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REVIEW OF THE SAFETY BENEFITS AND OTHER EFFECTS OF ROADWAY LIGHTING

FINAL REPORT

Prepared for
National Cooperative Highway Research Program
Transportation Research Board
of
The National Academies

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June 2009

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ABSTRACT

As part of National Cooperative Highway Research Program (NCHRP) Project 5-19, a number of studies on the effects of roadway lighting on safety, crime, perceptions of security, economic development and light pollution are summarized. There is a good amount of variability among published findings, and most likely there are biases that tend to inflate the benefits of roadway lighting in terms of nighttime crash reduction and crime reduction. Nonetheless, the literature reviewed in the present report suggests that roadway lighting can contribute to reductions in nighttime crashes and to reductions in crime.

EXECUTIVE SUMMARY

Outdoor lighting is designed, fabricated and installed for expected societal benefit at night. Determination of the *value* of outdoor lighting is hard to quantify, because its value rests not simply upon its tangible implementation and operation costs but on its expected benefits, which are inherently difficult to estimate.

The present literature review describes a number of reports that have attempted to make a statistical assessment of the safety (i.e., crash prevention) benefits of roadway lighting. A review of those reports that estimate the crime-reducing security benefits of outdoor lighting is also described. Most of these studies support the conclusion that outdoor lighting provides positive safety and security benefits for drivers and pedestrians.

The collateral effects of roadway lighting in terms of economic development and light pollution are also discussed.

A few other general statements can be made regarding the potential safety benefit of roadway lighting:

- Darkness (or the absence of lighting) results in a disproportionately large number (in relation to exposure) of crashes and fatalities, and in particular, those involving pedestrians. Pedestrians are the most vulnerable population on roads at night and in terms of crash reduction appear to benefit the most from street lighting. Sullivan and Flannigan (*92*) estimate that pedestrians are between 3 and 6.75 times more vulnerable in the dark than daylight. Schwab et al. (*14*), CIE (*1*) and Elvik (*2*) estimated that street lighting can reduce pedestrian crashes at night by approximately 50%, a value that is higher than for other crash types.

- Lighted intersections and interchanges tend to have fewer crashes than unlighted intersections/ interchanges (*2, 3, 10, 23, 30*), but there appears to be no major benefit of complete interchange lighting compared to partial lighting at interchanges along urban, suburban or rural freeways, as evidence is mixed for some locations (*16*).

- It is assumed that the issues involving pedestrian and intersection crashes at night are primarily associated with visibility; hence these are scenarios in which lighting might have the greatest effect in regards to the reduction of nighttime crashes; run-off road crashes on the other hand are likely due in large part to factors (e.g., fatigue, intoxication) in which lighting is not expected to have a direct influence.

CHAPTER 1
INTRODUCTION

Outdoor lighting is designed, fabricated and installed for expected societal benefit at night. Determination of the *value* of outdoor lighting is hard to quantify, because its value rests not simply upon its tangible implementation and operation costs but on its expected benefits, which are inherently difficult to estimate.

The present literature review describes a number of reports that have attempted to make a statistical assessment of the safety (i.e., crash prevention) benefits of roadway lighting. A review of those reports that estimate the crime-reducing security benefits of outdoor lighting is also described. Most of these studies support the conclusion that outdoor lighting provides positive safety and security benefits for drivers and pedestrians.

In examining estimates of the safety and security benefits of outdoor lighting, many of the heretofore published, expected benefits of lighting are probably overestimated. The collateral effects of roadway lighting in terms of economic development and light pollution are also discussed.

CHAPTER 2
ROADWAY LIGHTING AND SAFETY

METHODOLOGIES FOR QUANTIFYING LIGHTING'S IMPACT

Several metrics have been used in various studies to quantify the effect of lighting on crash risk. Perhaps the most sophisticated was discussed in the seminal reviews by CIE (*1*) and by Elvik (*2*). In both reviews a 'criterion of safety' metric in the form of odds ratios was discussed. This ratio, denoted r, can be applied to with/without assessments or to before/after studies. Using the subscript 'unlighted' to represent the 'without' or 'before' lighting condition, and the subscript 'lighted' to represent the 'with' or the 'after' lighting condition, the equation for the odds ratio (r) is:

$$r = \frac{N_{lighted}}{N_{unlighted}} \div \frac{D_{lighted}}{D_{unlighted}} \qquad \text{(Eq. 1)}$$

where N is the number of nighttime crashes and D is the number of daytime crashes. This formulation is assumed to control for differences in crash risk that are unrelated to lighting by incorporating the number of daytime crashes in lighted and unlighted conditions. Although this assumption is not necessarily valid, as discussed later in this section, if the value of the odds ratio (r) is one, then lighting is presumed to have no effect on nighttime crash risk. If the value of r is less than one, lighting is presumed to reduce nighttime crash risk with the reduction equal to the percentage difference between r and one (if r = 0.8, a nighttime crash reduction factor of 20% from lighting is assumed). If the value of r is greater than one, lighting is presumed to increase nighttime crash risk (if r = 1.1, a crash risk increase of 10% from lighting is assumed).

Other studies have used less sophisticated assumptions comparing, for example, night/day crash ratios based on the number of crashes within a certain period of time in lighted and unlighted conditions (either with-without comparisons or in a before/after study). In these studies, if the night/day crash ratio is lower in the lighted condition than in the unlighted condition, then a reduction in nighttime crash risk is presumed.

Because the amount of driving that occurs during the nighttime differs from the amount occurring during the daytime, some studies have calculated night/day crash rate ratios. For example, Box (*3*) estimated that 25% of driving occurred at night and 75% during the day, so a single crash at night is equivalent to three (75%/25%) crashes during the day, when adjusted for traffic volume. While the night/day crash rate ratios are typically larger in numerical value than night/day crash ratios, the former are interpreted on a relative basis in the same way as the latter: if the night/day crash rate ratio is lower in the lighted condition than in the unlighted condition, lighting is assumed to reduce nighttime crash risk.

In other studies, simple comparisons are made between the number of crashes, or the crash rate (on a per vehicle basis) between lighted and unlighted conditions. These types of comparisons are more prone to differences between locations, and to changes in locations unrelated to lighting (such as the addition of roadway markings at the same time lighting was installed) that could affect nighttime crash risk.

The decision to install roadway lighting is based upon a broad range of considerations such as cost, availability of technologies, and policies. But the main reason that lighting is installed is almost always in response to a higher than expected frequency of accidents at that location (*1*). Therefore, lighting is not "randomly assigned" to locations, compromising the validity of statistical comparisons based on ratios. Moreover, the installation of lighting at a location is almost always associated with additional interventions to improve safety such as lane markings, signalization, or channelization. These associated interventions may further compromise the validity of statistical comparisons between lighted and unlighted locations simply because lighting was not the only change implemented. Together, these basic problems compromise the fundamental assumptions underlying valid statistical comparisons using any form of ratio. There does, however, appear to be compelling evidence that the collective changes associated with lighting *do* improve safety and security, but the magnitude based on existing literature may be biased for the reasons noted above.

REPORTS OF ROADWAY LIGHTING AND SAFETY

The question of whether roadway lighting can reduce the risk of crashes (and to what extent it might) is one that has been debated and studied since roadway lighting was first introduced. A number of attempts to synthesize existing knowledge have been made to address this question since the late 1980s. This review relied heavily upon three sources to provide a historical context for important research in this area and for specific details about older studies for which access to original published reports is limited. They include:

- Value of Public Lighting, Illuminating Engineering Society of North America (IESNA) CP-31-1989 (*4*)
- Lighting as an Accident Countermeasure, Commission Internationale de l'Éclairage (CIE) 93-1992 (*1*)
- Meta-Analysis of Evaluations of Public Lighting as Accident Countermeasure, Elvik (*2*)

The IESNA (*4*) review is a summary of a number of studies, but does not provide detail about statistical significance, although it does indicate that most of the studies summarized showed a benefit of lighting in terms of nighttime crash risk.

The CIE's (*1*) review is perhaps the most comprehensive to date. In that review, 62 studies from 15 countries were evaluated. The studies provided 104 results and of these, 89 indicated lighting to be beneficial to safety with 28 reaching statistical significance ($p < 0.05$). An overall estimate of a 30% reduction in nighttime crashes is the figure recommended in the review for use in benefit/cost analyses. This figure is an amalgam of results from all road types investigated, which included three broad classifications, urban arterial roads, rural arterial roads and freeways, as well as intersections and interchanges. The review broadly categorizes crash types into one of three categories: all crashes, pedestrian, or casualty (defined as crashes involving injuries or fatalities). Beyond this level it is difficult to be specific about crash types, as well as other variables (e.g., traffic flow, road design characteristics, and weather).

The review by Elvik (*2*) is an attempt to resolve differences in statistical control among many of the studies that had been performed up to 1995 using meta-analyses. Table 1 summarizes the overall findings by Elvik's (*2*) review of 37 studies of roadway lighting at 142 locations. Elvik's (*2*) meta-analysis (using the log-odds method described by Fleiss [*5*]), was a statistical overview of the safety benefits of lighting. The analysis by Elvik utilized studies (from 1948 to 1989) that primarily analyzed the introduction of lighting to areas previously without lighting, rather than lighting upgrades. After normalizing the data, the author's result showed an overall effect of lighting equivalent to a 23% reduction in nighttime crash rate.

Freeways (Limited Access Highways in Rural and Urban Locations)

The CIE (*1*) examined the effect of lighting along freeways and found that in 11 out of 17 studies that were reviewed, lighting had a net beneficial effect in terms of crashes. In three of these studies a statistically significant effect was found. Of the six studies that did not show a beneficial effect, one showed no effect and the remaining five were found by the authors to be inconclusive (no inferences could be drawn from the data collected). Of the three freeway interchange studies evaluated, all three were found to demonstrate statistically significant beneficial effects on crashes.

The IESNA (*4*) reviewed three studies of lighting on freeways and found a range of nighttime crash reduction from 17% to 40% with lighting, in comparison to unlighted freeways.

Box (*3*) is a theoretical study and unique in the detail of data provided. The same data were reported in a separate publication (*6*). It was essentially a four-part study. The largest portion of the report was associated with a cross-section study, which investigated 203 miles of lighted and unlighted urban freeways from a number of North American cities (Toronto, Denver, Chicago, Atlanta, Dallas and Phoenix). Most of the routes were six lane freeways, running through urban or suburban areas. Data from other sample sites were collected as well (rural routes, plus 4, 8 and 10 lane urban freeways). The study is noted for its thoroughness in gathering crash data.

Twenty-two lighted routes met a broad range of criteria and were included in the analysis. These criteria included data availability for one year, a minimum length of road of one mile, similar numbers of lanes and frequency of interchanges, similar illumination, similar type of adjacent land use and similar traffic volume.

Box (*3*), assuming that nighttime traffic accounted for approximately 25% of the total volume on an urban freeway, calculated night/day crash rate ratios as three times the number of nighttime crashes divided by the number of daytime crashes. The lighted sites together for all types of crashes had an average night/day crash rate ratio of 1.43; for the unlighted freeway sites, the ratio was 2.37. The author interpreted these ratios as follows: An average lighted freeway with 1000 crashes during the day would be expected to experience 475 crashes at night, while an unlighted freeway of comparable volume would be expected to have 790 crashes at night. This results in a theoretical 40% reduction ($p < 0.01$) in nighttime crashes (all types) with the addition of lighting.

When considering only fatalities and injuries, the respective ratios for lighted and unlighted freeways were 1.69 and 3.53, respectively. These ratios were interpreted by Box (*3*) as follows: An average lighted freeway with 1000 fatality/injury crashes during the day would be expected to experience 560 fatality/injury crashes at night, while an unlighted freeway of comparable volume would be expected to have 1180 fatality/injury crashes at night. This results in a theoretical 52% reduction in nighttime fatalities and injuries taken together with the addition of lighting, a statistically significant difference ($p < 0.05$).

Concluding that lighting was beneficial to safety, Box (*3*) looked at the relative effectiveness of different light levels. The night/day crash ratio associated with the illuminance range between 0.3 and 0.6 horizontal fc (3 to 6 lx), in addition to being lower than the crash ratios for unlighted freeways, was statistically different from the higher illuminance ranges (0.8 to 1.1 fc and 1.3 to 1.5 fc), which had higher crash ratios. That is, in contradiction to expectation, higher light levels resulted in more crashes. Data were not available for light levels above 1.5 fc. The author stated that glare might have been a contributing factor for the higher crash rate with higher light levels, but no data on the glare conditions of the locations analyzed by Box (*3*) were provided. The CIE (*1*) review of this study considered that to achieve the higher light levels, fixtures likely had to be placed closer to one another thereby decreasing the uniformity ratio (or the lighting was too uniform, making it difficult to see certain objects against the background). Closer pole spacing might also simply provide more objects with which a vehicle could collide. Risk homeostasis or risk compensation has also been offered as one explanation why higher light levels might result in more crashes (*7*), if drivers overestimate the potential safety benefit of higher light levels.

Uniformity values were derived from a sample of the sites, with two formulations for uniformity investigated: average-to-minimum and maximum-to-minimum (horizontal) illuminance. Box (*3*) stated that with the variations in uniformity, light level and crash-rate ratios encountered in the field, a much larger sample size (more than ten times the size used in that study) would be required for a robust statistical test. The author therefore concluded, based on the available data, that no relationship could be deduced between uniformity of lighting and nighttime crash rate.

