Priority-Setting for the Distribution of Localized Hazard Protection

Paper accepted for publication and to appear in *Risk Analysis: An International Journal*

By James H. Lambert and Thomas Turley
Center for Risk Management of Engineering Systems
University of Virginia

June 2004

Abstract

We address the problem of distributing safety-enhancing devices across a region, where each identical device provides for only local protection of the population. The devices protect non-identical sectors of the population. The sectors of population are exposed to non-identical intensities of hazard. A method for the screening and prioritizing of needs for the protective devices is described. An approach of risk-benefit-cost analysis under uncertainty is recommended as follows. Measures of hazard intensity and population exposure are identified. Exogenous parameters that influence assessments of risks, benefits, and costs are identified. Uncertainties of the exogenous parameters are propagated by interval analysis. Several tiers of the plausibility of need for protection are identified. The tiers are useful in setting priorities for the distribution of the safety devices. The method is demonstrated in an engineering application to roadway lighting, but has implications for disaster preparedness, anti-terrorism, transportation safety, and other arenas of public safety.

Key words: system safety, benefit-cost analysis, risk-based decisions, priority setting, hazard protection, roadway lighting

Introduction

We motivate the need for priority-setting of localized hazard protection as follows. Experience has shown that roadway lighting can be an effective safety countermeasure for night accidents and for a general safety improvement to roadways. However, public agencies have limited resources and cannot address all identified. Screening is required in order to select the most beneficial needs based on crash reduction and safety improvement. Design of fixed roadway lighting is addressed by Staplin et al. (2001), Garber (2000), Khan et al. (2000), Couret (1999), Crawford (1999), Shaflik (1997), Jefferson (1994), FHWA (1993), and Janoff and Zlotnick (1985). The benefits of such lighting are addressed generally by Wilken et al. (2001), Kramer (1999, 2001), ANSI (2000), Cottrell (2000), Edwards (2000), IES (2000), Walton (2000), Watson (2000), Gransberg (1998), Sandhu (1992), APWA (1986), and Janoff (1984, 1986). A typical finding of such studies is that one fourth of traffic volume occurs at night when more than one half of crash-related fatalities are recorded. Thus darkness is associated with a fatality rate about three times higher than daytime. Empirical studies of the safety benefits of lighting are numerous. For example, Box (1989) shows that fixed lighting can reduce night crashes in a range of 20 to 36% and overall crashes at a rate of up to 14%. Griffith (1994) estimates a reduction of total property damage crashes of 32%. Box (1972) shows that illumination can reduce night crashes by 40% on freeways. CIE (1990) concludes that "roadway lighting is successful; however, the installation of lighting cannot be expected to result in a reduction in accidents if there is a major non-visual problem at any particular site." Other empirical studies include Dewar and Olson (2002), Owens and Sivak (1996), Trivedi (1988), Janoff (1984, 1986) and Marshall (1970). Understanding of exposure assessment and benefit-to-cost methods for fixed lighting is provided by IADOT (2001), NYMTC (2001), McFarland and Walton (2000) and Janoff and McCunney (1979). Lambert et al. (2003) describe a method of screening needs for roadway guardrail, which is similar to lighting in that it is typically fixed on the roadway to address the needs of particular sites. Some widely used methods of screening needs for fixed roadway lighting (AASHTO 1984, NCHRP 1974) are based on factors, scores, weights, or thresholds that have not been revisited in decades. Moreover, the underlying principles and assumptions are lost or diminished in relevance. There is a need to generalize and overtake such methods after more than two decades of evolution of driver behavior, vehicle characteristics, environmental and economic conditions, agency and public values regarding risk, roadway lighting improvement, and availability of competing or synergistic technologies.

The current effort thus develops a general approach to priority setting for the distribution of localized hazard protection, which will be specialized to priority setting among needs for roadway lighting. The approach is exemplified in a two-phase screening method to establish priorities for roadway locations that are identified as being in need of lighting installation or upgrade. The organization of the paper is as follows. First, we provide an overview of roadway lighting as a specific need or context for such a method. Next, we describe the two phases of the priority-setting method, exposure assessment and site-parameters assessment. Next, we make a case study of over eighty prospective lighting needs and describe a typical application of the method. Finally, we give suggestions for related future research both for the general topic and for lighting and visibility needs in particular.

Method development

Overview

We established above that widely used screening methods that assess the potential for fixed roadway lighting to decrease night crashes have not been updated in decades. The methods have arbitrary features, dilute the influence of factors that engineers lately consider to be important, and are inadequate for roadways where crash histories are either not available or relevant. A two-phase methodology will be shown to aid priority-setting among needs for fixed roadway lighting is as follows. In the first phase, an exposure assessment will contrast individual and population exposures to the hazard, presenting needs in terms of night-to-day crash rate and traffic volume. Crash rates are estimated from regional analyses stratified by road type, traffic volume, and posted speeds. Night crash histories on over eighty unlighted and lighted road sections will be collected and studied in demonstration of the methodology. In the second phase, a site-parameters assessment is performed to identify engineering factors that suggest the localized protection, e.g., lighting, would have benefit.

