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From: Markus Price
Acting Chief, Visibility and Injury Prevention Division

Reply to Attn. Of:

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Thru: Nathaniel Beuse
Office Director, Office of Crash Avoidance Standards

O. Kevin Vincent
Chief Counsel

for KV

The attached technical report, "Feasibility of New Approaches for the Regulation of Motor Vehicle Lighting Performance" is submitted for placement in the Docket NHTSA-2011-0145.

Should you have any questions, please contact me by telephone at (202) 366-0098.

Attachment

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FEASIBILITY OF NEW APPROACHES FOR THE REGULATION OF MOTOR VEHICLE LIGHTING PERFORMANCE

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John M. Sullivan

June 2011

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This is a final report on the feasibility of a performance-oriented version of FMVSS No. 108. David Hines and Markus Price provided technical support.

16. Abstract

This report evaluates the feasibility of developing a performance-oriented version of FMVSS No. 108 "Lamps, reflective devices, and associated equipment." The report describes how the standard might be made more performance oriented, and how such changes would be expected to affect vehicle lighting. A list of twelve potential effects is presented, and each is discussed in turn. Some of the expected effects of the potential performance-oriented changes are illustrated by determining how they would apply to current lamps. Most of those results were obtained using software that was developed during this project. A current version of the software is available and may be useful as a supplement to this report, but it is not needed in order to understand the major elements of the performance-oriented approach described here. In a concluding section, the current status of the performance-oriented approach is summarized and issues that might be addressed in future research are described.

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Executive Summary

Federal Motor Vehicle Safety Standard (FMVSS) No. 108 "Lamps, reflective devices, and associated equipment" is one of the largest and most complex of the Federal Motor Vehicle Safety Standards. It is also, in comparison to many of the other standards, more focused on equipment and less performance-oriented. It is often desirable, when possible and practical, to formulate a standard in performance-oriented terms in order to specify overall performance levels without dictating design aspects of equipment. The standard can then be more closely aligned with the effects it is intended to achieve, and it may be less restrictive toward new technologies that might achieve the same effects in different ways. The goal of this project is to evaluate the feasibility of reformulating a substantial portion of the current requirements in FMVSS No. 108 in more performance-oriented terms.

A similar effort to revise FMVSS No. 108 was made in the 1980s (Federal Motor Vehicle Safety Standards [FMVSS], 1989), but did not result in actual changes to the standard. The present effort differs from the previous one in several ways. First, the previous effort was intended to make fundamental changes in the requirements for lower-beam headlighting, whereas the present effort is not intended to develop new requirements but rather to translate the current requirements into performance-oriented terms. Second, the previous effort addressed only lower-beam photometry. Although the new approaches for regulation evaluated in this report are in fact primarily relevant to lower-beam photometry, the scope of the effort included all aspects of the standard. Third, developments in lighting technology since the 1980s have made it more important to consider the benefits that a performance-oriented approach may offer in being flexible toward new technologies. Important examples of relevant technologies are new light sources for automotive applications and a variety of types of adaptive headlighting that may have the potential to provide safety benefits to the public. Fourth, the maturation of computer methods for photometry has made the objective measurement of vehicle-based photometric criteria more practical.

Identifying promising opportunities for a performance-oriented approach is often a complex process. We used several methods to identify and make initial evaluations of the many possibilities. The primary elements of our approach were: (1) establishing an outline of current requirements in FMVSS No. 108 that highlighted the relationships of those requirements to photometry and driver vision, (2) a review of current and likely future technology for vehicle lighting, (3) a review of current literature on vehicle lighting, and (4) consultation with industry and other experts through a series of meetings of the SAE Performance-Based Lighting Task Force. Throughout these activities, much of the analysis of new regulatory approaches—especially with regard to the photometric requirements in FMVSS No. 108—was guided by the following question: What desirable effects would it be possible and practical to achieve if requirements could be vehicle-based, that is, based on photometric values at relevant locations in three-dimensional space around a vehicle? Vehicle-based photometry offers a fundamental advantage over lamp-based photometry because the desired visual effects that a standard is intended to insure—such as visibility of distant objects or protection of drivers' eyes from glare—are directly affected by the illumination of certain positions in space, but are only indirectly related to the luminous intensity values of individual lamps. In recent years, with the maturation of computer methods for photometry and headlamp evaluation, there are no longer technical obstacles to vehicle-based photometry. It is now a well-established practice to measure intensity matrices for individual lamps with a traditional goniometer and combine those matrices in software. In this way, for example, the light output from a vehicle's complete headlighting system can be reliably and objectively predicted without the need to mount all of the individual lamps on the vehicle and directly measure their combined output.