In a second part of the study, a before/after study on 5.3 miles of a 6 lane urban freeway, two distinct sections (A and B) of the road were studied. The 'before' data consisted of two years of crash data, while the 'after' data, owing to road surface changes and minor reconstruction, consisted only of one year of crash data. The results indicated that lighting upgrades were beneficial to safety. In one section of road (A), the night/day crash ratio changed from 3.0:1 (before) to 1.3:1 (after). The other section of road (B) changed from 3.1:1 (before) to 2.0:1 (after). After the re-lighting, the percentage of all crashes was reduced by 18% for section A and by 11% for section B. The percentage reduction in injuries/fatalities was 24% for both sections. Because of small sample sizes, the author stated that statistical analysis was lacking (*3*).

A third part of the study compared a lighted section of freeway to an unlighted section, using two years of crash data for the lighted section and four years of data for the unlighted section. Light level measurements indicated that the average horizontal illuminance was 0.33 fc with a uniformity ratio of 16:1. The unlighted section was described as being similar to the lighted section, with the exception of a wider median and lower traffic volume. This is one of the few studies which report details of crash type (rear-end, other vehicle, pedestrian and parked car, fixed object and other off-road) and location (mainline, ramp entrance, ramp exit, on ramp). The sample size was too small for analysis of pedestrian and parked car crash type. Analysis of the data for other types of crashes led the author to conclude that lighting was beneficial for rear end and other vehicle crashes. Box also found that lighting was not beneficial for fixed object crashes. Locations such as exit ramps had relatively few crashes, while ramp entrances had a relatively high percentage of rear end crashes. As Box noted (*3*), high rear end crash frequencies at ramp entrance locations could be attributed to lack of adequate acceleration lanes.

Box (*3*) also analyzed crashes on interchanges and sections between interchanges, both comparing unlighted to lighted sections and using (when possible) a before/after comparison. Overall, lighting resulted in fewer crashes at interchanges and between interchanges.

Lamm et al. (*8*) performed a study on a suburban freeway in Germany that was essentially a cross-section type, but had before/after data for both lighting installations and for reductions in lighting. As a cross-section study, the authors noted the difficulties associated with data interpretation due to changes occurring over the period of study (1972-1981). In particular, the rate of personal injury crashes steadily decreased since 1972. The assumed factors for this decrease included the energy crisis of 1973-1974, speed limit changes, stricter drunk driving laws, seat belt laws and mandatory safety-helmet laws.

Between interchanges, the divided freeway consisted of two lanes in each direction, with an additional emergency lane on each side. On the part of freeway studied, lighting was installed in 1973. It was assumed, based on a telephone conversation in 1985 with a government official that lighting was maintained to national standards during the study period (referred to in the paper as an average luminance of 1 cd/m^2 and a minimum-to-maximum uniformity ratio of 0.7) for the traffic volume of 900 vehicles/hour or more and a speed limit of 110 km/h or less.

The freeway section studied was divided into three sections: two were lighted, the third was unlighted. The period of investigation was divided into three categories: a 'before' (B) period and two 'after' (A1 and A2) periods. The B period consisted of one year of crash data, while the A1 and A2 periods contained data for longer periods of time.

During period B, all sections were unlighted. During period A1, two sections with curved geometries (S1 and S2) were lighted from dusk to dawn, while a third, straight section (S3) remained unlighted. During period A2, S1 was lighted from dusk to dawn and S2 was lighted from dusk until 10:00 PM. Between 10:00 PM and 5:30 AM, S2 was unlighted. From 5:30 AM until dawn, S2 was lighted only when daylight was not available. S3 remained unlighted during period A2.

The crash data came from police reports over a 9 year period (1899 reports total). No vehicle-pedestrian crashes were observed. Due to limited data, different crash types were not analyzed separately, although it was observed that run off road crashes approximately doubled during nighttime, while rear end collisions decreased at night.

Overall, lighting was associated with a reduction in nighttime crash rates. In section S2, the introduction of lighting from dusk to dawn (A1) was associated with decreased nighttime crash rates (p <0.05) that were significantly lower than the before period. Further, when lighting was reduced in duration during period A2, nighttime crash rates were increased significantly (p <0.05) relative to A1 (*8*).

Griffith (*9*) primarily used data from the Highway Safety Information System (HSIS) supplemented with data from the Minnesota Department of Transportation (MnDOT) in a cross-section study evaluating the effect of lighting on urban freeways. MnDOT provided information on where and what type of lighting existed at each location, as well as a videodisc photolog, which provided information about the road systems being investigated. Essentially the author found that urban freeways with continuous lighting are statistically significantly (p<0.05) safer (defined as having fewer nighttime crashes) than the same types of freeway with interchange-only lighting. Specifically, along sections of road between interchanges, continuous lighting reduced nighttime crashes by 16%.

The two comparison groups in the study were 54.6 miles of urban freeway with continuous lighting and 35.5 miles of urban freeway with interchange-only lighting. A major difference between these two sections pertained to the number of interchanges per mile. There were 1.2 interchanges per mile on the continuously lighted section, and 0.8 interchanges per mile on the interchange-only lighting section. All the continuously lighted sections had complete interchange lighting. The interchange-only lighting sections had either partial or complete interchange lighting; partial lighting being more common.

The day/night distribution of total vehicle miles traveled was found to be the same for both sections of road; approximately 76% of travel occurred during the day, and 24% at night. Traffic volumes were also similar (within 5%) between the two sections. The author made the assumption that other potentially extraneous variables (e.g., weather, vehicle fleet, driver demographics) between the two sections of road were similar since they were adjacent to one another.

Crash data from a five-year (1985-1990) period were used for analysis. Crash rates were categorized into all crashes, serious crashes, injury crashes, property damage only (PDO) crashes, interchange area crashes, and non-interchange area crashes. The total daytime crash rate for the continuously lighted sections was approximately three times higher than the total daytime crash rate for the interchange-only-lighted sections. This result was assumed to be a function of a greater number of interchanges along the continuously lighted sections.

The total nighttime crash rate divided by the total daytime crash rate resulted in the total night/day crash ratio. The ratio for the interchange-only lighting section was 12% higher than for the section with continuous lighting, and the difference was statistically significant ($p < 0.05$), indicating that continuous lighting decreased the nighttime crash risk.

When considering solely the interchange areas of each road section, the night/day crash ratios were statistically equivalent. According to the author this was expected, since interchanges in both sections were lighted, although as described above, some were partially lighted while others had complete lighting. When comparing night/day crash ratios for serious injury, injury and PDO crashes, the only meaningful difference found was for PDO crashes for the freeway sections with interchange-only lighting, which were 19% higher than for the continuously lighted section of freeway.

The night/day crash ratio for non-interchange areas was 18% higher for sections with interchange-only lighting compared to the continuously lighting lighted sections, a statistically significant difference ($p < 0.05$). With regard to crash type within non-interchange areas, the only significant difference was found in terms of property damage only (PDO) crashes, which were 32% higher in the interchange-lighting-only areas than similar areas in the continuously lighted section of freeway. The differences in serious injury and total injury crashes were not significant between these sections.

Following Box (*3*), the author (*9*) assumed that nighttime traffic accounted for approximately 25% of the total volume on an urban freeway and calculated night/day crash ratios as three times the number of nighttime crashes divided by the number of daytime crashes. In a separate analysis, the author estimated that the introduction of lighting to an unlighted urban freeway could theoretically result in 16% fewer crashes in areas between interchanges. This roughly corresponds to Box's (*3*) findings for areas between interchanges along urban freeways, where lighting reduced crashes in these areas by approximately 9% to 18%.

Bruneau et al. (*10*), in a study of continuous and interchange-only lighting, used crash data from 1990 to 1998 along 800 km of a four-lane rural Canadian freeway designated into 213 sections. Crash rates were computed for three categories of crashes: PDO crashes, fatal and injury crashes, and total crashes. The crash ratios were smaller for continuous lighting (by 33%, $p < 0.001$, in comparison to interchange-only lighting, and by 49%, $p < 0.05$, in comparison to no road lighting). No significant difference was found between complete and partial interchange lighting, but there was a significant difference between interchange lighting and no lighting.

Total crashes under continuous lighting versus no lighting were significantly lower by 33% ($p < 0.05$), and showed a 32% reduction ($p < 0.001$) compared to interchange-only lighting. Differences in lighting were found by the authors to be found regardless of traffic density. Comparisons for PDO crashes showed similar results. Continuous lighting reduced PDO crashes by 35% ($p < 0.001$) in comparison with interchange-only lighting, and by 43% ($p < 0.002$) compared to freeways without lighting. Injuries and fatalities failed to show a significant difference when comparing continuous lighting to either no lighting or interchange lighting.

Stark (*11*) examined a crash study involving urban freeways in Los Angeles that was conducted by Johnson and Tamburri (*12*). The crash data were used by Stark to compute night/day ratios in crash rates per million vehicle miles for comparing lighted versus nonlighted freeways. The calculations showed a night/day crash rate ratio of 1.58 for illuminated and 1.85 for nonilluminated freeways, a difference of approximately 15% attributable to lighting.

Yates and Beatty (*13*) performed a study of 8,373 freeways along between-interchange or mainline units. After computing the vehicle crash rates (crashes per million vehicle miles) for lighted mainline units versus non-lighted units, they found that, in general, nighttime crash rates were higher on mainline units with lighting than with no lighting. Since the data and analysis were limited, no statistical significance was calculated and the researchers concluded that the rates could have been influenced by other factors than lighting. The study has been criticized in past reviews (*14*) for the data used to represent nighttime crashes; it was not necessarily dark during the highest volume period of what was termed 'night'.

Sabey and Johnson (*15*) conducted a before/after study whereby lighting was either installed or upgraded, to national standards at the time, at 43 sites on trunk roads (a major road usually the recommended route for long-distance and freight traffic) in England. The study categorized data according to posted speed limit. Changes in nighttime crashes along lighted sites were compared with nighttime crashes along unlighted roads. Daytime crashes were not used as a control. Controls consisted of larger portions of roadways, either on the same or similar (with respect to posted speed limits) roads in the same police district. The authors used the same methodology for calculating effectiveness as CIE (*1*) and Elvik (*2*). An 'r' value less than 1.0 indicates that lighting is associated with a reduction in crashes. For most speed limits, crashes were reduced after new lighting. Only those roads with 70 mph speed limits appeared to show a statistically significant safety benefit (perhaps because of larger sample sizes for these posted speeds). A benefit/cost analysis for the 70 mph class of roads estimated that savings (owing to reduced crashes) amounted to approximately three times the annual cost of lighting.

Monsere and Fischer (*16*) evaluated the effects of reductions in light level and removal of lighting on lineal freeway sections. They developed statistical models for daytime and nighttime crashes of different severity levels, which predicted a statistically significant ($p < 0.05$) increase (of 29%) in the total number of nighttime crashes at locations with reduced lighting relative to those with the full amount of lighting. The models also predicted a statistically significant ($p < 0.05$) decrease (of 23%) in daytime injury (i.e., more severe) crashes at locations with reduced lighting.

Arterial Roads (Unlimited Access)

The review by the CIE (*1*) of studies of lighting along rural arterial roads with continuous lighting showed that in 16 out of 17 cases, lighting was found to have a beneficial effect on safety. Of these, five revealed statistically significant effects. One study indicated an adverse effect of lighting on safety. The IESNA summary (*4*) identified two studies of lighting along rural roadways; while statistical significance is not reported, reductions of 10% and 15% in nighttime crashes were found.

Harwood et al. (*17*) developed an accident modification factor (AMF) for roadway lighting on roadway segments and at-grade intersections along urban and suburban arterials. These AMFs are proposed for inclusion in the first edition of the Highway Safety Manual and are based on the meta-analysis research reported by Elvik and Vaa (*18*). When local jurisdictions can collect crash severity data, and stratify crashes by daytime and nighttime periods, Equation 2 is recommended to compute an AMF for lighting roadway segments along urban and suburban arterials:

$$AMF_{segments}=1-[(1-0.36p_{fnr}-0.72p_{inr}-0.83p_{nr})p_{nr}] \quad \text{(Eq. 2)}$$

where:

p_{fnr} = proportion of total nighttime accidents for unlighted roadway segments that involve a fatality;
p_{inr} = proportion of total nighttime accident for unlighted roadway segments that involve only a non-fatal injury;
p_{pnr} = proportion of total nighttime accidents for unlighted roadway segments that involve property damage only;
p_{nr} = proportion of total accidents for unlighted roadway segments that occur at night.

Using combined data from Michigan and Minnesota as an example, Harwood et al. (*17*) illustrated that an appropriate AMF for total accidents on arterial roadway segments with lighting would be approximately 0.96 for all roadway types (i.e., 4 percent reduction in total accidents after installing roadway lighting).

Rural Roads

There have been few recent studies on rural continuously lighted areas, with most recent literature focusing on rural intersections, as described later in this section. Wanvik (*19*) analyzed injury crash statistics for lighted and unlighted roadways in the Netherlands and estimated that the effect of lighting was a reduction in nighttime injury crashes of 50%, with larger reductions in crashes involving pedestrians and bicyclists, and smaller reductions during adverse weather.

Urban/Suburban Roads

The CIE's (*1*) review of studies of urban arterial roads with continuous lighting showed that, in 42 out of 49 cases, the results indicated that lighting had a beneficial effect on safety. In 14 of these studies, there were statistically significant effects. Four of the studies indicated an adverse effect of lighting, with 2 revealing statistically significant differences. Three studies showed no effect.