An aim of screening is to limit the number of local needs of protection that are subjected to costly engineering investigation, resulting in a better use of public resources. Since it may not feasible to address all needs, some needs must be rejected or postponed for funding.

Exposure assessment

An exposure assessment phase is developed to implement a simplified benefit-to-cost analysis with interval values of relevant parameters including several lighting costs, night-to-day crash-rate ratio, and average daily traffic (ADT). A graphical interpretation is found useful to relate the *exposure*, in terms of the average daily traffic exposed to the need, to the hazard *severity*, in terms of the night-to-day crash rate ratio. A need located in one zone of such a graph represents a low-exposure and low-severity situation. A need located in another zone of such a graph represents a high-exposure and high-severity situation. Benefit/cost analysis has been adapted to distinguish the several zones of such a graph as follows. A benefit-to-cost ratio is defined to be the ratio of the expected cost of the night crashes avoided per year by installing lighting to the annualized cost of lighting as follows.

$$Benefit-to-Cost\_Ratio = \frac{365 \times ADT \times \%N\_ADT \times N/D \times DCR \times CRF \times ACC}{100{,}000{,}000 \times (AIC + AMC + AEC)}$$

where the parameters ADT, %N_ADT, N/D, DCR, CRF, ACC, AIC, AMC, and AEC are as defined in Table 1. An interval range of potential values for each of the exogenous parameters, i.e., parameters other than ADT (average daily traffic) and N/D (night-to-day crash rate), is estimated for a geographic region of interest. In our application, the interval ranges given by Table 2 were set in consultation with experts from state transportation agencies, with the interval ranges of cost of crashes calibrated with Judycki (1994). Such interval analysis of the benefit-to-cost ratio can be described in a cartesian graph as follows. The *exposure* in terms of average daily traffic (ADT) is the horizontal axis of the graph. The *severity* in terms of night-to-day crash rate ratio is the vertical axis of the graph. For a benefit-to-cost ratio equal to 1.0 the extreme values of the interval calculation generate two curves separating three zones: (i) *Accepted,* whose needs have exposure and severity are such that the B/C ratio exceeds 1.0 for all possible values of the exogenous parameters, (ii) *Marginal*, whose needs are such that the B/C ratio exceeds 1.0 for some possible values of the exogenous parameters, and (iii) *Rejected*, whose needs are such that the B/C ratio does not exceed 1.0 for any possible values of the exogenous parameters. Lighting needs can be plotted in such a graph and their position in terms of *exposure* and *severity* relative to the zones yields the screening decision for the exposure-assessment phase. Adjusting of the ranges of exogenous parameters shifts the zones in response to local and regional particularities. A preliminary and simplified benefit-cost evaluation thus proceeds without a need for precise values of the exogenous parameters. Such a graphical display of needs contrasting *severity* and *exposure* makes it possible for users to grasp the priority of the need relative to the benefit-cost zones. Needs that are determined to be at least *marginal* at the exposure-assessment phase pass through to the next phase of site-specific parameters assessment, while others are rejected in this first phase of screening.

Site parameters assessment

An exposure assessment alone should not be sufficient for a screening decision in that a need justified by *severity* and *exposure* parameters may have no feasible remedy in the particular technology, e.g., roadway lighting. Thus this second phase of site-specific parameters assessment addresses the potential efficacy of the particular remedy (e.g., lighting) through development of a set of eight factors that represent local design and engineering characteristics. The eight developed factors for lighting are: traffic mix, veiling luminance, curvature and grade, lane configuration, section/intersection geometry, posted speed, level of service and intermodal transactions. With modern evidence, a qualitative scale of three levels is developed for each factor: *low*, *moderate*, and *high*. For a prospective need, the number of ratings obtained at each level is counted, where the extreme results are eight *high* ratings and eight *low* ratings. The requirement for a prospective need to be *accepted* in this second phase of screening is that at least one factor be rated as *high* or four factors be rated as *moderate*. Needs deemed *accepted* move to next stage of in-depth evaluation and those determined to be otherwise are given a lower priority for further investigation.

