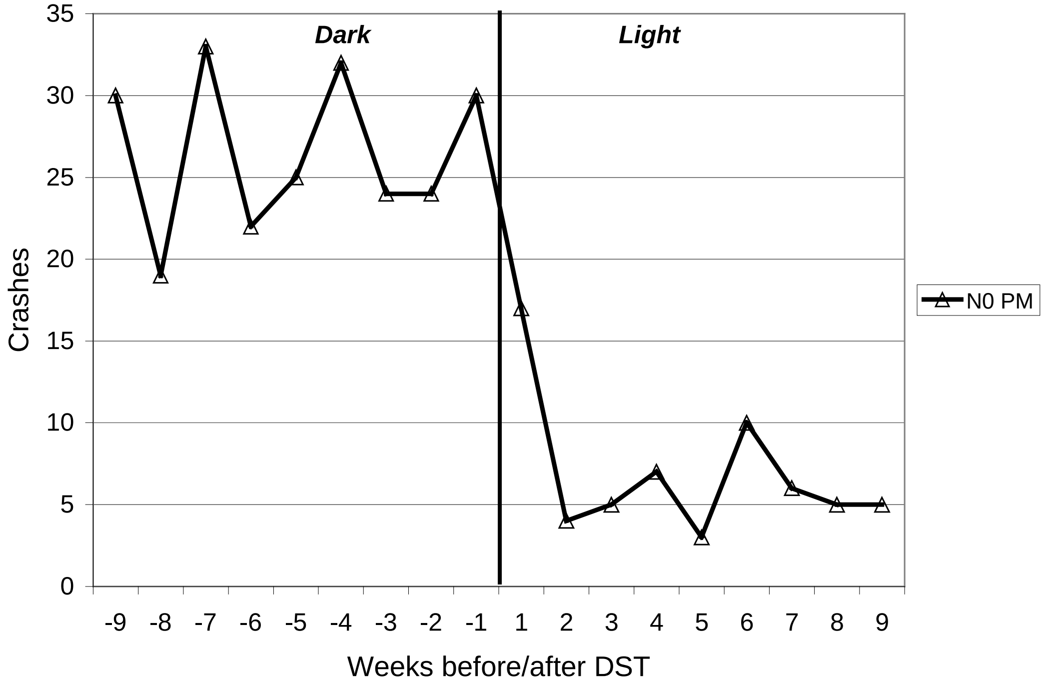

Figure 39. Cumulative spring P.M. crashes before and after the DST changeover in the evening for the N0 time interval for fatal pedestrian crashes at intersections. Data span 11 years, 1987 to 1997.