Tanner (*20*) is often referred to as the ‘classic UK study’ showing that ‘good lighting’ on urban routes results in fewer and less severe crashes at night. Despite being nearly 50 years old, the results of the study are largely consistent with the overall conclusions of this review, that crashes on urban roadways can be reduced by approximately 30% due to lighting, with pedestrians benefiting the most (a 45% reduction in pedestrian crashes).

Tanner (*20*) conducted a before/after study. Before relighting, the roads under study were considered to be poorly lighted (using gas or incandescent filament sources). Lighting upgrades (using various discharge sources such as low pressure sodium or mercury vapor) followed the national standards at the time. Crash data for up to three years before and after the change, were evaluated according to the same method as used by the CIE (*1*) and Elvik (*2*), utilizing an odds ratio to estimate the effect of lighting on nighttime crash risk.

Injury crashes were analyzed by severity (fatal, serious or slight), as well as by pedestrian or non-pedestrian crashes. Sixty-four sites were evaluated. For injury crashes as a whole, $r = 0.70$, indicating an apparent 30% reduction in nighttime crashes from lighting, a statistically significant effect ($p < 0.001$). A more detailed breakdown into pedestrian and non-pedestrian injury and by crash severity revealed that pedestrians benefit most, but both pedestrian and non-pedestrian crashes were reduced by a statistically significant amount.

When considering all pedestrian injury crashes together, the apparent reduction from lighting was 45% ($p < 0.001$), and for non-pedestrian injury crashes, the reduction from lighting was 23% ($p < 0.01$). Lighting proved beneficial in all scenarios except for non-pedestrian fatalities (where r = 1.27). This figure was assumed by the authors to be due both a small sample size and a decrease in daytime fatalities for the roadways studied.

Cornwell and Mackay (*21*) performed a before/after investigation, which basically set out to evaluate the findings of Tanner (*20*). They essentially confirmed Tanner's findings of a 30% overall reduction in nighttime crashes along urban routes. The authors also reported findings from rural locations. Rural sites appear to benefit slightly more from upgrades in lighting than urban sites. Data were collected from both police records as well as from the Department of Environment (UK). The authors collected data for 60 sites: 16 urban roads, 43 rural and trunk roads, and one road that was classified as part urban and part rural. Trunk roads are assumed to be rural freeways connecting urban areas.

The odds ratio (r) estimating the effect of lighting on nighttime crash risk was calculated in the same manner as by Tanner (*20*), the CIE (*1*) and Elvik (*2*). Daytime crashes were used as a control. The authors note that several unusual changes occurred during the study period: the introduction of the British Road Safety Act in 1967, and the introduction of British Standard Time in 1968.

The authors made adjustments and corrected for these changes, although these were not specified clearly by the authors. Both urban and rural sites showed a statistically significant reduction in crashes due to lighting, though rural sites showed a greater percent reduction and significance (and also had larger sample sizes). Trunk roads also showed statistically significant nighttime crash reductions between the before and after periods.

Box (*22*) completed a cross-section type study of collector streets (2000 to 5000 vehicles per day) and major streets (more than 5000 vehicles per day), totaling 105 miles within Syracuse, NY in 1970. The author compared crash data against light levels to evaluate optimal levels for each road class, and compared these values to recommended standards at the time. The author found that light levels lower than the recommended standards at the time were associated with fewer crashes at night. Sites were classified as downtown, intermediate or outlying areas. The first two included business districts and residential areas, while the third was defined as a low nighttime pedestrian traffic area, with many industrial areas. 329 total sites were used in the analysis. Crash data came from police records for 1967.

Using lighting field measurements supplied by a local utility, two groups within each category of road and site location were designated: sites lighted to 1963 recommendations (group A) and those with values less than the 1963 recommendations (group B). The night/day crash ratios for group B were smaller than for group A for most roadway types, implying that increasing the illuminances to meet the 1963 recommendations actually increased nighttime crashes relative to daytime crashes, a similar finding to Box's earlier (*3*) study. Based on these findings the author suggested that an optimal horizontal illuminance for downtown and intermediate areas was 1.8 fc, and for outlying areas was 1.0 fc. Illuminances above these values were not associated with reductions in nighttime crash risk.

Box (*23*) conducted a before/after study outside Chicago along a major suburban route with commercial land uses such as service stations and restaurants. The after period was for a period of time following widening of the road. Overall, statistically significant reductions (~30%) in nighttime crashes were observed after lighting installation. As well, intersections with lighting had a lower percentage of nighttime crashes than those without lighting (27% in the former compared to 42% in the latter).

After installation, the light levels were measured to be 5% higher, after correcting for depreciation, than the specifications for illuminance (15 lx), and the uniformity ratio was within 10% of the specified recommendations at the time. There was a reduction in all crash types after lighting was installed. When data were expressed as night/day crash rate ratios (1.35 for the before period, and 0.87 for the after period), the results revealed a statistically significant ($p < 0.01$), 36% reduction in nighttime crashes.

Lighting appeared to benefit all crash types with the exception of head-on crashes at intersections and mid-block driveway crashes along mid-block locations. Pedestrian crashes especially were reduced at all locations.

Box (*24*) performed a before/after study along 2.5 miles of urban arterial roadways in Florida, after half of the luminaires (every other luminaire) were turned off (halving horizontal light levels from 1.8 to 0.9 fc). Note that as of 1982, the American National Standards Institute (ANSI) recommendations for such roadways were 1.4 fc. The results indicated a nearly 40% increase in the number of nighttime crashes after the lower levels of illumination were used, including increases of 42% for PDO crashes and 33% for injury crashes. As discussed above, the changes in light level were almost always associated with changes in uniformity of illumination, and so it was not always possible to attribute changes in crash risk to one of these factors.

Intersections and Interchanges

Harwood et al. (*17*) developed an AMF for lighting intersections on urban and suburban arterials, based on the work by Elvik and Vaa (*18*). Using data from Minnesota and North Carolina, Harwood et al. (*17*) illustrated that an intersection lighting AMF for total accidents is 0.96, or a 4% reduction in total crashes after the installation of roadway lighting at intersections.

Rural Intersections and Interchanges

The CIE (*1*) review found that for rural intersections, of eight studies identified, seven indicated that lighting was beneficial to safety, and in two of these the results were statistically significant. One study indicated an adverse (but not statistically significant) effect of lighting. The summary of lighting studies along rural intersections by the IESNA (*4*) showed a net benefit of lighting in three studies, with nighttime crash rate reductions from 12% to 52%.

Walker and Roberts (*25*) performed a before/after study using three years of crash data representing each of the before and after periods. Statistically significant reductions in certain intersections were seen that were associated with lighting. Intersections were classified as either unlighted (before) or lighted (after). A general finding was that lighting had little effect on low volume roads with daily traffic densities of less than 3500 vehicles per day. Care was taken not to include sites where other major road changes took place over the entire study period. A total of 47 intersections were analyzed.

Lighting installation began on different years for different sites in the study by Walker and Roberts. Therefore, the 'after' period could have begun as early as 1964 or as late as 1968. Traffic counts were not complete for all six years and the authors (as in most of the studies reviewed) used existing data to estimate nighttime traffic volume for each three year period. To make this estimation, the authors assumed that nighttime traffic represented 27% of the total daily traffic to represent nighttime volume at the intersections. A general finding was that overall, traffic increased by approximately 11.6% from the first year of the study (year one, before) to the last year of the study (year three, after). Nighttime crash rates (expressed as crashes per million entering vehicles) reduced from 1.89 (before) to 0.91 for after, while daytime crash rates (per million entering vehicles) also decreased, but to a much lesser extent, from 1.58 (before) to 1.38 (after).

Intersections were categorized into channelized and unchannelized intersections. Both types saw a reduction in crashes at night with lighting, but only the channelized group saw a statistically significant ($p < 0.01$) reduction.

Green et al. (*26*) analyzed nighttime crash characteristics in the state of Kentucky. An analysis of the state's crash data from the years 1999 to 2001 was conducted. The data included all reported crashes on state-maintained roads. Comparisons were made between crash characteristics during the daytime and crash characteristics at night when lighting was not present. Most of the findings concur with other studies in the literature, in that crashes during darkness were more severe than during daylight, occurred more on weekends, involved a higher percentage of single vehicle crashes, were more frequent at horizontal curves, occurred more during the winter months, had greater proportion of fixed object, run-off road, animal and shoulder/parked vehicle crashes, and occurred more frequently in rural (30%) than in urban areas (22%).

For the before/after study, nine intersections was used by Green et al. (*26*) to analyze the effect of lighting on nighttime crashes. Overall, very few crashes were reported over an eight year period at these nine intersections. No statistical tests were reported, but the authors stated that the average number of nighttime crashes per year, using data from all the intersections, was reduced from 1.1 (before) to 0.6 after the introduction of lighting. This represents approximately a 45% reduction. Wortman et al. (*27*) reported on results of a study in Illinois that evaluated the effects of illumination on crashes at rural U.S. and state highway intersections. They analyzed a random sample of illuminated and non-illuminated intersections using analysis of variance. The study compared the ratio of nighttime to total crashes at each intersection. The researchers felt that this minimized the influence of variables that could not be included in the study, such as differences in geometric features, given that the ratio reflected differences only between daytime and nighttime conditions. The effects of lighting, channelization, and different number of approach legs on the ratio of nighttime to total crashes was tested by evaluating different combinations of those variables. They found that lighting could contribute significantly to the reduction of nighttime crashes but reported that the benefit only occurred when the number of nighttime crashes was at least 1/3 the number of daytime crashes.

Lipinski and Wortman (*28*) analyzed crash data collected at rural, at-grade intersections in Illinois. The data included 445 intersection-data-years. The before/after study was performed to determine the effects of lighting at both channelized and unchannelized intersections. The test results indicated that the overall night/day crash ratio was reduced from 0.33 to 0.26, or by 22%, after illumination was installed. The results also showed a 45% reduction in nighttime crash rate and a 35% reduction in total crash rate at all of the intersections. The authors also found channelization to reduce crash risk, and it was concluded that additional safety improvements, such as channelization, should be considered in combination with lighting at high crash intersections.

Preston and Schoenecker (*29*) conducted an analysis of rural, at-grade intersections for the Minnesota DOT. Crash data were used from 1984 to 1994 and the authors performed both a system-wide comparative analysis of nearly 3500 rural intersections with and without lighting and a smaller scale before-and-after analysis for the installation of lighting systems at twelve intersections. The nighttime crash rate in terms of crashes per million entering vehicles was calculated for the comparative analysis. The results of the comparative analysis were a nighttime crash rate (per million entering vehicles) of 0.47 for lighted and 0.63 for unlighted intersections. A before/after analysis of 12 intersections for which data were available revealed that after the installation of lighting, there was a reduction in the nighttime crash rate of about 40%, including an approximately 50% reduction in injury/fatal crashes.

Isebrands et al. (*30*), in another study for the Minnesota DOT, analyzed the safety effects of lighting at rural intersections. Both a cross-section and a before/after analysis were conducted. The cross-section study consisted of 3,622 intersections, 223 with lighting. The 34 intersections used in the before-and-after analysis were chosen based on the availability of sufficient crash data both before and after lighting installation. Crash information, along with traffic volumes and the number of entering vehicles were obtained for each intersection to determine crash rates and frequencies and their subsequent ratios.

The results of the comparison analysis were a night/day crash ratio of 0.61 for unlighted and 0.42 for lighted intersections, indicating a beneficial effect of lighting on nighttime crashes, although overall, there were more crashes (per intersection) at the lighted intersections than the unlighted ones, probably because those intersections that received lighting were seen as having higher crash risk potential. The before/after analysis resulted in night/day crash ratios of 1.13 before, and 0.56 after lighting was installed, an approximately 50% reduction in the risk of nighttime crashes attributable to lighting.

Bruneau and Morin (*31*) evaluated the effect of two types of lighting (relative to unlighted locations) on nighttime crash risk at rural intersections in Quebec, Canada: standard lighting using poles specifically constructed for the purpose of lighting and nonstandard lighting using previously existing utility poles (not necessarily optimized in terms of spacing and height for lighting). They calculated night/day crash rate ratios for each of the three types of sites (no lighting, standard lighting and nonstandard lighting) and found that the standard lighting had a 39% reduction in the night/day crash rate, while the nonstandard lighting had a 29% reduction. Both of these reductions were statistically significant ($p<0.05$) in comparison to the night/day crash rates at the unlighted locations.

Two small sample studies by Blythe (*32*) in Indiana and Onser (*33*) in France were also performed at rural intersections. Blythe analyzed crash data before and after lighting was installed at four intersections over a 15 year period. The results showed a 30% reduction in the total number of nighttime crashes after lighting was installed and a 93% reduction in fatalities. Onser performed a comparison study between 82 intersections with lighting and an equal number of matched intersections without illumination. Onser's results showed that the intersections with lighting had 39% fewer nighttime crashes.

Gramza et al. (*34*) also analyzed interchanges, primarily in rural areas, by using crash data from a number of different states. The first study utilized the Interstate Crash Research (ISAR) database, including ten years of crash data, while isolating the 1,312 interchanges where lighting had been introduced during the analysis period. The results consisted of a distribution of 119 crashes with a nighttime crash reduction of 43% after lighting had been installed.