Table 3 summarizes the eight factors of the site-specific parameters assessment. Following are the interpretations and modern evidence supporting each of the eight factors. For *traffic mix* we recognize that the amount of trucks in traffic increases the speed differential between vehicles thus increasing the likelihood of occurrence of crashes. Blower and Campbell (1998) describe that truck crashes at night tend to be more severe than during the day. For *veiling luminance* we recognize that the percentage of roadside that is developed and therefore illuminated affects the number of vehicle movements in and out of those areas. The location and identification of vehicles entering or leaving the roadway is of considerable importance in the driving task. In addition, the presence of development can generate pedestrian activity especially in urban areas. For *curvature and grade*, the curvature of a section of roadway is defined as the maximal curvature encountered and the grade is defined as the slope of the roadway in a range of percentages. Driver visibility is paramount in negotiating curves in a section of road. At night, it is increasingly difficult to identify the direction of the road (Dewar and Olson 2002 and Fizpatrick et al. 2000). For *lane configuration* we integrate the concomitant features of lane width and number of lanes. As the number of lanes increases, the ability of the headlights to effectively light the roadway periphery is greatly reduced, especially in inclement weather. Moreover as lanes become narrower, tracking becomes more and more difficult for the driver. For *section/intersection geometry,* we recognize that this factor specifically addresses the constraints that designers face when the cost of an ideal safety improvement is not supported by the budget. The components of this factor are addressed in Donnell et al. (2001), Garber (2000), Rumar (1998), Griffith (1994) and FHWA (1993). For *posted speed,* we recognize that speed limit is a factor that affects the safety of drivers. Visibility provided by headlamps is limited and can be less than the minimal stopping distance of the vehicle at the posted speed. Evidence shows that speed perception changes at night, and that it is more difficult to develop correct estimates of speed (Dewar 2002). For *level of service*, we recognize the impact of increasing complexity and density of vehicle-to-vehicle maneuvers. Lighting can improve a level of service by allowing drivers the visibility to see the evolution of traffic flow earlier, and adjust more gradually to accommodate such flow rather than depending on brake light signals. For *intermodal transactions* we combine the similar hazards generated by tourists and elderly drivers. We consider the potentially inadequate driving behavior expected from an unfamiliar or vision impaired driver (Hatch 1999, Rumar 1998). Additionally, the presence of intermodal platforms including airports, bus stations, bike paths, and other pedestrian-heavy areas in the vicinity of the need is considered.

Application of the method to lighting data

Study of over eighty prospective needs for lighting

A study of night-to-day crash-rate ratios was performed on a selection of two-mile sections of *unlighted* road in a six-year period between January 1, 1996 and December 31,

2001. The sections were selected from three regions: Tidewater Virginia, Central Virginia, and Northern Virginia, USA. Table 5 shows that the selected sections were stratified by average daily traffic, posted speed and lane configuration. We collected the number of crashes under each of daytime conditions and nighttime conditions, extracting only the sum of property-damage-only, injury, and fatal crashes. In addition, we collected the average daily traffic for each section. Next, we adopted the typical assumption that 2/3 of daily traffic occurs in daytime conditions and 1/3 under nighttime conditions; the assumption was vetted with engineers and planners of the system under investigation. We processed these data to obtain the night-to-day crash-rate ratios.

In addition to the study of two-mile sections, we studied a regional database of 122,000 crashes from January 1, 1997 through December 31, 2001, in Central Virginia, USA. We identified the *unlighted* locations in the vicinities of intersections and other landmarks and extracted the total crashes at each location under each of daytime and nighttime conditions. Next, we selected over forty locations that had the highest absolute numbers of crashes, found the average daily traffic of the locations, and generated the night-to-day crash rate ratios. We applied the same assumption of daytime and nighttime traffic distribution as described above for the study of two-mile sections.

We applied the exposure assessment phase of the developed screening method. Figure 1 gives the unlighted *two-mile sections* and unlighted *locations*, in all contrasting eighty-two prospective in terms of night-to-day crash rate ratios (*severity*) and average daily traffic (*exposure*). Three prospective needs are in the *rejected* zone of the figure, seventy of them are in the *marginal* zone, and the nine others are in the *accepted* zone. The default settings of the parameters of the exposure assessment prove to be soft, or permissive, with respect to this collection of prospective needs, since 85% of the studied needs are judged *marginal*. Recall that a *marginal* result indicates that it is plausible that to address the need through fixed roadway lighting would be associated with a benefit-to-cost ratio exceeding 1.0. Practical application of such a result would proceed with further investigation (as in the further example applying phase two below) of the prospective needs, moving from the upper right of the exposure chart to the lower left, and moving perpendicular to the curves of equally plausible benefit-to-cost ration that are superimposed on the figure.