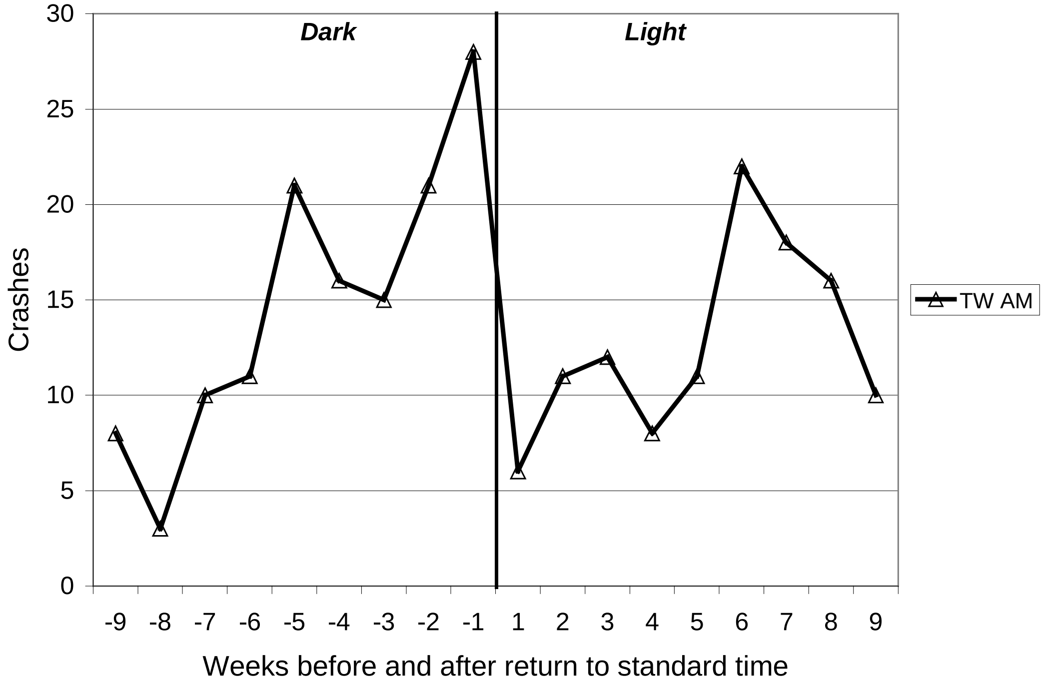

Figure 40. Cumulative fall A.M. crashes before and after the DST changeover in the morning for the TW time interval for fatal pedestrian crashes at intersections. Data span 11 years, 1987 to 1997.

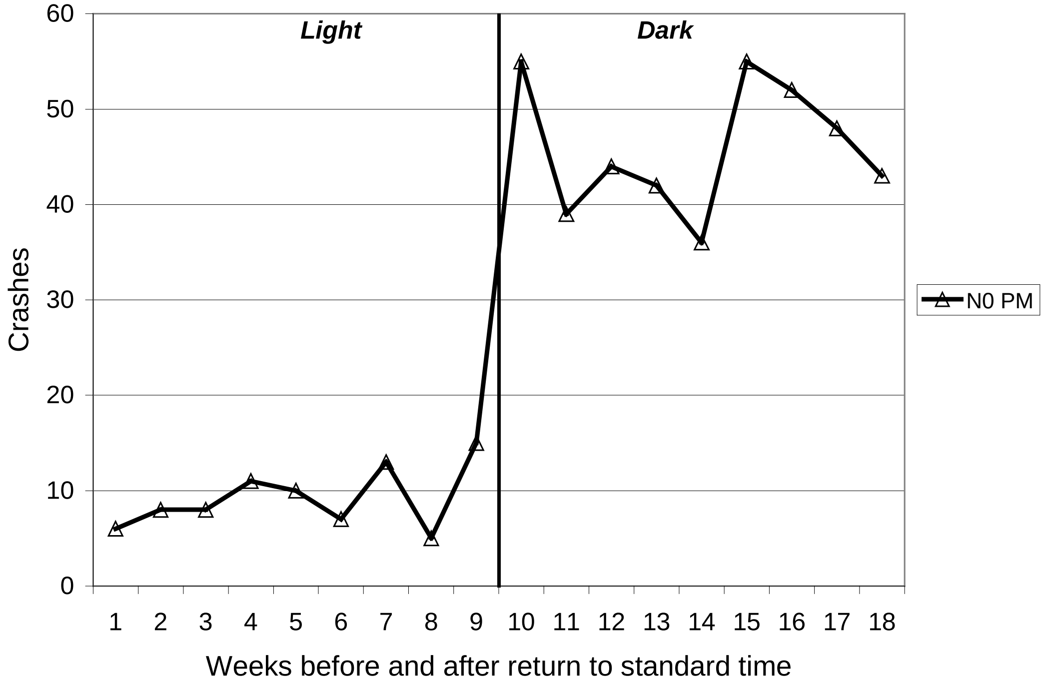

Figure 41. Cumulative fall P.M. crashes before and after the DST changeover in the morning for the N0 time interval for fatal pedestrian crashes at intersections. Data span 11 years, 1987 to 1997.

A.2 Scenario 2: DST Changeover Effects on Fatal Pedestrian Crashes on Straight Rural Roads.