Urban/Suburban Intersections and Interchanges

The CIE (*1*) review of studies of lighting along urban pedestrian crossings and intersections indicated that in nine out of nine cases, lighting was found to be beneficial to safety, with one of these showing statistically significant results.

Oya et al. (*35*) conducted a before/after study (with respect to a lighting upgrade) on a major urban route. Data were collected from the Japanese Comprehensive Database for Traffic Accidents. Eighteen intersections were selected. Each intersection was along a major road with daily traffic volume of at least 10,000 vehicles. Due to limitations of the data, 'before' data consisted on only one year (1990), while 'after' data represented the years 1992-1995. In general, the sample size was small, but results show a clear benefit of lighting at major urban intersections, with a statistically significant reduction in the after period for light levels at or above 30 lx, but not for lower light levels.

To evaluate the effectiveness of the installed lighting a similar criterion of safety effect as used by the CIE (*1*) and Elvik (*2*) was employed. Overall the authors found the daytime crash rate to remain fairly constant, while nighttime rates were reduced after improvement of lighting.

Oya et al. (*35*) found that light levels less than 20 lx did not appear to result in fewer crashes at night, while those levels over 20 lx did appear to benefit safety. Only sites with light levels at or above 30 lx resulted in significantly fewer crashes at night. This finding differs from those of Box (*3*), who found that there appeared to be an optimum illuminance with respect to nighttime crash risk, but it should be recalled that the studies by Box that found such an optimum were on freeways and major road types, while Oya et al. (*35*) studied intersections. It is possible that an optimum illuminance significantly higher than 20 lx could have been found in this study, if this hypothesis had been explored.

Monsere and Fischer (*16*) evaluated the effects of reductions in lighting at freeway interchanges, mostly concentrated in urban areas around Portland. They developed statistical models to predict daytime and nighttime crashes of different severity levels for interchanges that were reduced from full to partial lighting, and from "partial plus" (defined by the authors as a level between full and partial) to partial lighting. The models showed that illumination reductions from full to partial lighting were associated with statistically significant ($p < 0.05$) reductions in all daytime crashes (of 2%) and in daytime injury crashes (of 9%), and in statistically significant ($p < 0.05$) increases in all nighttime crashes (of 2%) and in nighttime injury crashes (of 12%). Illumination reductions from "partial plus" to partial lighting were associated with statistically significant ($p < 0.05$) reductions in daytime injury crashes (of 14%), and in statistically significant ($p < 0.05$) decreases in all nighttime crashes (of 35%) and in nighttime injury crashes (of 40%).

STUDIES OF LIGHTING PARAMETERS

Few studies directly deal with specific lighting parameters and crashes. Except where specific lighting parameters are mentioned, the only information that is usually available is that lighting was either installed or upgraded/improved. The CIE's (*1*) review of 62 studies from 15 countries, including the U.S., states that the phrase, "good lighting" often refers to the national standard at the time of evaluation. While no firm conclusions can be made from the studies reviewed, the few studies which have reported details of lighting (e.g., *36*) appear to indicate that uniformity might be an important issue and an area for further investigation. These studies seem to show that as uniformity of lighting increases beyond a certain point, crashes might increase as well. It is hypothesized that the increase in crashes is a visibility issue and is associated with a reduction in contrast between an object and its surrounding visual environment.

If one operationally defines 'good lighting' or 'improved lighting' to be lighting that meets the national standards at the time of investigation, a retrospective study would be needed to evaluate light levels, expressed as luminance or illuminance, as well as other lighting parameters (e.g., uniformity), since recommended standards have varied over time and by region of the world (*37*).

Box (*3, 22*) attempted to correlate nighttime crash frequency to illuminance level. Oya et al. (*35*) categorized improvements in safety thought to be related to lighting based on the light level that was utilized.

An important series of studies (*36, 38-40*) with the objective of relating safety to specific characteristics of lighting all are based on the same data. This work is unique amongst the literature reviewed, because the authors set out to evaluate which lighting parameters (illuminance, luminance, uniformity and glare), if any, had effects on crash rates at night. The work reported is limited to dry conditions, and only crash data which occurred under dry conditions were used. Based on availability of data, the authors concluded that roadway luminance is statistically related to night-day crash ratio. Scott (*36*) estimated that an incremental increase in average surface luminance of 1.0 cd/m^2 (range 0.5-2.0 cd/m^2) represents a decrease in the nighttime crash ratio of 35%.

A pilot study of 12 sites (*36*) provided indication of the random variability of accident frequency from site to site. From this analysis it was determined that a sample size of 90-100 sites would be needed. The pilot study also revealed significant differences among night/day crash ratios for roads with different speed limits; therefore, the data analysis was limited to two-way urban roads with posted driving speeds of 30 mph. The authors evaluated the effect of intersection frequency on night/day crash ratios and found no statistically significant difference;

therefore, intersection frequency was not a criterion for site selection. Sites selected contained three years of data from local authorities on personal injury crashes (between 1974 and 1977). Approximately 4600 total crashes were included in the analysis. Crash data were recorded over a different period than the light level measurements. The authors accounted for light loss depreciation in their analysis to estimate the levels at the time of the crashes. As described above, care was taken only to use crash data under dry conditions.

A mobile laboratory was constructed which utilized a closed-circuit television system to record the field of view from the driver's perspective. Average road surface luminance, overall uniformity, and average luminance level of the area surrounding the roadway data were extracted from the videotape. A data logger recorded veiling luminance (disability glare) and horizontal as well as vertical illuminance, at the road surface and 0.3 m above the road surface, respectively. Nighttime measurements were made late at night; this minimized influence of vehicle forward lighting. Over 18 months, 200 sites were visited.

As stated above, a sample size of 90 to 100 sites was the goal, but due to limitations in usable data, the resulting sample size was less. Only 49 sites had data for illuminance, while average road surface luminance, overall uniformity and surrounding luminance level data were available from 75 sites; average road surface luminance by itself, was available from 89 sites. Correlation coefficients between pairs of lighting variables were calculated using data from 41 sites, with a correlation coefficient (r) value greater than 0.31 representing statistical significance. The average road surface luminance and surrounding luminance, as expected, were highly correlated with horizontal and vertical illuminance, while metrics of disability and discomfort glare were not.

Using data on average road surface luminance, overall uniformity and surrounding luminance, the authors fitted each possible combination to see how incorporating each variable affected a model to predict night/day crash ratios. While overall uniformity alone was not strongly related to the crash ratio, its addition to models already containing either of the luminance measures, significantly improved the goodness of fit.

With respect to the average road surface luminance, it was found that a range of pavement luminances between 1.2 and 2 cd/m² resulted in significantly lower night/day crash ratios (about 20% to 30% lower) than lower ranges of luminances (between 0.3 and 0.9 cd/m² and between 0.9 and 1.2 cd/m²). The data also revealed a monotonic trend in terms of lower crash ratios with increasing surrounding luminance. With regard to uniformity it was found that increased uniformity of illumination was associated with higher nighttime crash risk, but the range of uniformity levels was not large and therefore not likely to be useful in predicting degrees of uniformity outside the range that was studied.

An equation for describing the relationship between roadway luminance (L) and night/day crash ratios is $N_R = 0.66\ e^{-0.42L}$. Scott (*36*) investigated certain relationships in more detail than the 1979 publications mentioned above. The author estimated that for average surface luminance an incremental increase of 1.0 cd/m^2 (range 0.5 to 2.0 cd/m^2) represented a decrease in crash ratio of 35%. Scott (*36*) also noted that, since the scatter in lighting and crash rates among individual locations was large, the models could not be used to give reliable predictions for single sites. Scott (*36*) further made no conclusions regarding overall uniformity, and stated that the results are conflicting.

Janoff et al. (*41*) performed a study using data from 84 urban roadway segments in Pennsylvania. Several lighting and visibility variables were analyzed for a relationship to crash rate. It was determined that visibility index and horizontal illumination readings in the 15th percentile category (denoted VI_{15} and HFC_{15}, respectively) produced the best relationships to the crash data. The results showed that segments with higher VI_{15} readings had lower crash rates and those with higher HFC_{15} values had higher crash rates. Since the HFC_{15} measurements took into account both illumination level and uniformity, it was therefore shown that visibility, not illumination or uniformity, is the basis for better lighting design.

Mace (*42*), in a study for the Federal Highway Administration (FHWA), performed an analysis to determine if Small Target Visibility (STV) design criteria (described in the 2000 IESNA recommendations for roadway lighting) had safety benefits equivalent to or greater than those from illumination or luminance based criteria. Mace hypothesized that since STV parameters predicted the visibility of targets in the roadway, that nighttime crashes involving objects in the roadway will be reduced as STV was improved.

As part of his research, Mace conducted a comparison of 56 sites with uniform lighting systems based on recorded crash data and a number of lighting system measurements. The analysis included calculations of night/day crash and crash cost ratios for relationships to photometric and STV criteria. The sites included urban and suburban freeways, arterials, and divided roadways. It was identified that less uniformity resulted in higher night/day crash rates and that the influence of STV and light level on night/day crash ratios was confounded with glare. Furthermore, the data did not support the conclusion that increases in illumination are more likely to reduce crashes than increases in visibility.

The sample size was insufficient to form any definitive connection between STV design criteria and safer nighttime roadways. However, it was determined that STV design criteria are no worse than conventional design criteria and that it might have the potential to be better with more controlled testing.

Gransberg et al. (*43*) in a project sponsored by the Texas Department of Transportation (TxDOT), evaluated roadway lighting systems using STV design to identify roadway lighting issues and their relationship to crash reduction potential. It was shown by the study group that the parameters used in the STV design tests were inadequate to form any decisive conclusions. Additionally, no prior studies had shown a decrease in nighttime crash rates as a result of the STV design methodology. The team concluded that the current illumination warrants and lighting design policy used by TxDOT did not need to account for STV design recommendations and that further, more encompassing analysis was required.

The meta analysis by Elvik (*2*) reflects the general, current understating of the effects of lighting on crash reduction, notwithstanding the fundamental methodological issues associated with statistical analyses based on ratios that were discussed previously. Despite the bias in the absolute numbers, Table 1 from Elvik reveals that the positive effect that lighting (and presumed other, associated, but undocumented changes) on reducing fatal crashes at night appears to be larger than on reducing injury-only and property-damage only (PDO) crashes. Fatal accidents are usually associated with vehicle-pedestrian conflicts. From a theoretical perspective this is intuitive because pedestrians are not self-luminous and since people usually over-drive their headlights (*44*), illumination provided by fixed lighting or by daylight is needed to give drivers a longer time to respond to upcoming and unexpected hazards like pedestrians. Crashes at junctions are more positively affected by lighting than at midblock locations. This again is intuitive because there are more opportunities of conflict at junctions than at midblock locations, so illumination will have a positive benefit where there is a higher likelihood of conflict. In this context it is interesting to examine the differences among countries. Table 1 indicates that lighting has a greater effect on nighttime crashes in Japan and Israel, than in Denmark and Australia. As illustrated in Figure 1, there appears to be some relationship between the nighttime crash reduction potential of lighting and population density suggesting that illumination helps most at locations where there are more people and, in general, where conflicts are more likely to occur (intersections, interchanges, gores, turn outs, pedestrian crossings). Overall, Table 1 indicates that fixed roadway lighting would have an expected safety benefit of between 20% and 30% for nighttime crashes (if nighttime traffic is taken to be about a quarter of total traffic, this corresponds to a 5% to 8% reduction in overall crashes). Finally, it should be noted that many of the studies reviewed by Elvik (*2*) were included in a more recent meta-analysis (*45*). They also reported an overall nighttime crash reduction factor of 20% to 30% associated with roadway lighting.

Table 1. Estimate of lighting's effect on nighttime crash reduction for different crash types, during different decades, in different countries (2).

Lighting's Impact on Nighttime Crash Reduction		
Variable	**Category**	**Estimated Percent Reduction (Nighttime Crashes)**
Crash Severity	Fatal	65%
	Injury	29%
	PDO	17%
	Unspecified	18%
Decade of Publication	1940's	15%
	1950's	30%
	1960's	19%
	1970's	22%
	1980's	31%
Country	Australia	19%
	Denmark	17%
	Finland	22%
	France	39%
	Germany	24%
	Great Britain	32%
	Israel	46%
	Japan	56%
	Sweden	24%
	Switzerland	21%
	United States	20%
Traffic Environment	Urban	22%
	Rural	26%
	Motorways	23%
Type of Crash	Not Stated	21%
	Pedestrian	52%
	Vehicle Only	17%
	Junctions	30%
	Midblocks	14%
All	**All**	**23%**

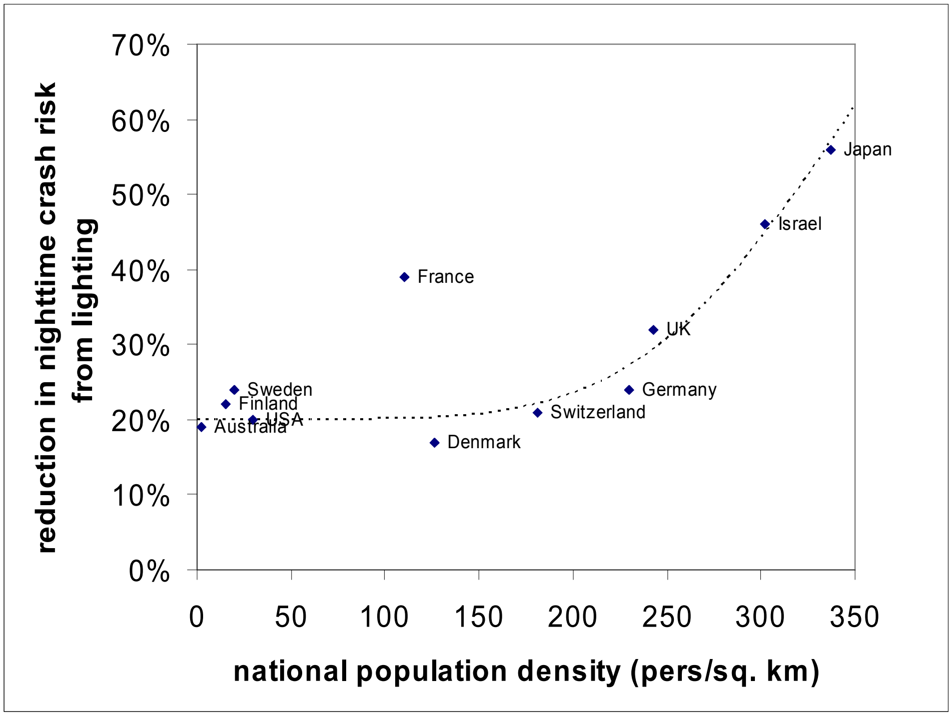


Figure 1. Relationship between nighttime crash reduction attributable to lighting and population density for studies (evaluated in [2]) from 11 countries. Also shown is the best-fitting (goodness of fit, r^2 = 0.97) sigmoid curve to the data, excluding those for France.