Example: Application to a single need for localized protection

We consider a single prospective need for fixed roadway lighting, at the interchange of route 460 and interstate 85 in Central Virginia, and apply both phases of the developed screening method. For the exposure assessment phase, the night-to-day crash rate ratio and average daily traffic are 1.0 and 45,000 vehicles per day, respectively. Figure 2 indicates that the result of exposure assessment is *marginal*, since the need is located between the upper and lower curves. The result is consistent with 85% of the prospective needs studied above. In the ensuing site-parameters assessment, there are *moderate* results in two of the eight factors: *veiling luminance* and *posted speed*. There six *low* results across the other six factors. A *low* result can indicate unavailable information. The overall result of the site-parameters assessment is considered to be *marginal*, since neither a single *high* nor a sufficient number of *moderate* ratings were achieved. The aggregate result of applying the two phases of the screening method for the interchange of Route 460 and Interstate 85 is *marginal* since each of the exposure assessment and site-parameters assessment qualified the need as *marginal.* The prospective need would typically not pass into a subsequent phase of evaluation for funding. Such a phase would consider precise estimates of lighting costs, the circumstances of individual crashes, review of alternative visibility technologies, engineering design reviews, and the merits of competing visibility and other safety needs. The same interchange of Route 460 and Interstate 85 received 45 points in application of the rate-and-weight scoring method recommended by NCHRP (1974). At least 75.0 would have been required to pass into a subsequent phase of review. Engineering judgment was counter to the result of the NCHRP method in the particular case, the fact of which in part led us to undertake the current effort.

Indirect estimation of night-to-day crash-rate ratio

In practical application of the exposure assessment, it is recommended to perform an indirect estimation of the night-to-day crash rate ratio of a section of road where no accident data is available, such as with new or altered highways. Indirect estimation should be performed with knowledge of the identified stratification characteristics of the road section that are identified above. The indirect estimation will proceed from use of results of a regional study of similar unlighted sections. Table 5 (which is cited above) represents the results of such a regional study. To introduce an appropriate conservatism with an indirect estimation, the estimates can be scaled by a coefficient before use in the exposure assessment phase of screening. The use of a coefficient of 0.50 is consistent with the so-called 'warranting methods' recommended by AASHTO (1984). Thus an indirectly estimated night-to-day crash rate of 2.0 would be reduced to 1.0 before being entered as an input to the exposure assessment, assuming the average daily traffic counterpart is known or has been estimated.

Closure

The contributions of this paper are as follows. Quantitative benefit-to-cost analysis is introduced directly into screening of needs for hazard protection, applying interval arithmetic where there is imprecise knowledge of underlying parameters. Theoretical zones of screening decision are defined based on whether the condition of the benefit-to-cost ratio is plausible to exceed 1.0. The theoretical zones of decision are calibrated and compared with an extensive study of protected and unprotected locations. In a second phase of screening, we develop design and engineering factors that highlight the potential local benefit of the particular technology or protection device. An approach to use stratified sampling to indirectly assess the intensity of hazard is suggested for when history is unavailable.

We demonstrated the general approach in a specific case: needs for roadway lighting. The method is used to screen road sections to which the addition of fixed roadway lighting could have significant benefits to reduce crashes. The developed method accounts for the exposure of a motoring population and the severity of the night-to-day effect, particularly with imprecise knowledge of benefit-to-cost ratio parameters. We develop a stratification of unlighted roadways by traffic volume, posted speed and lane configuration. The method furthermore develops a set of engineering factors to address the design configuration and other relevant characteristics of the sections.

The use of the method is to recommend protection needs that qualify for further investigation. The method thus promotes a reasoned and effective use of resources in the distribution of localized protection. The developed priority-setting method can be adapted (through the quantification of benefits and costs) to particular technologies, to local costs, and to local risk-relevant databases.

Future work on the larger topic of hazard screening, must address the geographic distribution of a pool of technologies with similar aim. The work should assess the appropriate means to enhance safety from among the pool of all available protection-enhancing technologies. For example, other technologies that can be used to improve roadway visibility are: reflective pavement markings, vanes on median and glare screens, night vision and other vehicle-based visibility enhancements, navigation systems, active warning lights, pedestrian-activated lighting, and signage or post-mounted delineations. The effort must distinguish: (i) evidence that any improvement (e.g., visibility enhancement) would be beneficial to safety; and (ii) evidence that any other available technology would be uniquely beneficial. Such a second tier of evidence is important to demonstrate what technology (e.g., lighting or other visibility technology) is the most beneficial technology to improve safety. For example, *veiling luminance* is a factor arguing for fixed roadway lighting over, for example, reflective materials and pavement markings: increasing the contrast can be improved uniquely by lighting. Future work will serve the public interest that localized protection technologies be distributed so as to achieve the greatest safety improvement at the lowest cost.