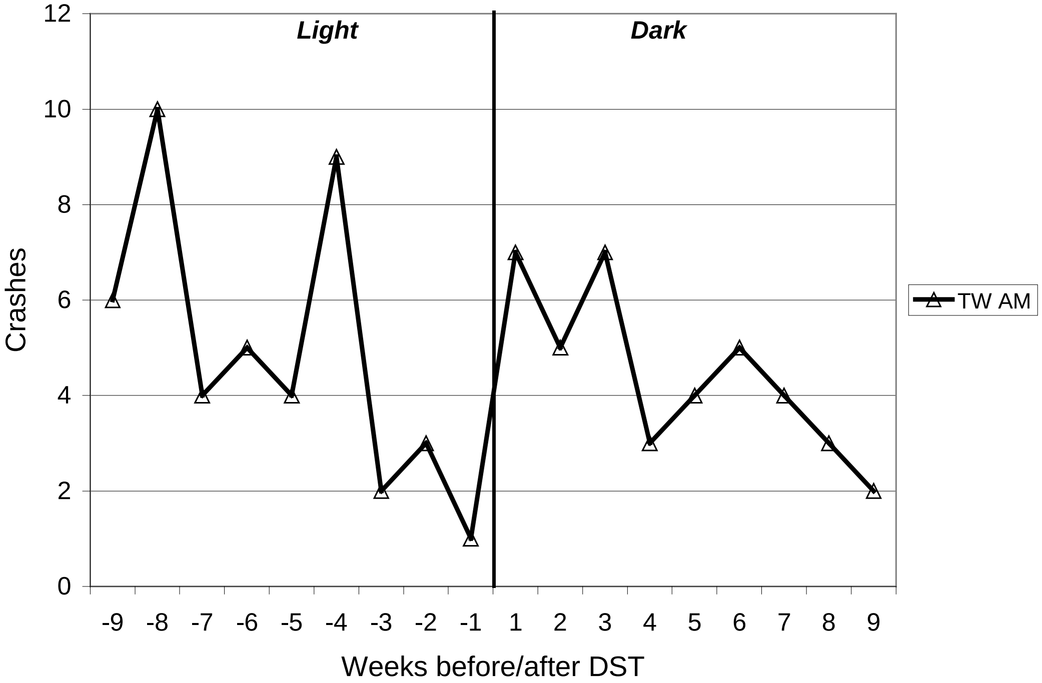

Figure 42. Cumulative spring A.M. crashes before and after DST changeover during the morning TW time interval for fatal pedestrian crashes on straight, rural roads. Data span 11 years, 1987 to 1997.