SUMMARY OF FINDINGS

The results of the review of roadway lighting as it relates to safety can be summarized as follows:

- Published studies having different methodologies tend to converge on an overall average reported 20% to 30% reduction in nighttime crash risk from lighting.
- The positive safety benefit of roadway lighting appears to grow larger with increased roadway geometric complexity, population density and has the largest benefit at locations with pedestrian activity. The effect is smallest at locations where there are the fewest opportunities for pedestrian conflict and for conflicting traffic patterns such as midblock locations.
- While a broad understanding of the role that lighting plays in reducing nighttime crash risk can be gleaned from the literature, there is much less certainty with respect to *why* lighting appears to reduce the risk of crashes, and what specific aspects of lighting (illuminance/luminance, glare, uniformity, distribution of light, spectral power distribution) have the greatest effect on safety-related outcomes. Although the role of lighting for supporting visibility has been studied extensively, but with many different methodologies, a theoretical bridge between visibility and safety has not been

established. Also, it is much less clear if lighting plays a role in providing information or messages to roadway users beyond the intended effect of illumination per se on visibility.

CHAPTER 3
ROADWAY LIGHTING AND CRIME

Historically, street lighting was introduced, in part, to help prevent crime (*46*), but it was not until the 1960s in the U.S. and later in the U.K. that systematic research into the effect of lighting on crime prevention actively began. As with the investigations of lighting and roadway safety, lack of appropriate control conditions may lead to biased estimates of the security benefits of lighting. Similar to roadway lighting too, it is difficult to isolate through statistical analyses the effect of specific outdoor lighting factors such as light level, uniformity, and spectrum on crime rates. Recognizing these important limiting issues, a meta-analysis of 13 studies by Farrington and Welsh (*47*) indicates there is an approximate 20-30 % reduction in overall incidence of crime due to lighting. Again, it must be recognized that lighting is not randomly assigned to locations and other factors associated with lighting (e.g., increased police patrols) may also affect crime rates. To exacerbate these issues, crime is often unreported, so unlike the more careful data collection and documentation associated with the safety effects of roadway lighting, it is inherently more difficult to reach firm conclusions about the effect of lighting on crime.

One consistent finding in the literature is that installation/improvements in lighting can lead to a reduction in the fear of crime (*47-52*). This in itself can be a justification for installing outdoor lighting in some locations.

SELECTED PAPERS

Tien et al. (*52*) performed an early review looking at 15 lighting projects in the early and mid 1970's. The authors were unable to find statistical evidence for a direct relationship between street lighting and crime, but data "strongly" indicated that perception of safety is greatly increased with improved lighting.

Painter (*51*) evaluated Tien et al.'s study and criteria for data inclusion and identified three aspects which might have limited the sensitivity of the results:

Data aggregation:

- Investigations looked at large areas, which may have lead to averaging of results; not isolating the potential effect of lighting from other environmental factors, which may impact the level, type and perception of crime.

- There was no investigation into the effects of different types of lighting on the incidence of various types of crime. Different lighting installations are likely to have differing effects on different types of crime, therefore grouping all criminal behavior will lessen any effect lighting might have.

Measurement error:

- Use of police crime data only. Crime statistics often do not differentiate types of criminal offenses, rather are grouped into wide range of offenses, and not all crimes are reported to the police.

Painter (*51*) conducted a before/after study (before: low pressure sodium lamps, 0.6 – 4.5 lx on the road surface; after: high pressure sodium lamps, 6.0- 25.0 lx). The author showed a trend in a reduction of crimes by type and an overall reduction in the fear of crime in the after period compared to the before period.

Painter (*50, 53*), following the 1988 study, used surveys to collect crime data from residents, showed the variability in lightings' effect on different types of crime over a 12 month period before and after lighting improvements. Overall there were fewer crimes, but certain crimes increased in number, while other decreased (see Table 2). This study showed that respondents felt safer by 41%, while fear of particular crimes varied. Those afraid of being robbed reduced by 25%, while those afraid of vandalism reduced by 14%, and afraid of sexual assault, reduced 10%.

Table 2. Crime experience by households on the estate before and after the lighting was improved, after Painter (53) and Boyce (48).

Type of crime	*Number of respondents experiencing*	
	Before lighting change (n = 197)	*After lighting change (n = 197)*
Burglary with loss	46	25
Attempted burglary	53	51
Outside household theft	35	10
Theft from person	6	1
Street robbery	15	3
Public physical assault	9	19
Vandalism/home	25	27
Vehicle stolen	5	5
Theft from vehicles	5	15
Vandalism/vehicle	25	13
Pestered/insulted	81	64
Sexual assault/rape (women only)	2	0
Sexual harassment (women only)	42	35
Total	349	268

Atkins et al. (*54*) performed a before/after study and concluded that there was no effect of improved street lighting on crime rates. This study is often used as an example of how authors have differed in their assumptions and conclusions on when (night-only or both night and day) improvements in lighting result in fewer crimes.

Pease (*49*) reanalyzed the Atkins et al. (*54*) data with the assumption that daytime crimes might be reduced as well and concluded that there was a 15% reduction in crimes reported after lighting improvements.

A 1997 study by Painter and Farrington (The Dudley project, *55*) along with a 1999 study by Painter and Farrington (The Stoke-On-Trent project, *56*), are perhaps the most rigorous studies on the lighting-crime relationship to date. The earlier Painter and Farrington (*55*) study used a large sample size (440 before/370 after) consisting of surveys inquiring about crime within the 12 months prior to lighting changes and 12 months following lighting changes, thereby avoiding relying on data reported to police. Detailed information on "lighting changes" is lacking, but generally higher light levels and increased uniformity are associated with lighting improvements. Sample size was chosen to be confident of detecting a crime reduction of at least 10%, and a control area (not re-lighted) allowed for comparison of the effects of lighting. Detail checks were made about extraneous variables (e.g., weather conditions) to minimize effects attributed to elements outside lighting.

In the area with improved lighting crime was reduced by 41%. In the control area crime was reduced by 15%. The difference between the area with improved lighting and the control area was significant. The proportion of victimization (prevalence of crime) reduced by 23% versus 3% in the control area (significant difference in relation to control). Pedestrian counts in the improved lighted area showed that the number of women and men on the street after dark greatly increased compared to the control area.

The later Painter and Farrington (*56*) study was similar to the earlier Painter and Farrington (*55*) study, but the analysis included three areas:

- An experimental re-lighted area (new light source, HPS; decreased pole spacing-increased uniformity, resulting in 2.5 lx (min)/ 6 lx (max))
- An adjacent area to the experimental area (not re-lighted, to evaluate crime displacement and crime reduction diffusion)
- A control area (not re-lighted)

Overall there was a 42.9% reduction in crime in the experimental area, 45.4% reduction in crime in the adjacent area and a 2% reduction in crime in the control area. The difference, for both experimental and adjacent area versus the control area was significant.

The number of male pedestrians on the street in the experimental area increased by 70% compared to 29% and 25% increases in the adjacent and control areas, respectively. There was also a 70% increase in female pedestrian traffic at night, compared to 42% and 41% in the adjacent and control areas, respectively. Increased pedestrian traffic at night is thought to represent an economic gain for local businesses and government.

Farrington and Welsh (*47*) re-evaluated eight controlled before/after studies conducted in the U.S. In four of the projects, the original studies interpreted the data as showing no decrease in crime rate, while the other four were interpreted to show a decrease in crime. The four that did not show a change, looked only at nighttime crime rate, while the studies that did demonstrate a reduction, evaluated both daytime and nighttime data. A meta-analysis by Farrington and Welsh (*47*) resulted in 7 of the 8 studies showing a reduction in crime rate in the experimental area compared to the control area (see Table 3).

Table 3. Meta-analysis of US street lighting evaluations (47).

Location	**Odds-Ratio**		
	Total Crime	**Violent Crime**	**Property Crimes**
1. Atlanta	1.39, $p < 0.05$ *	1.3	1.47
2. Milwaukee	1.37, $p < 0.05$ *	1.09	1.03
3. Portland (N)	0.94	1.04	0.83
4. Kansas City (N)	1.24	1.79, $p < 0.05$ *	0.88
5. Harrisburg (N)	1.02	0.81	1.14
6. New Orleans (N)	1.01	0.86	1.07
7. Fort Worth	1.38, $p < 0.1$	-	-
8. Indianapolis	1.08	-	-
Total (1-8)	1.08, $p = 0.064$	1.07	1.02
Total (1,2,7,8)	1.28, $p < 0.002$ *		

(> 1.0 indicates beneficial towards crime reduction) N = only night data available, * = significant

The meta-analysis utilized the odds ratio method with before-and-after data from both experimental and control areas to establish a relative measure of effect. Again, the odds ratio indicates the proportional change in crime in the control area compared to the experimental area; an odds ratio > 1.0 indicates a reduction in crime, while < 1.0 indicates an increase in crime.

The overall effect after combining the studies indicates a nearly significant (odds ratio = 1.08, p = 0.064) decrease in crimes in the experimental areas compared to the control areas. Crime decreased by 7% in the experimental areas compared to the controlled areas, conversely crime increased 8% in the control areas relative to the experimental areas. As noted above, a broad assumption has to be made when considering effects on crime (whether or not to expect crime during daytime as well as nighttime to be affected by lighting improvements). When the analysis is limited to only those studies (1,2,7 and 8) which provide both day and nighttime data, the overall effect size was significant, odds ratio = 1.28, p < 0.002.

Farrington and Welsh (*47*) also included in their review five more recent studies from U.K., which showed an average 42% decrease in total crime rate. Table 4 below shows that most studies indicate statistically less crime in the experimental areas compared to the control. Crimes increased in the control areas by 42% versus the experimental areas, or conversely crimes were decreased in the experimental areas by approximately 30 % compared to the control areas.

These 5 U.K. studies combined with the 8 U.S. studies, resulted in an odds ratio = 1.25. Therefore there was a 25% increase in crime within the control areas in relation to the experimental areas, which translates into the conclusion that crimes were decreased in the experimental areas by approximately 20% compared to the control areas. While lighting was shown to reduce crime, the studies did not find that nighttime crime rate decreased significantly more than daytime crime rates. The authors feel this indicates that the mechanism may have more to do with the 'message' sent by lighting improvements, rather than by the increase in visibility at a distance. The assumption being, street lighting increases a sense of community, which in turn translates into an informal social control over their neighborhood.

Table 4. Meta-analysis of UK street lighting evaluations (from 47).

Location (See CA9 in Appendix)	**Odds-ratio**		
	Total Crime	**Violent Crime**	**Property Crimes**
1. Dover (P)	1.14	-	1.14
2. Bristol	1.35, $p < 0.05$ *	0.48, $p < 0.1$	1.57, $p < 0.05$ *
3. Birmingham (P)	3.82, $p < 0.05$ *	-	3.82, $p < 0.05$ *
4. Dudley	1.44, $p < 0.05$ *	1.76, $p < 0.05$ *	1.33, $p < 0.05$ *
5. Stoke-on-Trent	1.72, $p < 0.05$ *	1.89, $p < 0.05$ *	1.59, $p < 0.05$ *
Total UK	1.42, $p < 0.05$ *	1.41, $p < 0.05$ *	1.58, $p < 0.05$ *
Total US and UK (13 studies)	1.25, $p < 0.05$ *	1.12, $p < 0.1$	1.19, $p < 0.05$ *

> 1.0 indicates beneficial towards safety; P = data available for property only; * = significant

In a study published the same year, Loomis (*57*) stated that homicide is the second leading cause of death for workers in the U. S. His study found strong and consistent reductions (odds ratio, 0.5; 95% confidence interval 0.3 - 0.1) in the risk of convenience store workers being killed on the job when bright exterior lighting was present.

The crime-reducing benefits of outdoor lighting *plus* the factors associated with that lighting are about the same as that for crash reductions attributed to roadway lighting. Again, the effects of lighting per se cannot be evaluated unambiguously from the literature. What does seem unambiguously true, however, is that people believe that lighting reduces crime.