Acknowledgements

This paper was presented at the Annual Meeting of the Society for Risk Analysis in Baltimore, Maryland, December 2003. The case study of lighting needs was supported in part by the US Federal Highway Administration, the Virginia Department of Transportation (VDOT), and the Virginia Transportation Research Council (VTRC), whose details are provided by Lambert and Turley (2003). The authors are grateful to Della Dirickson at the University of Virginia for editorial and administrative assistance. Personnel of VTRC and VDOT who contributed to the effort are Travis Bridewell, Benjamin Cottrell, Wayne Ferguson, Michael Perfater, Steve Brich, Pamela Brookes, Chandra Clayton, Butch Cubbage, Mark Hodges, Ilona Kastenhofer, Karen Rusak, Jon Sayyar, Al Smith, Jim Gillespie, Robert Feldman, Robert Rasmussen, Ralph Jones, Llewellyn Slayton, Jaroslaw Jastrzebski, Ray Khoury, and Timothy Rawls. In addition, Carl Andersen of the Federal Highway Administration and Jim Havard of the IESNA Roadway Lighting Committee contributed to this effort. Former University of Virginia students who contributed to the data collection are Raynelle Deans, Andrew Miller, Jenny Murrill, James Sanders, Max Aronin, Raynelle Callender, Amre Massoud, Kenneth Peterson, and Clare Patterson.

References

AASHTO, 1984. *An Informational Guide to Roadway Lighting*. American Association of State Highway and Transportation Officials, Washington, D.C.

ANSI, 2000. *Roadway Lighting*. RP8-00. American National Standards Institute, Washington, D.C.

APWA, 1986. *Let There Be Light*. 1986. APWA Institute for Professional Development, Management Series No. 1. American Public Works Association, Washington, D.C.

Blower, D. and K. Campbell, 1998. *Fatalities and injuries in truck crashes by time of day*. University of Michigan, Transportation Research Institute

Box, P.C., 1972, *Comparison of Accidents and Illumination*, Highway Research Board record 416

Box, P.C., 1989. *Major Road Accident Reduction by Illumination*. Transportation Research Board report 1247.

CIE (Commission Internationale de l'Eclairage), 1992, *Road Lighting as an Accident Countermeasure.*

Cottrell, B., 2000. *Literature Search on Non-Interstate Roadway Lighting*, VTRC memorandum number 23.7.64.

Couret, C., 1999. Let There Be Light…But Make Sure It Balances Aesthetics and Safety. *American City and Country,* Vol. 114:3, 51-57. Atlanta, GA: Intertec Publishing Corporation.

Crawford, D., 1999. Let's Save Our Dark Sky, *World and I*, February 1999.

Department of Transportation Bureau of Transportation Statistics and the Center for Transportation Studies (DOT BTS), 1995. *Level of Service Multimedia Representation*. http://yerkes.mit.edu/DOT1/LOS/LOS.html, Accessed November 15, 2002.

Dewar R.E. and Olson P.L., 2002, *Human Factors in Traffic Safety*, Lawers & Judges Publishing Company, Inc.

Donnell, E.T., D.W. Harwood, K.M. Bauer, J.M. Mason, 2001. *Analysis of Highway Median Safety in Pennsylvania*, Institute of Transportation Engineers, Monterey, California.

Edwards, J.D., Ed., 2000. *Traffic Engineering Handbook*, 5th ed., Institute of Transportation Engineers, Washington, D.C.

Federal Highway Administration (FHWA), 1978. *Roadway Lighting Handbook*. U.S. Department of Transportation, Washington D.C.

Federal Highway Administration (FHWA),1993. RD-93-046, *The Association of Median Width and Highway Accident Rate*, Highway Safety Information System summary report from a study by the Highway Safety Research Center, University of North Carolina

Florida Department of Transportation (FDOT), 2000. *Manual for Uniform Traffic Studies, Chapter 15*. Florida: Florida Department of Transportation.

Florida Department of Transportation (FDOT), 2001a. *Highway Lighting Justification Procedure*. 29 September 2001. http://www.dot.state.fl.us/trafficengineering/muts/Chapter15.pdf

Florida Department of Transportation (FDOT), 2001b. *Safety Programs*. Florida Department of Transportation. 20 September 2001.

Garber, N. J., 2000, *The Effect of Speed, Flow, and Geometric Characteristics on Crash rates for Different Types of Virginia Highways*, Transportation Research Board record 1676, Civil Engineering Department, University of Virginia.

Gransberg, D.D. 1998, *Evaluation of Roadway Lighting Systems Designed by STV Methods*, Texas Tech University, Texas DOT research study number 0-1704

Griffith, M.S., 1994, Comparison of the Safety of Lighting Options on Urban Freeways. *Public Roads Online*. September 1994.

Hatch, S., An Eye on Older Drivers, *Road & Bridges* July 1999

IES, 2000. *American National Standard Practice for Roadway Lighting***.** Illuminating Engineering Society, New York.

Iowa Department of Transportation (IADOT), 2001. *Cost-Benefit Analysis Procedure.* 21 October 2001.

Janoff, M.S., 1984. Effects of Partial Lighting on Traffic Operations at Freeway Interchanges. *Lighting Design and Application,* Vol. 14:5. New York: Illuminating Engineering Society.