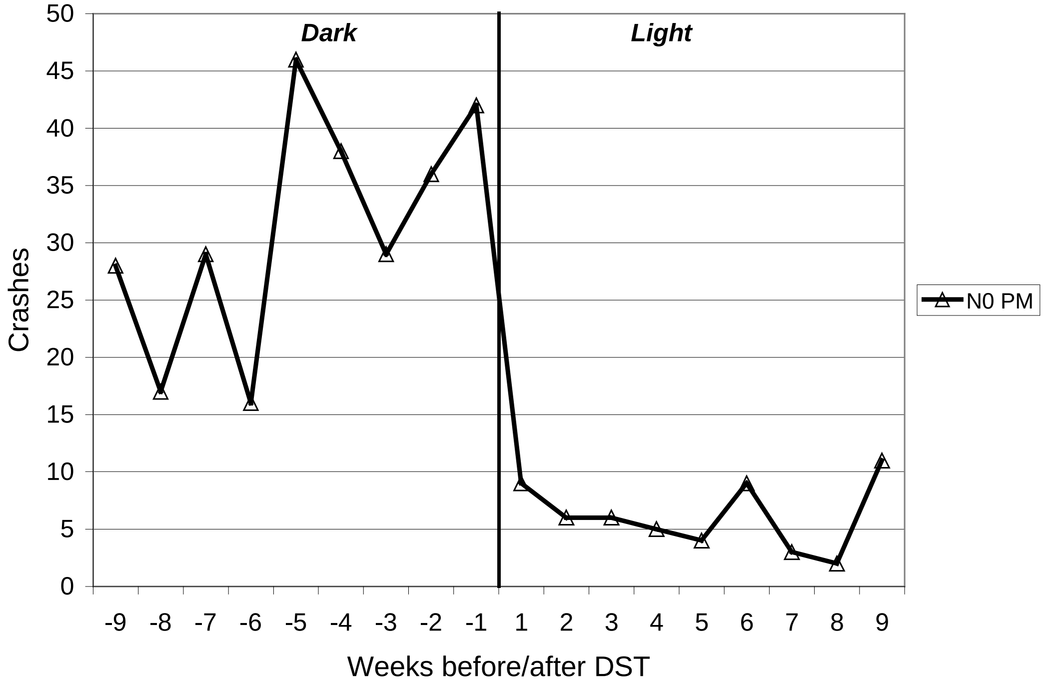

Figure 43. Cumulative spring P.M. crashes before and after the DST changeover in the evening for the N0 time interval for fatal pedestrian crashes on straight, rural, high-speed roads. Data span 11 years, 1987 to 1997.

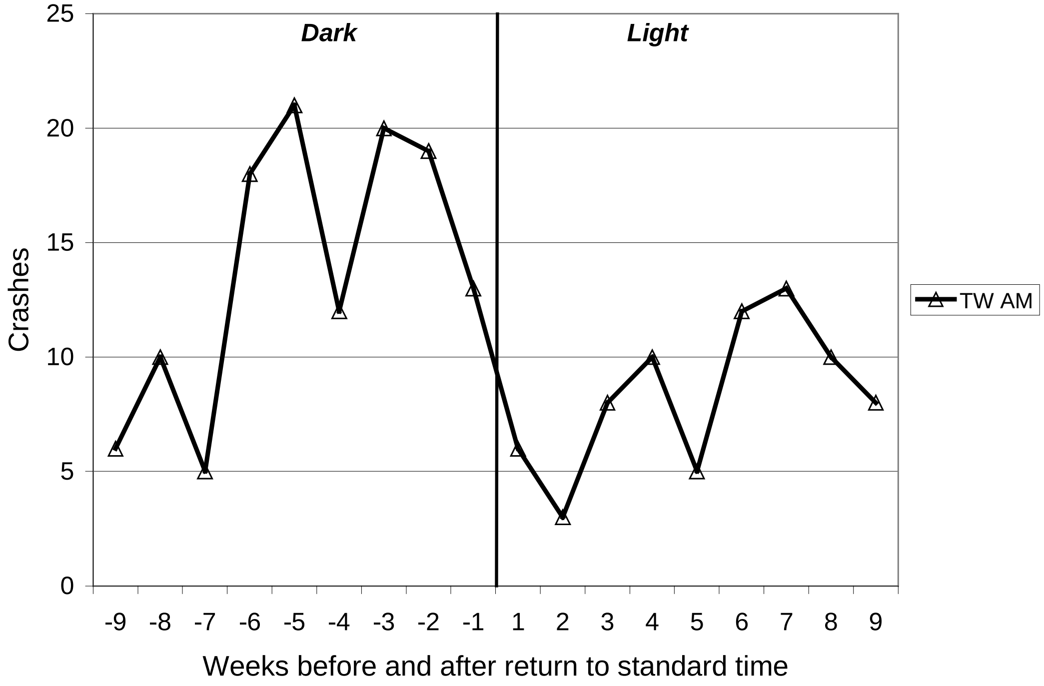

Figure 44. Cumulative fall A.M. crashes before and after the DST changeover in the morning for the TW time interval for fatal pedestrian crashes on straight, rural, high-speed roads. Data span 11 years, 1987 to 1997.