Rombauts et al. (*58*) found a vertical illuminance of 0.8 lx was needed for confident face recognition at 4 meters (the assumed 'personal space zone'), and 33 lx was required at a distance of 17 meters. Additionally, Boyce and Rea (*59*) found a vertical illuminance produced by security lighting of 4-10 lx will usually ensure a high level of intruder detection and recognition. Further, low pressure sodium (LPS) lamps were as effective as high pressure sodium (HPS) lamps for the detection of intruders.

Boyce et al. (*60*) found a subjective evaluation of what is considered "good security lighting" in an urban setting to be ~ 40 horizontal lx. Boyce found that between 0-10 horizontal lx, small increases in illuminance produce large increases in perceived safety, while for horizontal illuminances above 50 lx, increases in illuminance made little difference to perceived safety. Boyce also showed that for suburban environments, to achieve the same perception of safety, light levels could be slightly lower.

Most studies on the subject have been conducted by criminologists, not lighting experts and consequently detailed information about the lighting conditions leading to more confidence are often lacking. While detail is lacking, these studies often mention lighting improvements of: higher light levels, more uniformity, and better color rendering. Although a clear systematic evaluation of the various lighting characteristics is not available, Boyce's synthesis of the literature concludes that for pedestrian areas, a good color rendering source be used, the average illuminance on the pavement should be 10-50 lx, uniformity (max to min) should be less than 15/1, and the glare ratio (veiling luminance to average luminance) should be less than 4.

In addition to the visual benefits supplied by lighting , the 'message' of an improved lighting installation can be interpreted as 'people care about this neighborhood', thereby enhancing community confidence and an informal sense of control by the community. This informal deterrence is thought to result in a reduction of crime during the day as well as during night (*47*). Differing research assumptions regarding lighting's effect on day and night crime is one potential reason why conflicting research results exist.

In summary, it appears that lighting has a positive effect on reducing crime and the positive benefits are similar to those observed for roadway lighting reducing crashes. As with roadway lighting, the positive benefits of outdoor lighting must be based on improved visibility. Further research should identify what aspects (e.g., illuminance/luminance levels, uniformity) of lighting are important for crime reduction but the principles should be the same for both outdoor lighting and roadway lighting. In addition, lighting may send a message that goes beyond visibility as a means for providing a community with a crime-reducing benefit.

CHAPTER 4
OTHER EFFECTS OF ROADWAY LIGHTING

ECONOMIC DEVELOPMENT

The economic development of downtown urban areas is very often a major reason why outdoor lighting is installed. However, no specific studies addressing the relationship between outdoor lighting and economic development were found. The logic behind using lighting for economic development is most likely twofold. The Stoke-on-Trent study of roadway lighting and crime (*56*) showed that nighttime pedestrian traffic increased by 70% after lighting improvements. It is therefore possible for business at night to increase, resulting in economic development for the local community, including increased property values and taxes.

Lighting has been shown to contribute to the perceived sense of safety and security in an outdoor location (*61*). Of interest, perceptions of safety are related to the average light level but the relationship is not linear; rather, above illuminances of 10 to 30 lx on the pavements, further increases in illumination are unlikely to improve perceptions of safety and security (Figure 2). Leslie and Rodgers (*62*) used these data to develop *patterns* for roadway and exterior lighting installations that met criteria such as those from the Illuminating Engineering Society of North America (*63, 64*) and resulted in perceptions of good security lighting (Figures 3 and 4).

In general then, it would appear that lighting could possibly improve economic development, but a decision to provide outdoor lighting should be examined first in terms of roadway safety and crime prevention together with the other safety and crime-reducing strategies closely associated with lighting (e.g., signalization and increased police patrols). If these are accomplished, economic development may simply be a natural consequence of these decisions.

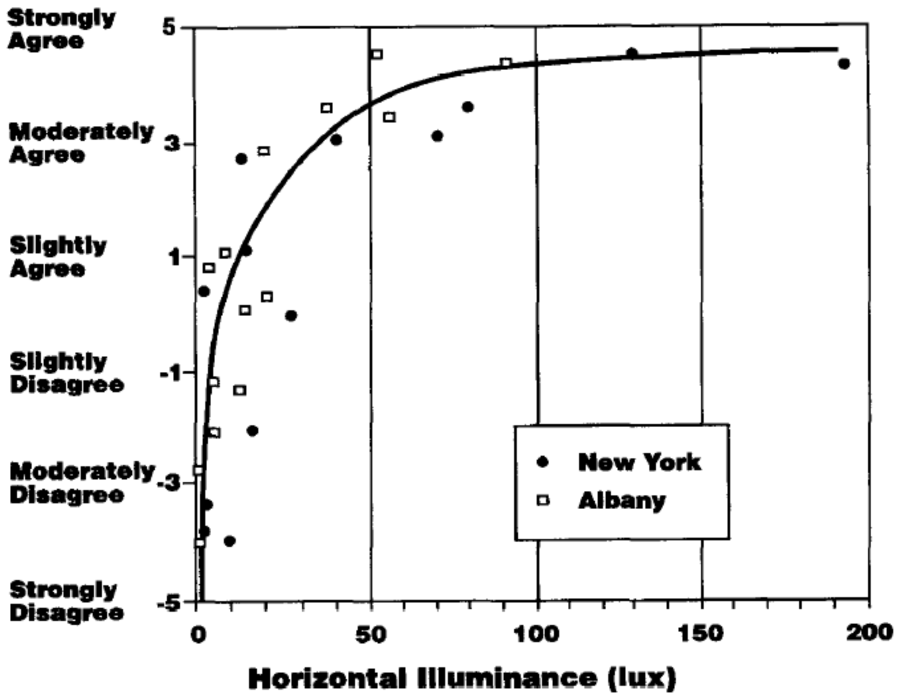
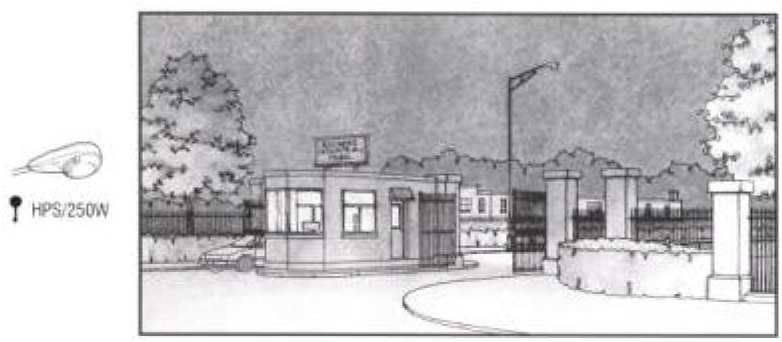


Figure 2. Relationship between average horizontal illuminance and agreement or disagreement with the statement ,"This is a good example of security lighting," for exterior locations in Albany, NY and New York City (62).



Sense of Security	Appearance	Initial Equipment Cost	Annual Cost		Average Horizontal Illuminance	Connected Load
			Maintenance	Energy		
★	★	—	$0	$0	1.0 fc	—

Figure 3. Base-case street lighting installation from the Outdoor Lighting Pattern Book (62).

Sense of Security	Appearance	Initial Equipment Cost	Annual Cost		Average Horizontal Illuminance	Connected Load
			Maintenance	Energy		
★★★★	★★★	$4400	$110*	$390	4.3 fc	900 W

* Does not includes painting.

Figure 4. Redesigned street lighting installation for improved perceptions of security from the Outdoor Lighting Pattern Book (62).

LIGHT POLLUTION

Light pollution is an unintended consequence of roadway lighting and includes such effects as sky glow, light trespass, and glare (*65, 66*). Sky glow is the brightening of the sky due to outdoor lighting and is usually objected to because it inhibits one's ability to see and appreciate the stars. Light trespass is light falling where it is not wanted or needed. Light from a streetlight or a neighbor's floodlight that illuminates one's bedroom at night is an example. Glare is excessive brightness causing discomfort or visual disability and a good example is an unshielded luminaire where the lamp can be directly seen.

Aside from potentially interfering with the enjoyment of the nighttime surroundings, light pollution can also have detrimental environmental impacts. Street lighting on coastal roadways can be visible from beaches and can disrupt the nocturnal orientation of turtle hatchlings as they crawl toward the sea (*67*). If roadway lighting is turned off during hatching periods, or in-pavement lighting is used in place of roadway lighting, turtle disorientation can be reduced. However, these approaches may result in a decrease of overall traffic safety or an increase in crime. This example illustrates the tradeoffs that are common when trying to balance societal concerns, such as the balance between traffic safety and environmental impacts.

Recommendations to mitigate light pollution resulting from roadway lighting are given in various lighting publications and guidelines (*68-70*). Suggestions for reducing light pollution include avoiding excessive lighting to minimum recommended light levels including light levels on the windows of residences on adjacent properties to avoid light trespass, using cutoff luminaries to reduce the amount of light emitted directly upward by the luminaries, selecting appropriate luminaire lamp spectrum (e.g., to take advantage of improved peripheral visibility provided by lamps with "whiter" color than high pressure sodium lamps most commonly used for roadway lighting), using efficient lamp technologies, and using lighting zones (defining limits on light pollution based on the characteristics of a local area [e.g., in downtown

Manhattan, even relatively large amounts of light trespass might have negligible impacts, whereas in environmental preserves, small amounts of light trespass will be unacceptable]) to limit lighting depending on the population. None of these approaches are entirely successful at limiting light pollution, partly because equipment-based proscriptions do not guarantee against light pollution (*71*) and partly because the characteristics of adjacent properties are rarely known by the roadway lighting engineer (*72*).

Recently, a quantitative framework has been developed (*66, 72*) by which the roadway lighting engineer can assess the performance of a roadway lighting installation in terms of quantities likely to contribute to sky glow and light trespass. This framework, called the outdoor site-lighting performance (OSP) method, involves construction of a hypothetical ‘box’ around the property boundaries associated with the lighting installation. The potential for sky glow is assessed by calculating the average illuminance on the surfaces of the box. The potential for light trespass is assessed via the maximum illuminance on any of the vertical surfaces of the box. Brons et al. (*66, 72*) collected data on more than 100 exterior lighting installations including roadways so that the performance of an installation can be compared to normative data.

Using the property boundaries (or in the case of roadway lighting, the rights-of-way) permits the lighting specifier to use the amount and distribution of light needed to achieve the objectives of the lighting, but ensure that the potential negative effects for occupants of adjacent properties are minimized. Light crossing the property boundaries could be reduced through careful selection of equipment, judicious use of plantings or trees, or by outfitting luminaires with house-side shields. The OSP framework has the benefit of being able to be included into the lighting design process using commercially available software, and can be field validated as it is based upon illuminance quantities that can be measured along a roadway or other outdoor lighting installation.

In response to the demand to reduce light pollution, research and development efforts have focused on advancements in technology to design luminaries efficiently to direct light where it is needed. Luminaire manufacturers have concentrated on providing highly efficient luminaries with given beam distributions while meeting the cutoff classifications set forth by the IESNA (*63*) to reduce glare as well as wasted light. Advancements in lamp technologies have resulted in producing high efficiency light sources that reduce light pollution and have the added benefit of saving energy. The IESNA (*73*) recently developed new luminaire classifications that more accurately describe the light leaving a luminaire in different angular regions that will provide more information in the selection process of luminaires. Nonetheless, it has been shown that information about specific luminaire classifications is unlikely to successfully predict the light pollution impact of a lighting installation (*71, 74-76*).

Many states have adopted legislation controlling outdoor lighting, more states have pending outdoor lighting bills in front of their legislators. Numerous adopted and pending local ordinances pertain to the lighting of cities, towns, and counties.

Legislation typically includes requirements for full cutoff luminaries, minimum light levels, lumen or wattage limitations, light source limitations, controlled operating periods, curfews, and the elimination of certain kinds of lighting (*77*). Curfews for outdoor lighting are generally defined by local planning authorities based on anticipated use of the area and, thus, a need for lighting. During pre-curfew times, the need for lighting is warranted, so lighting levels are generally higher than during post-curfew times. In addition to preserving dark skies, legislation is being justified on the basis of minimizing wasted energy and money, reducing unwanted light on adjoining properties (such as light in bedroom windows), reducing glare, and preserving animal breeding and migration habitats.

Luminaires are designed to have lighting distributions that are appropriate for specific applications. Virtually any luminaire can generate sky glow, light trespass, and glare if installed improperly or in the wrong application. These problems can be avoided by selecting luminaries that have the appropriate distribution for the application and installing them correctly to limit spill light and uplight.

Although the goal may be to eliminate light pollution, in some locations light pollution cannot be avoided altogether. The environmental consequences of the pollution, however, need not be equally detrimental across all locations. The Commission International de l'Eclairage has outlined four environmental zones to establish a basis for outdoor lighting regulations (*78*). The environmental zone rating can be used to help ensure that the lighting goals of an environment are appropriately defined and met, but not exceeded. The IESNA has adopted the concept of environmental zones and recommends their use in developing new outdoor lighting (*64*). In some states legislation is being considered that would restrict outdoor lighting by environmental zone. For example, California has adopted environmental legislation that includes the designation of outdoor lighting zones (*79*). Application of environmental zones is first envisioned for the protection of natural park preserves and astronomical observatories. Environmental zones promise to reduce overall light pollution by helping to limit, or in some cases eliminate, light wastage.