Several promising opportunities for making FMVSS No. 108 more performance-oriented were more fully developed and evaluated. Those opportunities were in the following areas: (1) headlighting photometry, (2) headlamp test voltage, (3) sensitivity of headlamps to vertical aim, (4) luminance of signaling and marking lamps, (5) masking of front turn signals, and (6) reliability of photometric testing ("design to conform" versus "conform").

Major types of requirements for which we considered the feasibility of a performance-oriented approach, but for which there did not appear to be good opportunities, were: (1) physical tests (except for certain changes in the associated photometric performance requirements), and (2) the range of the angular locations of test points for signaling and marking functions (for which changes might be appropriate, but for which there is currently too little research evidence to make specific recommendations).

Although the new approaches discussed here cover signaling and marking functions as well as headlighting, headlighting accounts for a major portion of the possible changes that were evaluated. There are therefore two sections of this report dedicated to headlighting: one describing the development of photometric criteria for headlighting, and one describing the application of those criteria to a set of sample lamps. Another section of the report describes twelve areas in which we would expect substantial effects of the performance-oriented approach. Those areas, and the nature of the effects, are as follows:

1	Whole-vehicle testing	Vehicle-based criteria can be used; actual photometric procedures still involve candela matrices for individual lamps, combined in software
2	Headlamp test voltage	Probably not actual individual vehicle voltages, but possibly 13.2 V as a better single value to represent most vehicle voltages
3	Asymmetrical headlighting	Vehicle-based photometry allowing more asymmetry than the present standard, thereby allowing better tradeoff of seeing and glare

4	Headlamp mounting height	Implicit height limits based on realistic 3-D locations of test points
5	Light for retroreflective signs	Control of sign luminance incorporating the effect of observation angle
6	Adaptive frontlighting	Softened distinction between upper and lower beams; photometric limits based directly on road geometry, allowing incorporation of curvature
7	Preventing gaps in headlighting	Photometric limits based on combinations of many test points, grouped into zones, providing better coverage
8	Headlamp aim	Initial aim constrained by realistic 3-D locations of test points
9	Signal lamp luminance	Control of luminance based on actual lamp area rather than number of lighted sections
10	Front turn signal masking	Turn signal intensity requirements based on headlamp intensity at corresponding observer locations
11	Stray up light from headlamps	Control of stray up light based on the driver's field of view
12	Conform vs. design to conform	More predictable test methods involving partially redundant points, possibly allowing the elimination of the provision to design to conform

In several instances in this report, the expected effects of potential performance-oriented changes are illustrated by determining how they would apply to current lamps. Most of those results were obtained using software that was developed during the project. A current version of the software is available and may be useful as a supplement to this report, but it is not needed in order to understand the major elements of the performance-oriented approach described here. The type of photometric data necessary to make use of the software is also described in this report. Although the potential performance-oriented changes are largely vehicle-based—meaning that photometric tests are defined in terms of a vehicle as a whole rather than individual lamps—the most practical way to implement the performance-oriented elements described here is probably to obtain photometric data for individual lamps and to integrate the data using software.

Beyond the opportunities to make FMVSS No. 108 more performance-oriented that are described in this report, there are several areas that may offer additional opportunities but for which further research would be required: (1) changes in the range of angular test locations for signaling and marking functions, (2) the possibility of developing universal physical tests, and (3) the possibility of extending the performance-oriented headlighting requirements to adaptive headlighting systems. Also, many adjustments might be made in the specifics of the approaches described in this report. Prominent possibilities include: (1) revising the test points for headlighting photometry to provide better coverage of all portions of roadways, and (2) refining the combination rules used with those test points to establish the best balance between full coverage and ensuring that the test outcomes are not overly sensitive to small deviations from the photometric criteria. The performance-oriented headlighting photometry as described here was tested with a set of recent headlighting systems, and the results were reasonably favorable. However, perhaps the most valuable extension of this work would be to supplement that testing with a large number of current or proposed headlighting systems.