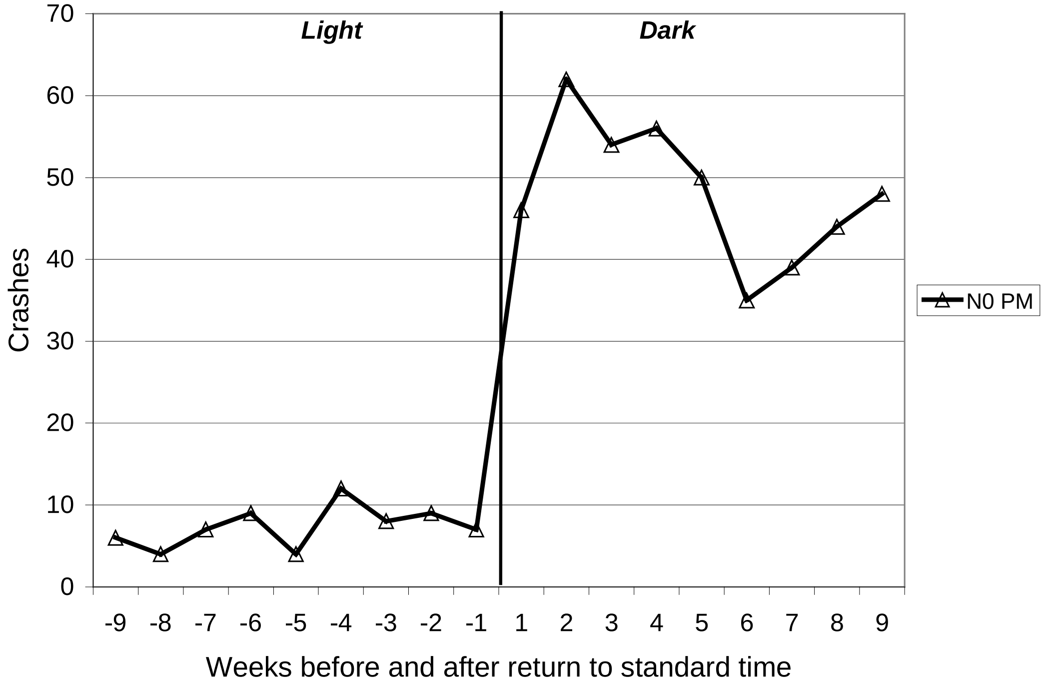

Figure 45. Cumulative fall P.M. crashes before and after the DST changeover in the morning for the N0 time interval for fatal pedestrian crashes on straight, rural, high-speed roads. Data span 11 years, 1987 to 1997.

A.3 Scenario 3: DST Changeover Effects on Fatal Single-Vehicle Run-Off-Road Crashes.

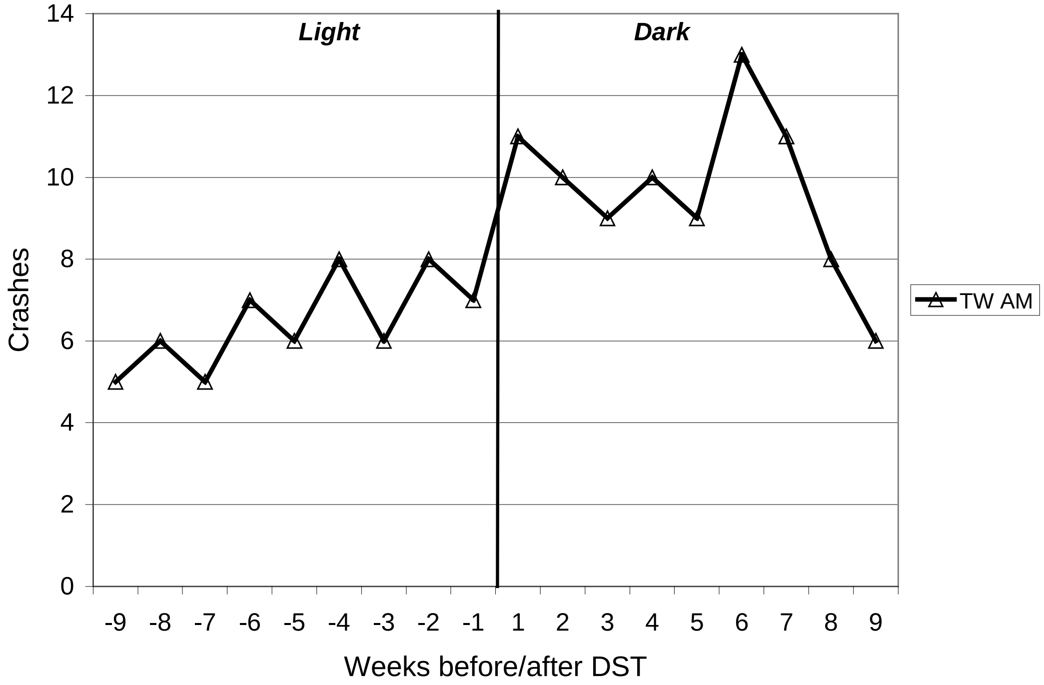

Figure 46. Cumulative spring A.M. crashes before and after DST changeover during the morning TW time interval for fatal run-off-road crashes. Data span 11 years, 1987 to 1997.