What is common among all of the efforts to reduce light pollution is that there has been practically no research performed to assess the actual impacts of outdoor lighting on sky glow, light trespass and glare. The tools provided within the OSP system could be extended to quantitatively assess the impact of outdoor and roadway lighting on visibility, although this has never been systematically undertaken. Nevertheless, once it is decided to specify and install outdoor lighting the OSP system enables an engineer or architect to quantitatively assess the unintended consequences of outdoor lighting.

CHAPTER 5
ROADWAY LIGHTING ECONOMICS

Benefit/cost analyses are common amongst crash and crime studies. Overall, using the literature that has converged on a 20% to 30% nighttime crash reduction associated with lighting, roadway illumination has been found to be a cost-effective countermeasure in terms of crashes.

Benefit/cost analysis is a method for trading off the costs of a specific action relative to the expected benefits of that action. The benefits usually refer to the reduced crash or societal costs as a result of decreases in the number and/or severity of crashes/crimes/etc. The costs of implementing the action are the direct costs to the highway agency for initial installation, maintenance, and repair costs. If the ratio of the benefits to costs (Equation 3) exceeds 1, then the benefits derived will be worth the investment over the analysis period. The benefit costs ratio can be used to compare several different actions against each other and against the no action option.

$$\text{B/C Ratio}_{j\text{-}i} = \frac{CCi - CCj}{DCj - DCi} \qquad \text{(Eq. 3)}$$

where: B/C Ratio$_{j\text{-}i}$ = Incremental benefit/cost ratio of alternative j to alternative i

CC_i, CC_j = Crash, crime or other societal costs under alternatives i and j (annualized over the analysis period)

DC_i, DC_j = Direct costs for alternatives 1 and 2 (annualized over the analysis period)

Crash and other societal costs are sometimes referred to as associated costs.

LIFE CYCLE COST ANALYSIS

As illustrated in the New York State Energy Research and Development Authority (*80, 81*) guidelines for street and roadway lighting for municipal decision-makers, the initial costs of a lighting system make up only a part of the overall costs, when energy and maintenance are considered into the entire life-cycle cost. Because of this, decisions to install lighting should be balanced by the type of equipment, their expected life, and other factors that will determine the life-cycle cost characteristics. While these factors might not directly affect nighttime crash risk, they can make some lighting options more or less viable financially, which in turn could affect when certain potentially beneficial lighting installations are performed.

ESTIMATES OF BENEFIT/COST

Outdoor lighting and roadway lighting have associated costs and benefits. The tangible capital and operational costs are easy to assess, but the intangible or intractable costs such as medical/ambulance services, productivity loss (including time delayed by traffic flow), mental health support, police/fire services, property loss and quality of life are largely unknown. The benefits too are difficult to quantify because it is the deferred safety and security costs that constitute the benefits. In terms of benefit/cost estimates associated with roadway lighting, the

1996 FHWA Annual report to Congress (*82*), covering 1974-1995, indicated that illumination had a benefit/cost ratio of 26.8; this ranked highest of all highway safety improvements (see Table 5).

Table 5. Highway safety improvements with the highest cost-benefit ratios (82).

HIGHWAY SAFETY IMPROVEMENTS WITH THE HIGHEST BENEFIT-COST RATIOS 1974-1995		
Rank	**Improvement Description**	**Benefit-Cost Ratio**
1	Illumination	26.8
2	Upgrade Median Barrier	22.6
3	Traffic Signs	22.4
4	Relocated/Breakaway Utility Poles	17.7
5	Remove Obstacles	10.7
6	New Traffic Signals	8.5
7	Impact Attenuators	8
8	New Median Barrier	7.6
9	Upgrade Guardrail	7.5
10	Upgrade Traffic Signals	7.4
11	Upgrade Bridge Rail	6.9
12	Improve Sight Distance	6.1
13	Median for Traffic Separation	6.1
14	Groove Pavement for Skid	5.8
15	Improve Minor Stricture	5.3
16	Turning Lanes and Channelization	4.5
17	New RR Crossing Gates	3.4
18	New RR Crossing Flashing Lights	3.1
19	Pavement Markings and Delineatior	3.1
20	New RR Crossing Lights & Gates	2.9

Many studies mentioned in this FHWA review included ones having a benefit/cost analysis. Based on crash analysis, reports by Box (*3, 23*), Anderson et al. (*83*), Griffith (*9*), Green et al. (*26*) and others all concluded that the installation of roadway lighting systems was cost effective (i.e., B/C > 1) for different applications.

Janoff and McCunney (*84*) developed a complete methodology for conducting a benefit/cost analysis for roadway lighting systems. The formulas use input from several variables including crash rate, area type, population density, and visibility-related quantities along with crash and system costs. A more in-depth approach was created earlier at the Texas Transportation Institute where researchers combined various lighting design criteria and roadway geometrics in their analysis technique (*85*). The analysis was created to calculate costs on a per mile basis and included estimated costs associated with vehicle-illumination unit crashes.

Multiple economic analyses were completed by Box (*23*) for comparing illumination levels and lighting systems to crash costs as part of his various research projects. Box (*23*) concluded in his study that the cost savings of improved lighting due to crash reductions was $253,000. Box's (*3*) cost analysis of the multi-state IERI data study resulted in benefit/cost ratios of 2.3 for lighting 4-lane, 1.4 for lighting 6-lane, and 1.7 for lighting 8-10 lane urban freeway sections.

An economic before-and-after analysis conducted by Preston and Schoenecker (*29*) resulted in a benefit/cost ratio of 15. It was concluded that illumination of rural intersections is a cost effective nighttime crash countermeasure and safety improvement system, superior to other, statistically unproven systems in use.

In terms of benefit/cost analyses for outdoor lighting associated with crime, Painter and Farrington (*86*) using official crime valuation data, reanalyzed their two earlier studies, Dudley (*55*) and Stoke-on-Trent (*56*), both studies occurring in the United Kingdom. According to the authors, conservative benefit/cost ratios of the Dudley and Stoke-on-Trent lighting improvement were 10:1 and 2.4:1, respectively.

In Dudley, the annual number of prevented crimes is estimated to result in a savings equivalent to approximately $900,000. The initial cost of the lighting improvements was about $90,000. After one year, the resulting benefit/cost ratio was approximately 10:1, which the authors say is conservative. Assuming a 20-year payback, the ratio increases to 121:1.

In Stoke-on Trent, the costs associated with crimes prevented were estimated at approximately $300,000. The initial cost of the lighting improvements was equivalent to about $125,000. After one year the resulting benefit/cost ratio was 2.4:1, or considering a 20 year payback, 24:1. All of the costs of crime mentioned above are for tangible costs only, as well as for experimental areas only. These figures do not take into account benefits to adjacent areas, or intangible cost-savings. The results from these studies suggest that lighting can influence criminal activity, but by no means do they prove conclusively that roadway lighting will always reduce crime.

In general then, the benefit/cost calculations for crash and crime reduction exceed unity.

PROCEDURES FOR WARRANTING ROADWAY LIGHTING BASED ON BENEFIT/COST

Lambert and Turley (*87*) have reported methods for establishing the cost effectiveness for roadway lighting projects. The purpose of their report was to formulate an objective process of applying quantitative and qualitative assessments of lighting needs by developing revisions to two existing screening methods (*88, 89*). The authors provide several disadvantages of these existing approaches that they would attempt to address:

- Existing warranting methods have not been substantially updated since the 1970s, and thus do not account for changes in vehicle technology, roadway design, and public opinion and values regarding roadway lighting

- AASHTO (*88*) emphasizes exposure (e.g., annual average daily traffic [AADT]) but assigns arbitrary thresholds of concern for variables

- NCHRP Report 152 (*89*) adds emphasis to roadway geometry and operational parameters, but scoring system is sometimes complex and unclear

- Neither method provides guidance for obtaining relevant crash rates for new or reconstructed roadways where there are limited or no data on existing travel conditions

The procedure developed by Lambert and Turley (*87*) for the Virginia DOT and summarized below only addresses the needs for roadway lighting based on safety. Other potential significant benefits of fixed roadway lighting, such as increased security and economic development, are not addressed.

The Virginia DOT study resulted in the compilation of a screening (screening instead of warranting is used by the authors) test that was broken into two phases: exposure assessment and site-parameter assessment. The phase I exposure assessment builds upon certain concepts from the American Association of State Highway and Transportation Officials (*88*) guidelines for roadway lighting. It involves observing of night/day crash rate ratios versus ADT levels and subsequent benefit-cost ratio regions. Phase II was the compilation of a multifaceted site-parameter assessment which upgrades evaluation concepts outlined in the NCHRP Report 152 (*89*).

In the Phase I exposure assessment, a benefit/cost analysis is indirectly performed based on the relationship of a set of variables including ADT, percentage of night traffic, night/day crash rate ratio, crash reduction factors and lighting installation, maintenance, and energy costs. Using ranges for these variables, a decision aid was created which plots night/day crash rate ratio versus ADT (Figure 5). The graph is divided into three areas: accepted (B/C > 1 for all ranges of input variables), marginal (B/C > or ≤ 1 depending on variable values used), and rejected (B/C always < 1). If the needs fall into the marginal or accepted region, then the next phase, site-parameters assessment, is initiated to determine if lighting is a feasible remedy to decreasing the night/day crash rate at the location of interest.

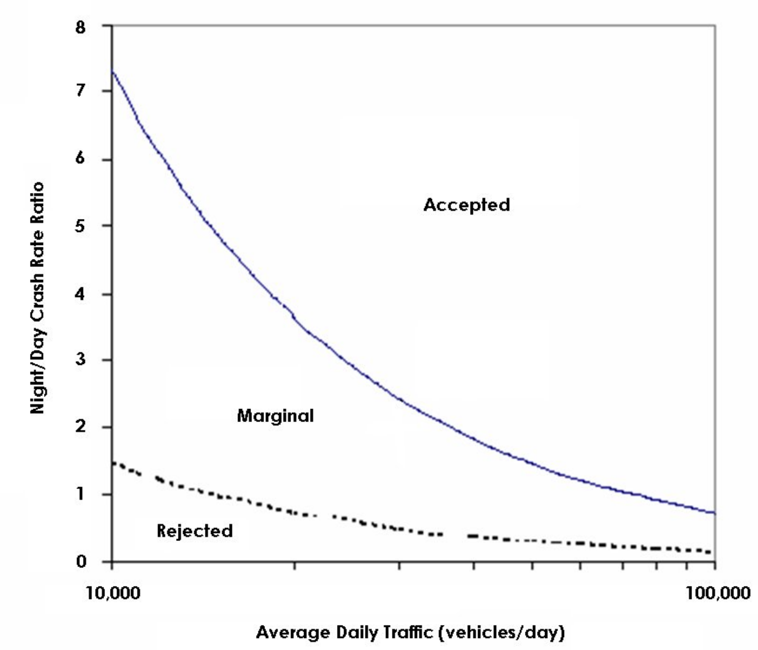


Figure 5. Chart for assessing benefit/cost categories based on ADT and night/day crash rate ratio (87).

The exposure assessment phase offers a quantitative procedure to make decisions regarding further evaluation of roadway lighting in a user-friendly format. It is similar to figures that have historically been used in the roadside safety area to determine the need for concrete or metal barriers. It should be noted that the decision tool which plots the decision regions on a graph of ADT versus night-day crash rate ratio is based on ranges of variables that have been developed from expert opinion and historical literature. The authors note than these ranges may be adjusted based on site specific characteristics. The proficiency at which these adjustments could be made would be dependent on information that is available to the user/decision maker.

Projects that receive an exposure assessment rating of accepted or marginal qualify for the site-parameters assessment. Its purpose is to determine if roadway lighting would be potentially effective at these locations that had marginal or accepted needs under Phase I. In the site-parameters assessment, each of eight parameters are scored according to ratings of high/moderate/low to indicate whether the installation of lighting would have some/possible/no benefit in terms of corresponding crash reduction. The eight parameters are section/intersection geometry, traffic mix, vehicle conflict opportunities, posted speed, curves and grades, veiling luminance, level of service, and inter-modal transactions. The scores are then evaluated based on the resultant categories of accepted, marginal, or rejected, similar to the exposure assessment.

The site-parameters assessment adopts the concept of scoring each roadway from NCHRP Report 152 (*89*), but in a more efficient and simplified fashion. First, rather than using the four lists of twelve to twenty parameters in the NCHRP report (*89*), the Virginia screening method (*87*) utilizes one unique list of eight parameters. Additionally, the Virginia site-parameters assessment uses just three thresholds for defining each of the eight parameters while the NCHRP report (*89*) uses up to five. The link between the site parameters, safety, and lighting are made through reasonable assumptions, but sometimes these assumptions lack quantitative support. In addition, thresholds between the three regions (e.g., high, moderate, low) of the eight parameters have been based on expert opinion, existing literature, and the NCHRP (*89*) warrants. Although this may have been the best information that existed at this point, research findings related to the safety benefits of roadway lighting given different levels of these parameters would be needed to validate this process.

Projects that pass both the exposure and site-parameter assessments with a rating of "accepted" identify a critical need and are nominated for a detailed benefit/cost analysis to determine the allocation of funding for fixed lighting improvements. Those that receive an overall assessment of "marginal" are given a lower priority and are more dependent upon resource availability. Needs scoring "rejected" are left in the needs database for future consideration. A prototype software program that incorporates this procedure has been developed.