1 Introduction

Since it was first made effective in 1968, Federal Motor Vehicle Safety Standard (FMVSS) No. 108 has been, in comparison to some of the other FMVSS's, less performance oriented and in certain ways more focused on equipment. An example of this is that it explicitly defines and refers to specific forms of equipment, including a variety of types of sealed beam headlamps. The standard is also equipment oriented in that some of its provisions are based on implicit assumptions about the use of certain technologies. Such an assumption is involved in the way the standard controls the luminance of some signaling and marking lamps: by adjusting photometric intensity criteria on the basis of the number of lighted sections that make up a lamp. Number of lighted sections was originally used as a surrogate for lamp area, a relationship that is likely to be valid as long as one can assume that signal lamps will be designed using incandescent bulbs that are all within a certain range of light output (Flannagan, Sivak, & Traube, 1998). However, that relationship may not extend to lamps that use large numbers of sources, each with low individual light output, such as the LEDs that have been used in some recent signaling and marking lamps.

Perhaps the most important and pervasive equipment-based aspect of the standard has been the form of the photometric criteria that are used for most of the lighting functions that the standard covers. The criteria are defined in equipment-based terms, as light intensities for various angular locations relative to isolated lamps (e.g., a minimum intensity of 15,000 cd at 1.5° down and 2.0° right relative to the optical axis of a headlamp).[1] In order to describe the difference that a performance-oriented approach would make in this context it is important to note that the desired visual effects that the standard is intended to insure—such as visibility of distant objects or protection of drivers' eyes from glare—are directly affected by the illumination of certain positions in space, but are only indirectly related to the luminous intensity values of individual lamps. The performance-oriented approach would therefore favor specifying photometric criteria in vehicle-based terms, as illuminance values produced by an entire lighting system at certain positions relative to a vehicle (e.g., a minimum illuminance of 23 lux on a vertical surface at a position on the pavement 30 m in front of a vehicle and 1 m to the right of the vehicle center line).

Because lamp locations vary across vehicles, the current format for photometric criteria may reduce the level of actual performance that the standard can insure in the real world. The recent SAE information report SAE J2829 "Pedestrian visibility – Low beam optimization to

[1] A notable, although minor, exception to this is the treatment of license plate lamps, which must produce a minimum illuminance value at each of a set of points covering the location where a license plate is mounted.

reduce night-time fatalities" described the worldwide situation with regard to equipment-based versus vehicle-based photometric criteria for lower-beam headlighting as follows:

> It is clear that vehicle headlighting plays a significant role in the effort to reduce the pedestrian fatality rate but current legislation only addresses the minimum performance requirements of an individual headlamp (or a system in the case of the Adaptive Front-lighting System (AFS) introduced into ECE regulations). Other factors such as installation height, separation, aim and operating voltage actually influence the effectiveness of the headlamp performance in the real-world driving context. (SAE, 2009, p. 1)

These examples illustrate that it is often desirable, when possible and practical, to formulate a standard in performance-oriented terms. That approach allows the specification of overall performance levels without basing those levels on specific equipment. A standard can therefore be more closely aligned with the effects it is intended to achieve, and it may be less restrictive toward new technologies that might achieve the same effects in different ways. However, a major limitation in applying a performance-oriented approach is that comprehensive performance criteria may be so complex that they are difficult to measure objectively. As an extreme example, a performance-oriented criterion for headlighting might require that a vehicle be capable of being driven "safely" over a certain test course at night. Although it might in fact be possible to design such a criterion in a way that would provide a comprehensive assessment of the desired performance of a headlighting system, it might not be practical or even possible to objectively test a vehicle in that way. It is probably most useful to regard the distinction between the equipment-oriented and performance-oriented approaches as a continuum, on which all standards can be described as more or less performance-oriented. The goal of this project is to evaluate the feasibility of reformulating a substantial portion of the current requirements in FMVSS No. 108 in more performance-oriented terms while insuring that the criteria involved can be practically applied using objective measurements.

It is useful to consider the current effort in the context of a previous effort that was also intended to make FMVSS No. 108 more performance oriented. That effort began in the 1980s, leading to a notice of proposed rulemaking near the end of that decade (54 FR 20084, May 9, 1989). However, the rulemaking effort was terminated without changes having been made to the standard (60 FR 58038, November 24, 1995). The reasons for not revising the standard at that time were primarily (1) that the major increase in illumination required by the proposal was not available from headlighting systems of the time, (2) that the potential safety benefits of the increased illumination were not established, and (3) that "adaptive headlighting" was "not sufficiently developed for lighting and vehicle manufacturers to decide how the present lighting regulations help or hinder the application of these new lighting technologies ” (see 60 FR 58039, November 24, 1995).