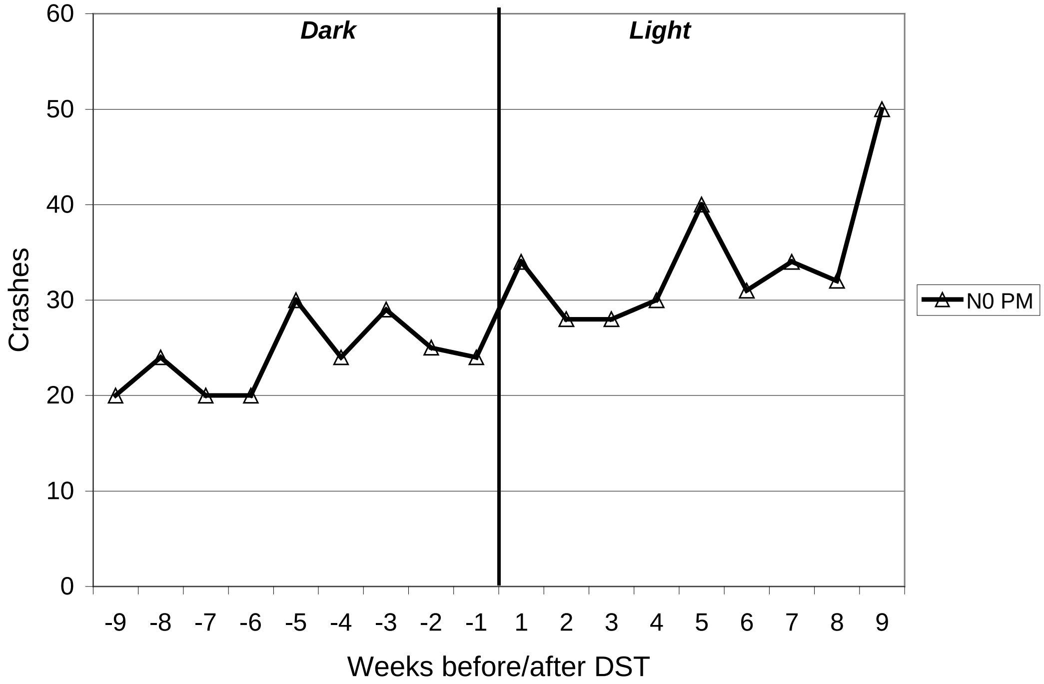

Figure 47. Cumulative spring P.M. crashes before and after the DST changeover in the evening for the N0 time interval for fatal run-off-road crashes. Data span 11 years, 1987 to 1997.