The Lambert and Turley (*87*) cost effectiveness screening method for roadway lighting is different from other roadway lighting warrants reviewed, and may offer significant advantages in assessing when roadway lighting should be installed. The two step process is comprehensive in calculating safety benefits versus monetary costs. The process has adjustable parameters to suit different situations or reflect new insights. It is based upon information from existing warrants, standards, and expert advice, and allows for the definition of parameter defaults for ease of use. Despite being an attractive method that is relatively transparent and easy to use, this method does also have some issues that make it difficult to use. It does not directly include lighting design parameters into the benefit/cost calculation. It does not presently incorporate different crash reduction factors for different roadway types, geometries, or situations, and is not suitable for areas where crash data are not known, especially for newly constructed roadways.

NCHRP Report 152 (*89*) outlines a process for evaluating roadways on the basis of multiple parameters and an analysis of the costs associated with lighting the warranted roadways. The evaluation is conducted through a series of forms for each functional class of roadway and a resultant score is computed. Parameters used in the evaluation are grouped into the categories of geometrical, operational, and environmental conditions along with crashes as represented by night/day crash ratio. Night/day crash ratios rating within certain threshold values can score between eight and forty points toward the total sum based on a unit weight of eight for each of five ratings. Roadways scoring over the NCHRP predetermined warrant limit are considered candidates for roadway lighting (*89*).

Some states, notably Texas and Kentucky, use a combination of standards and internal operations to evaluate the need or potential of roadway lighting systems. As discussed earlier, the safety of roadways is often classified by the ratio of night/day crashes. Walton and Rowan (*89*) established that the "ideal" condition exists when the night/day crash ratio is less than 1.0. Using this as a basis, locations with night/day crash ratios greater than 2.0 were recommended for continuous lighting. Similarly, Texas DOT warrants stipulate the use of continuous lighting where night/day crash ratios exceed 2.0. Further recommendations include complete interchange or intersection lighting where crash ratios exceed 1.5 and partial lighting where ratios are greater than 1.25 (*43*). These recommendations mirror those outlined in the AASHTO warrants (*88*).

The Kentucky Transportation Cabinet also uses guidelines along with an internal system for ranking safety improvements. This system is based on a cost-optimization procedure that determines the costs and benefits of each improvement (*90*). In order to accurately determine the cost effectiveness of a potential project, crash data are collected and computations involving estimated nighttime crash reduction factors are completed. These estimates are based on state surveys and results taken from literature reviews, similar to those shown in Table 6. The nighttime crash reduction factors developed for roadway lighting systems by the Kentucky Transportation Center are listed in Table 7.

Table 6. Location of lighting improvement and reported reduction factors (90).

Lighting Location	Type of Crash	State Survey (37)		Literature Review (61)	
		# Reporting	Reduction Avg.	# Reporting	Reduction Avg.
General	All	6	25%	5	10%
New Roadway	All	10	28%	8	18%
	Night	12	45%	5	38%
Upgrade Roadway	Night	2	42%	-	-
New Intersection	All	8	31%	2	22%
	Night	12	49%	6	64%
Upgrade	All	2	38%	-	-
Intersection	Night	1	50%	2	50%
New Interchange	All	5	25%	3	42%
	Night	4	50%	3	56%
Railroad Crossing	All	9	34%	2	46%
	Night	5	60%	6	61%
Bridge	Night	7	48%	5	52%
Illuminate Sign	All	-	-	1	15%

Table 7. Kentucky Transportation Center recommended crash reduction factors (90).

Lighting Location	Type of Crash	Recommended Reduction Factor
General	All	25%
	Night	50%
Roadway Segment	All	25%
	Night	45%
Intersection	All	30%
	Night	50%
Interchange	All	25%
	Night	50%
Railroad Crossing	All	30%
	Night	60%

Isebrands et al. (*30*) discussed intersection/interchange warrants for rural versus urban environments, indicating that Minnesota warrants for roadway lighting systems need to better accommodate rural intersections. The current Mn/DOT warrants are for both urban and rural intersections and are often too stringent for rural intersections to comply. In contrast, bordering Iowa utilizes specific rural intersections warrants.

CHAPTER 6
SURVEY OF STATE, DISTRICT, AND COMMONWEALTH TRANSPORTATION AGENCIES

SURVEY DEVELOPMENT

Survey questions were developed by the research team with assistance from the project panel and NCHRP staff. The survey was conducted to identify potential sources of data for analyses of the safety effects of roadway lighting, and to identify what types of information transportation agencies use when making decisions with respect to lighting.

Questions focused on several issues:

Presence and type of lighting records in each state.
Presence and type of crash data in each state.
Current lighting practice in each state.
Preferred resources for lighting decision-making.

Survey questions were administered in an electronic survey on the Lighting Research Center website. Participants were asked to enter their contact information, click buttons, and type text into some fields. The survey was conducted in 2005.

SURVEY DISTRIBUTION

The project team compiled a list of engineers from states, districts, and commonwealths who could comment on their policy about roadway lighting. Several sources were used to develop this list, as follows:

- Several members of the NCHRP 5-19 project panel who were associated with state DOTs.
- Personal referrals were obtained for engineers in several states.
- Representatives who served on the AASHTO Joint Technical Committee on Highway Lighting.
- The AASHTO Highway Subcommittee on Traffic Engineering contains representatives from nearly every state, district, and commonwealth. Each committee member was contacted to obtain a referral to illumination specialists in their state.
- For any remaining states or areas, agency websites were consulted and relevant personnel called for contact referrals.

As shown in Table 8, thirty-seven states (73%) participated in the survey.

Table 8. States, commonwealths, and districts participating in the survey.

States and Districs Participating in Survey		States and Commonwealths Not Participating in Survey as of 1/06
Alabama	Nebraska	Arkansas*
Alaska	Nevada	Connecticut
Arizona	New Hampshire	Delaware
California	New Jersey	Florida
Colorado	New York	Georgia
Hawaii	North Carolina	Indiana
Idaho	North Dakota	Louisiana
Iowa	Ohio	New Mexico
Illinois	Oklahoma	Pennsylvania*
Kansas	Oregon	Puerto Rico
Kentucky	South Carolina	Rhode Island
Maine	South Dakota	Tennessee
Maryland	Utah	Texas
Massachusetts	Vermont	Washington State
Michigan	Virginia	Wisconsin
Minnesota	Washington DC	
Mississippi	West Virginia	
Missouri	Wyoming	
Montana		

* Offered comments, rather than participating in survey

SUMMARY OF SURVEY RESULTS

Response

Almost three-quarters of states in the USA responded to the survey (37 out of 50).

Lighting Data

Two-thirds of responding states reported that they kept records about fixed lighting systems on roadways, half of which were only in hardcopy format. Typical data recorded were location, fixture type, wattage, and pole height and spacing, and date of installation. Some states reported that they recorded target illuminance, manufacturer photometric file number, and maintenance information.

Crash Data

Crash data were nearly always kept in electronic format, and in half the states, in hardcopy format as well. Crash data were rarely kept in hardcopy format only. Typical data fields included time, location, weather, pedestrian involvement, and severity, as cited by over 80% of respondents. Presence of lighting and roadway geometry were cited as typical data fields by about half of respondents. Some states reported miscellaneous comments such as the type of crash, type of vehicle. Two states indicated that they recorded a great many data fields per incident.

Lighting and Safety Resources

The AASHTO design guidelines for roadway lighting (*88*) were used by 80% of respondents to learn about the effect of lighting on safety. IESNA publications (such as RP-8, *63*) were helpful to over two-thirds of respondents. Other resources listed included FHWA guidelines on roadway lighting, recent research results, manufacturer information, and state requirements.

Additional Factors, When Considering Lighting

"Safety" was selected by nearly all respondents as a factor in decision-making. Also important were costs (86%) and light pollution (70%). Economic development was important to half of respondents. Contrary to expectation, "crime" was the driver of decision-making for less than one-quarter of respondents.

Places Always Lighted

Just over half of respondents cited two places as commonly lighted: roundabouts and ramps. Roundabouts may not be common in states that did not select this option. Intersections and crosswalks were selected by about 40% of respondents. Commonly cited "other" spaces were interchanges, and places with parking and pedestrians such as rest areas, welcome centers, and park-and-ride lots.

Conditions Always Lighted

State agencies were motivated by a wide diversity of criteria to install lighting on existing roadways. Most common were "high night/day crash ratio" and "high traffic volume" with 65% of responses, followed closely by "high nighttime crash rate" (59%). "High pedestrian conflict" and "poor visibility" were cited by 46%. Other comments focused on lighting for complex traffic merging points and community development. Dark ambient conditions were not a major motivator to install lighting.

Useful Guidelines in Decision Making

The AASHTO roadway lighting guidelines (*88*) were most commonly cited (80%). The IESNA publication RP-8 (*63*) was cited by about half of respondents. NCHRP Report 152 (*89*) was cited by just over a quarter of respondents. Other guidelines included recent research results, and state guidelines/requirements.

Supplemental Information Sought

When asked whether additional information had been sought by agencies in developing plans for lighting, almost half of those who responded replied in the affirmative. Respondents explained what information they were looking for as follows: light pollution was the leading topic for additional inquiry (63%), followed by cost analysis (56%), and economic development (38%). As shown above, crime was not a major topic for additional inquiry (13%).

CHAPTER 7
CONCLUSIONS

Can road lighting result in fewer crashes at night? Can outdoor lighting reduce crime at night? A simple conclusion that could be drawn from the literature review is "yes" in both cases. The summary by the IESNA (*4*), the CIE (*1*) review, and Elvik's (*2*) meta-analysis, all converge with one another. Additionally, other reviews such as that by Schwab et al. (*14*) and Fisher (*91*) show similar trends. Studies by Painter (*53*) and by Farrington and Welsh (*47*) using meta analyses consistently show that lighting can reduce crime. All of these reviews, both for crash reduction and crime reduction, indicate that lighting can improve safety and security by 20% to 30%.

However, this is statement must be carefully qualified in light of the potential biases that are inherent to the study of lighting, safety and crime. First, and foremost, these estimates may be biased because of other safety and security measures closely associated with the implementation of lighting (*4*). Moreover, these statistics give no indication of where and when lighting might or might not affect safety and security. Indeed, assessments of the security effects of outdoor lighting will remain difficult to perform and interpret because no large and systematic databases exist that link the presence of lighting with the occurrence of crimes.

With respect to safety, it appears for example that lighting has little benefit in areas where there is limited chance of vehicle-vehicle or vehicle-pedestrian conflict. It must be remembered too that collateral effects associated with roadway and outdoor lighting need to be considered, in particular light pollution which heretofore has been unmeasured.

Aside from the discussion above, a few other general statements can be made regarding the potential safety benefit of roadway lighting:

- Darkness (or the absence of lighting) results in a disproportionately large number (in relation to exposure) of crashes and fatalities, and in particular, those involving pedestrians. Pedestrians are the most vulnerable population on roads at night and in terms of crash reduction appear to benefit the most from street lighting. Sullivan and Flannigan (*92*) estimate that pedestrians are between 3 and 6.75 times more vulnerable in the dark than daylight. Schwab et al. (*14*), CIE (*1*) and Elvik (*2*) estimated that street lighting can reduce pedestrian crashes at night by approximately 50%, a value that is higher than for other crash types.

- Lighted intersections and interchanges tend to have fewer crashes than unlighted intersections/ interchanges (*2, 3, 10, 23, 30*), but there appears to be no major benefit of complete interchange lighting compared to partial lighting at interchanges along urban, suburban or rural freeways, as evidence is mixed for some locations (*16*).

- It is assumed that the issues involving pedestrian and intersection crashes at night are primarily associated with visibility; hence these are scenarios in which lighting might have the greatest effect in regards to the reduction of nighttime crashes; run-off road crashes on the other hand are likely due in large part to factors (e.g., fatigue, intoxication) in which lighting is not expected to have a direct influence.

An interesting question regarding the mechanism(s) at play in the reduction of crashes at night, particularly those involving pedestrians and at intersections is: Does the purported effect of lighting simply relate only to increases in visual performance? Or could the ‘message’ or information sent by the lighting installation, perhaps telling a driver to exercise caution, also be an important factor. For example, Carstens and Berns (*93*) investigated intersection lighting that was not intended to support visibility but rather only to guide a driver to an intersection. They found no effect of this approach on crash risk, but only studied low-volume roads. It is not known whether such an approach might assist in reducing nighttime crash where traffic volumes are higher. Almost exclusively, the research reviewed to this point has focused on the visibility-supporting aspects of lighting, but as is discussed in the crime and security sections of this report, the presence of lighting might convey a message to roadway users that might result in changes in driving behavior.

In order to assess the possible role of lighting in safety, two parallel research efforts were made through NCHRP Project 5-19, and are documented in companion reports entitled "Analysis of Safety Effects for the Presence of Roadway Lighting" (*94*) and "Analysis of Visual Performance Benefits from Roadway Lighting" (*95*). In the former effort, large statistical samples of roadway lighting presence and crash data were assembled and analyzed to identify the role of lighting. Using statistical models, the approach attempted to control for traffic volume, posted speed limits, and roadway geometric characteristics that have not been considered in past studies of lighting and safety. In the latter effort, the role of lighting to affect visibility is assessed under different lighting conditions to identify the role of different light levels and lighting systems on visual performance for potential conflicts along roadways. Each of these yielded consistent findings regarding the effects of roadway lighting on safety.

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