The current effort is different from the previous one in several ways. Unlike the previous effort, there is no intention to fundamentally change the requirements for headlighting, or any other part of the current requirements. Instead, the purpose is to translate the current requirements into performance-oriented terms, inferring the intended effects of the requirements from the way they are currently formulated and leaving those effects unchanged. Also, the current effort is intended at least to review the potential for a more performance-oriented approach in all aspects of FMVSS No. 108, not just in lower-beam headlighting, which was the sole concern of the 1980s effort. As will be demonstrated later in this report, and perhaps not surprisingly, the changes that are considered most promising in the current effort are primarily in the area of lower-beam headlighting. However, that is not the result of a prior restriction in scope, and several of the changes are in fact outside of headlighting.

Another contrast between the current effort and the 1980s effort involves changes in lighting technology. Since the earlier effort, many advances have taken place in automotive lighting technology, and several major potential improvements are likely in the near future. New light sources have been introduced for headlighting and other functions (HID, LED); the transition from sealed beam to replaceable-bulb headlamps has been virtually complete; some forms of adaptive headlighting have been introduced in the U.S.; and more advanced forms of adaptive headlighting (“adaptive driving beams”), with promise to greatly improve the tradeoff between seeing and glare, are being developed in Europe (e.g., Enders, 2001). These differences between the current effort and the 1980s effort—both in terms of the scopes of the two projects and the states of lighting technology within which they were begun—suggest that the current effort is more promising.

However, perhaps the most important contrast with the 1980s effort is the maturation of computer methods for photometry and headlamp evaluation that has taken place since then. It is now a well-established practice to measure intensity matrices for individual lamps with a traditional goniometer and combine those matrices in software. In this way, for example, the light output from a vehicle’s complete headlighting system can be reliably and objectively predicted without the need to mount all of the individual lamps on the vehicle and directly measure their combined output.

Computer methods to combine the light output of multiple lamps—and to evaluate the resulting illumination in various ways—have been under development for several decades. A notable early step was the development and validation of computer methods at the University of Michigan to evaluate various concepts for a “midbeam” (i.e., a headlighting system that would be between lower-beam and upper-beam systems in terms of the tradeoff between seeing light and glare protection) (Mortimer & Becker, 1973, 1974). Shortly after that, Ford Motor Company developed the so-called CHESS system, which was designed to evaluate the driver visual performance that could be expected with a wide variety of possible headlighting systems, potentially made up of many individual lamps (Bhise et al., 1977). Work by Ichikoh expanded on the vision modeling used by Ford (Nakata, Ushida, & Takeda, 1990), and Ford applied similar computer methods in developing a system that was complementary to CHESS in that it was designed to evaluate headlighting in terms of consumer preferences rather than objective visual performance (O'Day et al., 1997). SAE recently published an information report that comprehensively reviewed possibilities for optimizing lower-beam lighting patterns, with emphasis on increasing pedestrian visibility (SAE, 2009). The analyses of headlighting systems in that report were heavily based on software methods for combining and evaluating photometric data (Kosmatka & Rattunde, 2005).

The availability and maturity of computer methods for photometry provides several potentially useful options for the format of photometric criteria. Perhaps most importantly, the ability to combine the output of multiple lamps allows the objective measurement of vehicle-based criteria without requiring that those measurements actually be made on an entire vehicle, with all lamps operating simultaneously. Whole-vehicle testing could be used for vehicle-based criteria whenever it was considered practical, but computer methods would probably always offer a much simpler and more practical alternative.

Furthermore, the efficiency of computer methods may allow photometric criteria to be specified in ways that make them both more comprehensive and more robust. Traditional testing has involved using a goniometer to measure light intensity at a limited number of points (typically in the range of 10 to 20 points, and perhaps involving scans of lines and zones). In contrast, with computer methods, it is common to characterize the light output of a lamp comprehensively by measuring the intensity of the lamp at an extensive matrix of points, specified in two-dimensional angular terms and spaced appropriately for the intensity gradients involved. Software interpolation can then be used to determine the corresponding illuminance value for any point within that angular matrix at any distance from the lamp. The resulting value can be combined in software with other calculated illuminance values for the same point in space produced by additional lamps.