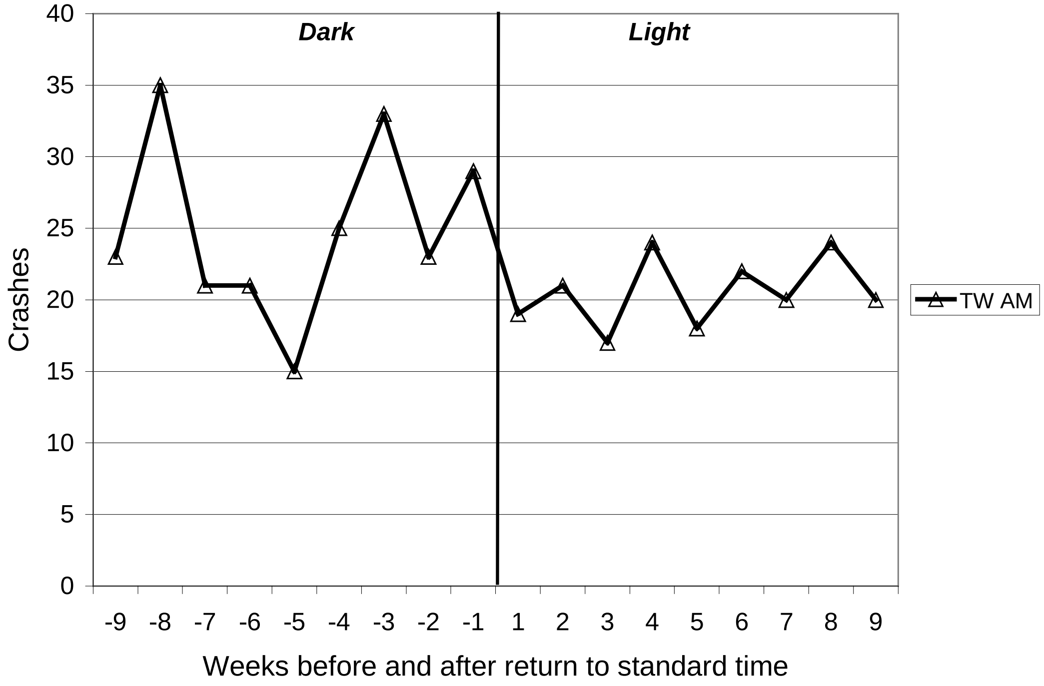

Figure 48. Cumulative fall A.M. crashes before and after the DST changeover in the morning for the TW time interval for fatal run-off-road crashes. Data span 11 years, 1987 to 1997.

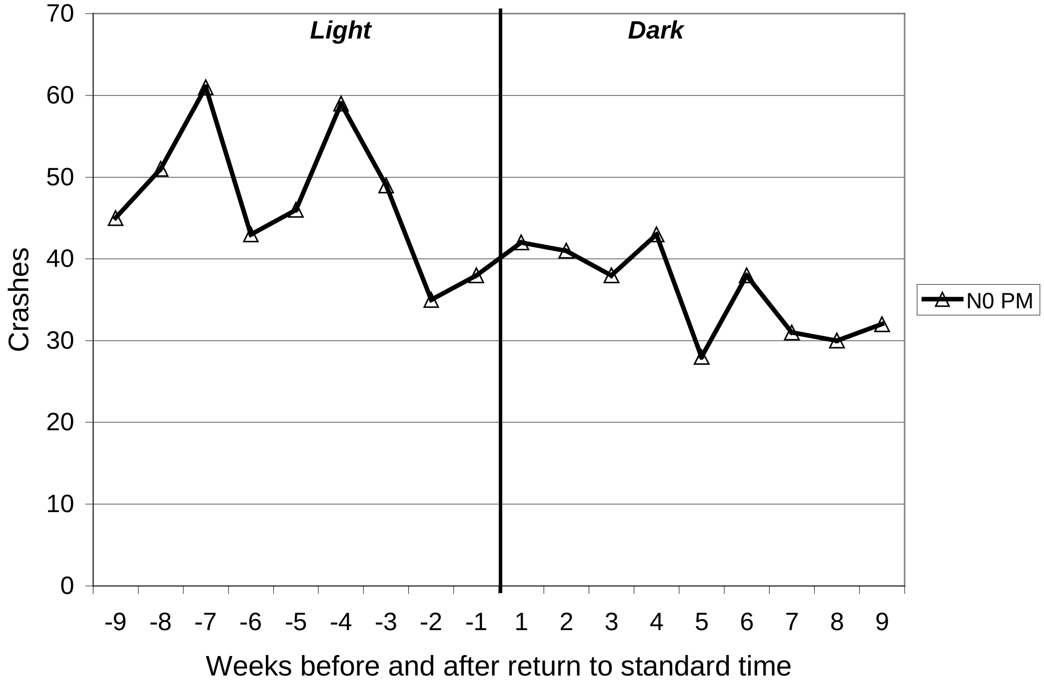

Figure 49. Cumulative fall P.M. crashes before and after the DST changeover in the morning for the N0 time interval for fatal run-off-road crashes. Data span 11 years, 1987 to 1997.