Janoff, M.S., and W. McCunney, 1979. Economic Analysis of Roadway Lighting. *Journal of Illuminating Engineering Society,* Vol. 8:4, 244-249. Illuminating Engineering Society, New York.

Janoff, M.S., and N.L. Zlotnick, 1985. Reduced Freeway Lighting. *Lighting Design and Application,* Vol. 15:8, 35-42.

Janoff, M. S., Staplin, L. K. and Arens, J. B. 1986. *The Potential for Reduced Lighting on Roadways*. Public Roads Vol. 50:2, 33-42.

Jefferson, B., 1994. The On-Off Dilemma of Public Lighting: Urban Aesthetics. *American City and County*, August 1994: 60 – 64.

Judycki, D.C., 1994. Motor Vehicle Accident Costs. FHWA Technical advisory. http://www.fhwa.dot.gov//legsregs/directives/techadvs/t75702.htm

Khan, M, S. Senadheer, D. Gransberg and R. Stemprok, 2000. *Influence of Pavement Surface Chrematistics on Nighttime Visibility of Objects*. Transportation Research Record. 1 (2000): 39-48.

Kramer, E.J., 1999. Should Vision Influence Roadway Lighting Design? *Better Roads.* October 1999: 16-18.

Kramer, E.J., 2001. New Lighting Designs Offer Advantages. *Better Roads.* January 2001: 45-47.

Lambert, J.H., and T. Turley, 2003. *Screening Methodology for Needs of Roadway Lighting*. Research Report FHWA/VTRC 03-CR-14. Charlottesville, VA: Virginia Transportation Research Council. June 2003. 70 pp.

Lambert, J.H., J.A. Baker, and K.D. Peterson, 2003. Decision aid for allocation of transportation funds to guardrails. *Accident Analysis and Prevention*. 35(1):47-57.

Marshall, A., 1970. *Roadway Lighting and Reduction of Accidents* International Road Federation – VI World Highway Conference, Montreal.

McFarland, W.F. and N.E. Walton, 2000. *Cost Effectiveness Analysis of Roadway Lighting Systems*. Report No. 137-1. Texas Transportation Institute: Texas State Department of Highways and Public Transportation.

National Cooperative Highway Research Program (NCHRP), 1974. *Warrants for Highway Lighting*, report number 152.

New York Metropolitan Transportation Council (NYMTC), 2001. *Cost-Benefit Analysis Procedure Example*. 07 October 2001.

Owens, D.A. and M. Sivak, 1996. *Differentiation of Visibility and Alcohol as Contributors to Twilight Road Fatalities*, Human Factors 38(4), 680-689.

Rumar, K., 1998. *Vehicle Lighting and the Aging Population*, Transportation Research Institute, University of Michigan

Sandhu, D. 1992. *Seeing the Light.* World Highways Vol. 1:6, 51-3. Route One Publishing Ltd, United Kingdom.

Shaflik, C., 1997. *Environmental Effects of Roadway Lighting*. University of British Columbia. Tuscon, Arizona, 1997.

Staplin, L., K. Gish, L. Decina, K. Lococo, D. Harkey, M. Tarawneh, R. Lyles, D. Mace and P. Garvey, 2001. *Synthesis of Human Factors Research on Older Drivers and Highway Safety.* The Scientex Corporation, Pennsylvania.

Trivedi, R., and P. Schonfeld, 1988. *Safety Benefits of Highway Lighting*. University of Maryland, Maryland Department of Transportation, College Park, Maryland.

Walton, N.E., 2000. *Engineering Economy and Energy Considerations; Warrants and Priorities for Roadway Lighting*. Report No. 214-13. Texas Transportation Institute: Texas State Department of Highways and Public Transportation.

Watson, C.P., 2000. Designing Roadway Lighting Systems for the Next Millennium. *International Municipal Signal Association Journal*, Vol. 38.2, pp. 40-43. International Municipal Signal Association. Newark, NY.

Wilken D., Ananthanarayanan B., Hasson P., Lutkevich P.J., Watson C.P., Burkett K., Arens J., Havard J., Unick J., 2001, Federal Highway Administration PL-01-034, *European Lighting Technologies*, International Technology Exchange Program

Table 1. Parameters in application of the priority-setting method to needs for roadway lighting

Parameter	Parameter description	Unit
ADT	Average daily traffic	vehicles per day
%N ADT	Percentage of night traffic	% of average daily traffic
N/D	Night-to-day crash rate ratio	-
DCR	Day crash rate	crashes per 10^8 kilometers traveled
CRF	Crash reduction factor	% of current crashes
ACC	Average crash cost	$ per crash
AIC	Annualized installation cost of lighting	$ per year per kilometer
AMC	Annual maintenance cost	$ per year per kilometer
AEC	Annual energy cost	$ per year per kilometer