Computer methods therefore make it practical to use a number of test points that is potentially much larger than has been traditional. Current criteria tend to involve, for example, isolated photometric minima that are expected to insure adequate light across a broad area because the photometric gradients between the points are assumed to be smooth. With computer methods, it may be preferable to use a much larger number of points, spaced more finely, and define the critical tests not in terms of whether a value is met at each individual point, but in terms of summaries over groups of points. This approach may allow the outcomes of photometric tests to be more closely aligned with the visual functions that lighting systems are expected to support, and at the same time make the tests less sensitive to incidental deviations at individual points that may be less important for overall visual performance.

Early in the current project, in April 2007, the members of the SAE Performance-Based Lighting Task Force were asked their opinions about several issues related to this effort and the 1980s effort. Their answers provide a simple snapshot of expert opinion at the time. The most basic questions they were asked were the following three (with all answers to be given as ratings on scales from 1 to 10):

1. How desirable or feasible would it be to reformulate FMVSS No. 108 in performance-based terms?
2. How much do you remember or know about the effort to produce a performance-based version of FMVSS No. 108 that was conducted in the 1980s?
3. Have circumstances changed in the last 20 years to make a performance-based version of FMVSS No. 108 more desirable or feasible?

As shown in Figure 1, the group was strongly positive about the overall feasibility of updating the standard to make it more performance-oriented. As shown in Figure 2, this group of lighting experts in 2007 included many who were, by self-report, quite unfamiliar with the 1980s effort. Figure 3 shows responses to the question about changes that might favor the feasibility of a new effort to modify FMVSS No. 108, indicating that most task force members believed that changes had made the situation more favorable. Interestingly, many of those who believed that changes had made the situation more favorable also indicated that they were not themselves very familiar with the previous effort. However, that is not necessarily inconsistent, since their judgments about changes could be based on general experience with vehicle lighting, without specific knowledge of previous attempts to revise the standard.

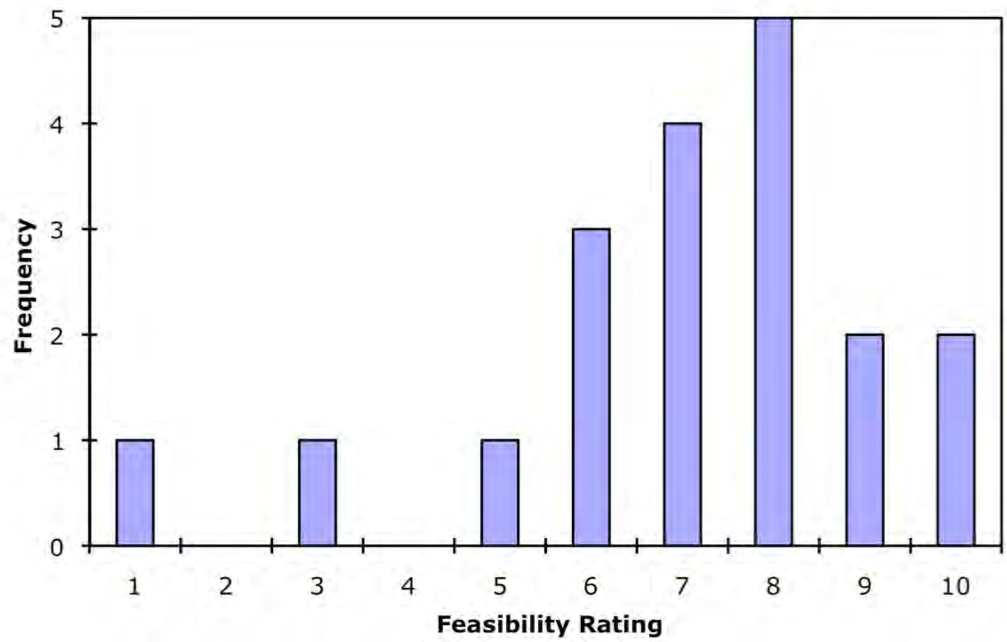

Figure 1. Responses to the question about feasibility of reformulating FMVSS No. 108 (1 = not at all, 10 = very much).

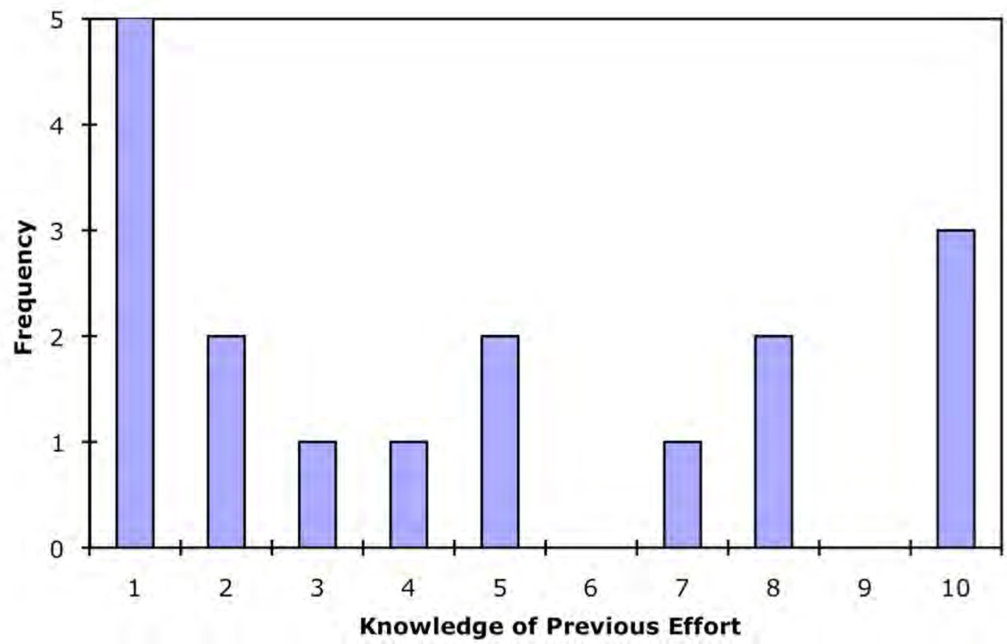

Figure 2. Responses to the question about personal knowledge of the previous effort (1 = very little, 10 = very much).

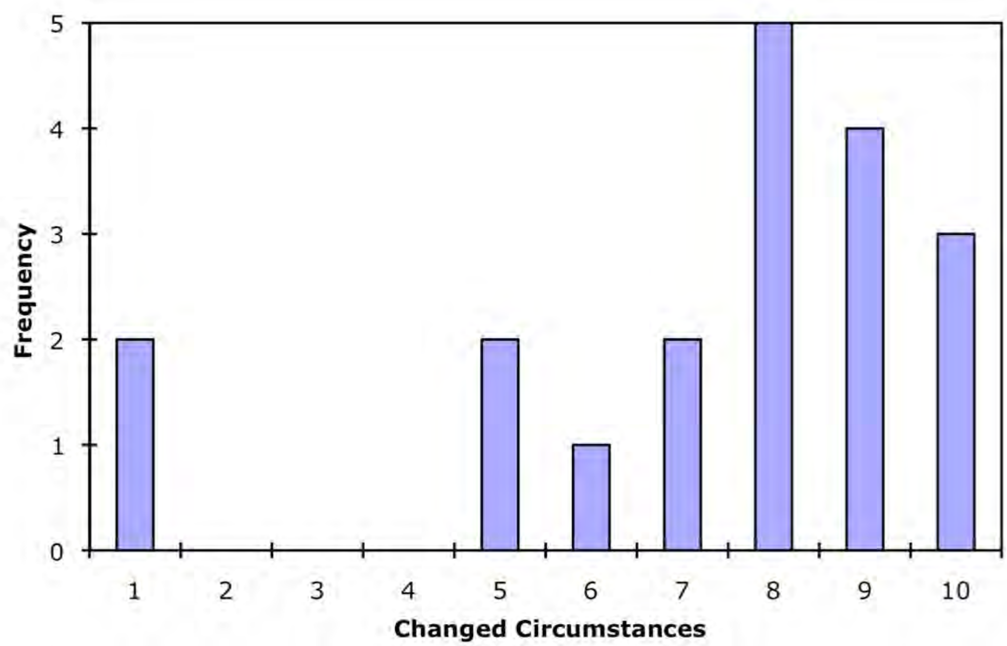

Figure 3. Responses to the question about changes favoring the feasibility of reformulating FMVSS No. 108 (1 = not at all, 10 = very much).