Table 2. Interval ranges of parameters for application of the priority-setting method to roadway lighting

Parameter	Low parameter value	High parameter value	Unit
B/C ratio	**1**	**1**	None
Night ADT	**25%**	**25%**	None
Day crash rate	**60**	**95**	Crashes / 10^8 VKT
Crash reduction	**30%**	**50%**	None
Crash Cost	**50,000**	**75,000**	$ / crash
Cost of lighting	**120,000**	**160,000**	$ / (kilometer * year)

Table 3. Factors that aid in priority-setting among lighting needs

Factor	Low benefit	Moderate benefit	High benefit
Traffic mix (percentage of qualified trucks in the overall traffic)	0 – 15 %	15 - 25 %	> 25 %
Veiling luminance (percentage of luminous development frontage)	0 – 25 %	25 - 70 %	70 – 100 %
Curvature and grade			
Curvature	≤ 3 °	4 ° - 5 °	≥ 6 °
Grade	Level - Rolling	Mountainous	n/a
Lane configuration			
Lane width or	≥ 3 m	< 3 m	n/a
Number of lanes	6 or less lanes undivided	6 or more lanes divided	
Section/Intersection geometry			
Sight distance or	≥ 170 m	< 170 m	n/a
Median width or	4 - 10 m	≤ 4 m	
Shoulder width or	> 2.5 m	≤ 2.5 m	
Intersection/Interchange frequency	< 2 /km	≥ 2 /km	
Posted speed	< 75 km/h	> 90 km/h	n/a
Level of service	D or better	E or worse	n/a
Intermodal transactions			
Distance to tourist, elderly venues and intermodal platforms	1.6 km	800 m	n/a
Adjacent parking spaces	Prohibited both sides	Permitted both sides	n/a

Table 4. Regional night-to-day crash rate ratio collected to demonstrate application of the priority-setting to roadway lighting needs

	Average daily traffic					
Operating Speed km/h	**<10,000**		**10,000-20,000**			**>20,000**
	2 lane	**4 lane div.**	**2 lane**	**4 lane div.**	**4 lane undiv.**	**4 lane div.**
75	1.33, 1.09, 10.32	1.67	0.38, 1.06, 1.52, 1.74	-	1.23, 1.33, 1.35, 1.40, 2.33, 3.32	1.08, 1.11, 1.50, 1.80, 1.93, 2.02, 2.09, 2.23, 2.28
90	0.25, 0.50, 1.24, 1.65, 1.83, 3.00	0.79, 1.50, 3.50	1.86	1.01, 1.48, 1.85, 2.01, 2.40, 3.21	1.00, 1.20, 2.16	1.25, 1.43