This report presents and evaluates the feasibility of several performance-oriented approaches for the requirements currently in FMVSS No. 108, including both headlighting requirements and requirements for signaling and marking functions. The major differences in the new approaches with regard to headlighting involve changes from lamp-based photometry to vehicle-based photometry. Therefore, to a large extent, the performance-based elements of the approach could also be referred to as “vehicle-based” elements. In addition to being open to virtually any new lighting technology, these changes may offer better control of most of the basic functions of headlighting: seeing light on the road, control of glare, and lighting for overhead signs. The format of the new headlighting requirements is also compatible with many new approaches to adaptive headlighting, including current proposals for “adaptive driving beams” that would virtually eliminate the traditional distinction between lower-beam and upper-beam lamps (e.g., Dreier & Rosenhan, 2009; Schmidt, Kalze, & Irmscher, 2009).

Although the new approaches cover signaling and marking functions as well as headlighting, headlighting accounts for a major portion of the potential changes evaluated here. There are therefore two sections of the report dedicated especially to headlighting: one describing the development of the new requirements for headlighting, and one describing the application of those requirements to a set of sample lamps. Another major section of the report is organized around 12 areas in which we would expect substantial effects of a performance-oriented approach. Most of the effects concern lower-beam headlighting, but there are also items on signaling and marking functions. As we describe the expected effects of the performance-oriented system, we explain the rationales for the various decisions that we have made and for the approaches that we have adopted in developing the system.

Illustrative photometric values for the approach described in this report are presented in tables in the Appendix, and are implemented in software that is briefly described in a later section of the report. For some very specific purposes, it may be helpful to review the documentation for that software or even to run the software, but it should not be necessary to gain an understanding of the most important aspects of the performance-oriented system.

2 Selection of opportunities for performance-oriented changes

Identifying opportunities for application of a performance-oriented approach among the many requirements of FMVSS No. 108 is necessarily a complex process. We used several methods to identify and make initial evaluations of the many possibilities. The primary elements of our approach were: (1) establishing an outline of current requirements in FMVSS No. 108 that highlighted the relationships of those requirements to photometry and driver vision, (2) a review of current and likely future technology for vehicle lighting, (3) a review of current literature on vehicle lighting, and (4) consultation with industry and other experts through a series of meetings of the SAE Performance-Based Lighting Task Force.

Also, throughout all of these activities, we emphasized possible vehicle-based solutions, i.e., solutions in which some advantage could be gained by applying requirements to the entire vehicle rather than to components. Therefore, much of the analysis of possible performance-oriented opportunities—especially with regard to the photometric requirements in FMVSS No. 108—was guided by the following question: What desirable effects would it be possible and practical to achieve if requirements could be based on photometric values at relevant locations in three-dimensional space around a vehicle? That question leads to the heuristic device of formulating all photometric requirements so that they could, at least in principle, be applied by testing an entire vehicle in a simple, large light-controlled room with photometers in all appropriate test locations. As further discussed in section 5.1 of this report, we regard the idea of such a facility more as a way to envision the effects of the system than as a practical approach to photometry. More conventional goniometric measurements, combined in software, probably offer a better practical approach. However, the vehicle-based photometry that we present could in fact be performed on whole vehicles in such a facility if that approach proved to be useful.[2]

A schematic outline of the factors addressed by requirements in FMVSS No. 108 is shown in Figure 4. This figure emphasizes the distinction between two broad areas that the requirements address: (1) the vehicular and environmental factors that can affect the efficiency of lamps and other devices (represented on the left), and (2) the desired visual functions served by the lamps and other devices (represented on the right). The vehicular and environmental factors are addressed primarily by the physical requirements in the standard, whereas the visual functions are most directly addressed by photometric requirements and closely related requirements having to do with location or size. Figure 4 distinguishes among the visual functions in terms of the variables that affect them, and which therefore may be appropriate to take into account in FMVSS No. 108.

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[2] A practical precedent for such testing is the testing of emergency-vehicle lighting in SAE J2498 "Minimum performance of the warning light system used on emergency vehicles" (SAE, 2004).