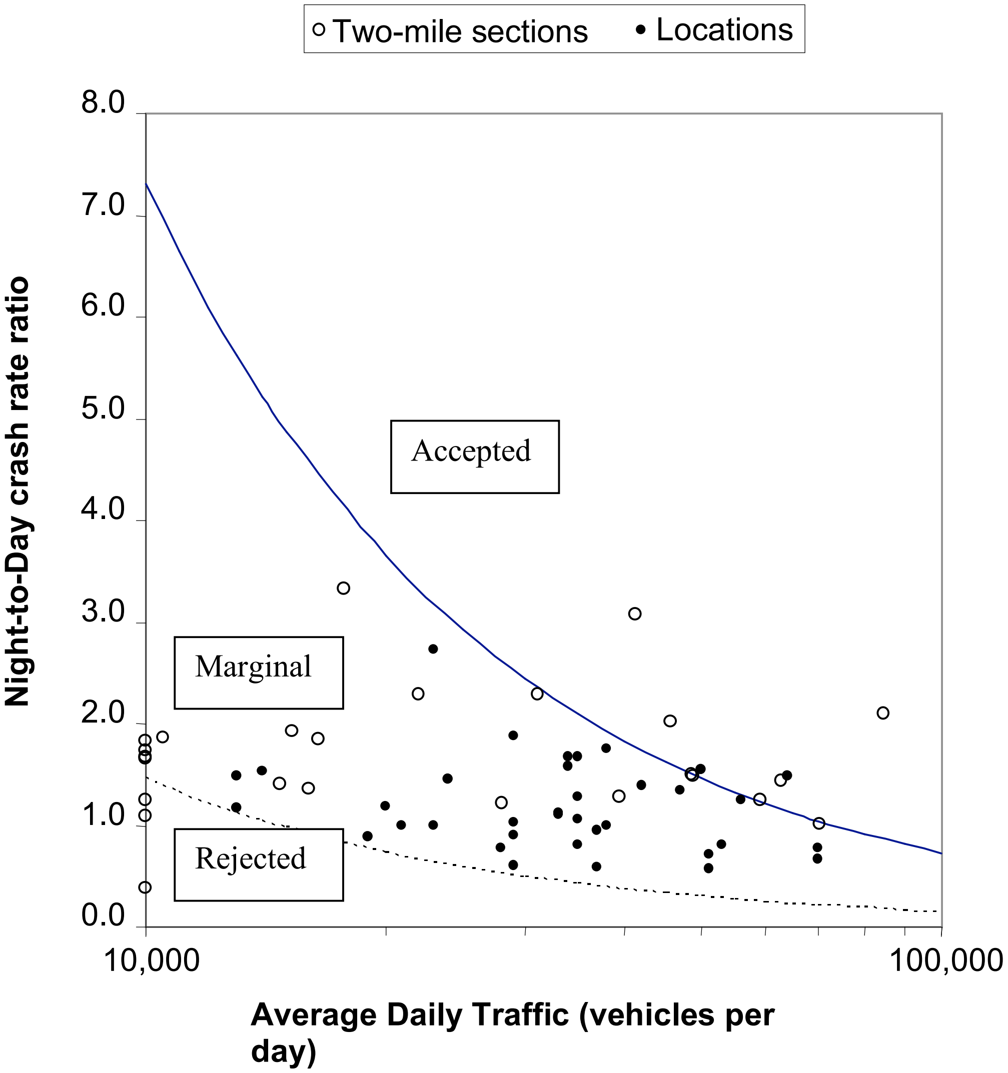

Figure 1 Case study of the priority-setting method: Lighting needs contrasted by night-to-day crash rate ratios and traffic volumes

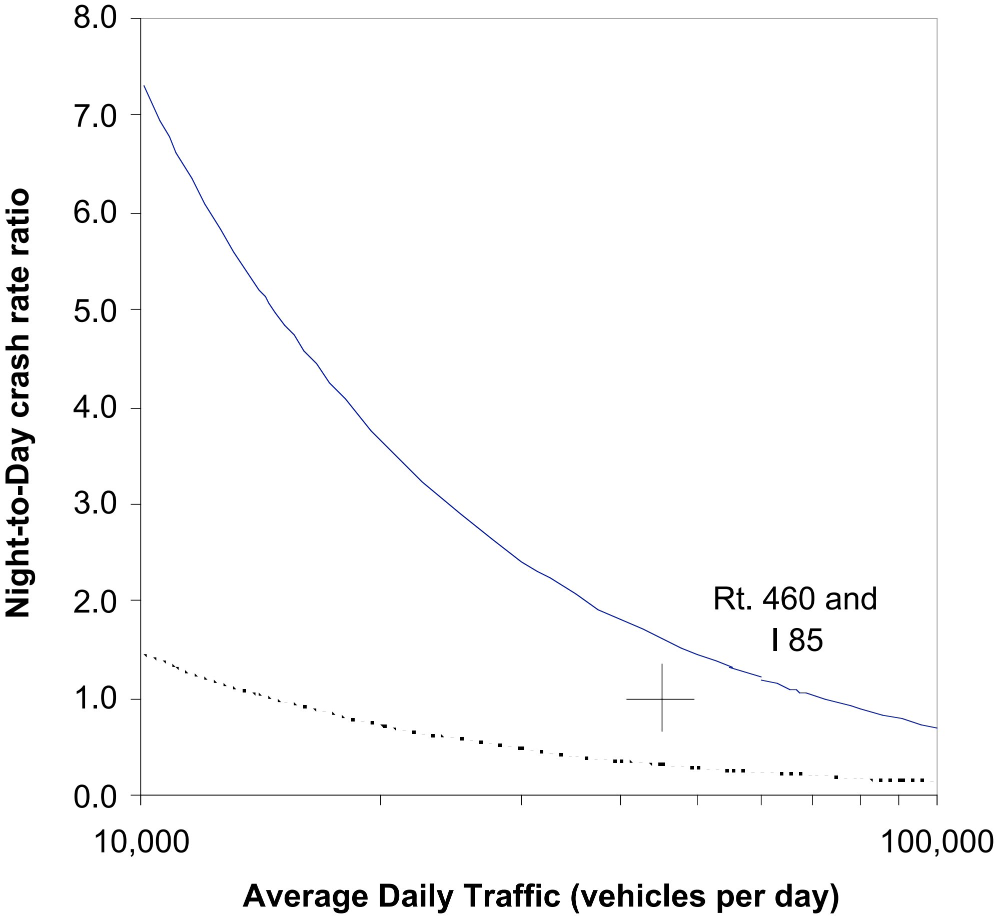

Figure 2. Application of the priority-setting method to contrast hazard intensity and hazard exposure with the several zones of plausible benefit-cost ratio exceeding 1.0; the + denotes a lighting need with a plausible B/C > 1.0