For characterizing effects on driver vision, illumination of diffusely reflecting surfaces (e.g., by headlamps, backup lamps, and license plate lamps) is most directly evaluated by total illuminance for relevant surface locations and orientations. Combining effects of multiple headlamps, for example, may make sense for such functions. In contrast, illumination of retroreflective surfaces can and perhaps should also involve the locations of light sources, illuminated objects, and the driver's eyes. Those locations determine the various angles that can affect retroreflective appearance, of which at least observation angle is probably important to take into account. For signaling and marking functions, various characteristics of the images presented to a driver's eyes may matter. Primarily, those characteristics are the intensities of the devices involved. However, because signaling and marking functions involve images as seen by a driver, other characteristics (area or luminance) may matter as well. This differs, for example, from the situation for the illumination function of headlamps, where the image of the source or sources does not matter. (However, note that headlamps also can serve a marking function by indicating the width of a vehicle, in which case more characteristics of the images of the sources may be worth taking into account.)

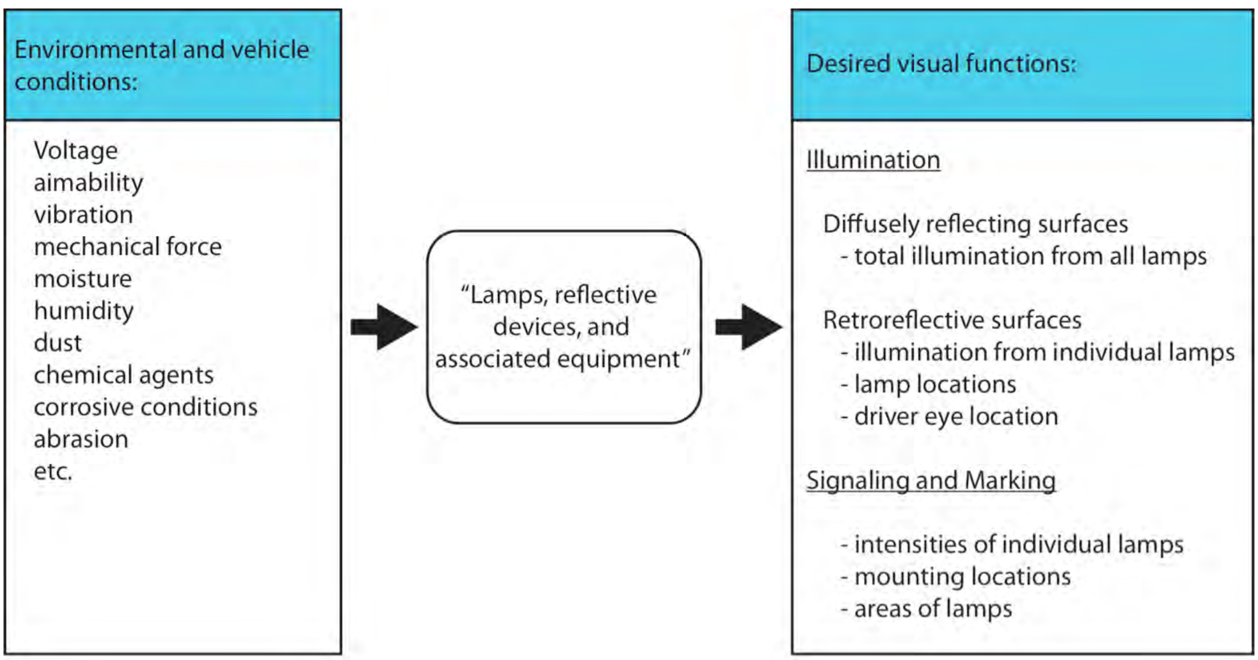

Figure 4. Schematic outline of the factors addressed by requirements in FMVSS No. 108.

Table 1 provides a summary of the current and future lighting technologies that we identified as possibly raising issues for FMVSS No. 108. Perhaps of most interest are the various forms of adaptive forward lighting systems that are either already in use or are being considered for the near future (e.g., Dreier & Rosenhan, 2009; Schmidt, Kalze, & Irmscher, 2009). These concepts are particularly interesting from a vehicle-based perspective because they may be able to offer much finer control of where light is directed, meaning that the approximations that have allowed photometry to be specified for isolated headlamps—thus neglecting the actual locations of lamps on vehicles—may be less desirable.

Table 1. Technologies that may raise issues relevant to FMVSS No. 108

Technology	Issues relevant to FMVSS No. 108
LED illuminating lamps	Spectral effects on glare Spectral effects on color rendering Sensitivity to heat Definition of failure Detection of partial failure Visual effects of many sources (“beam contributors”)
LED signaling and marking lamps	Sensitivity to heat Effective lamp size for visual purposes Definition of failure Detection of partial failure May encourage adaptive signal lighting May encourage novel geometries
Adaptive forward lighting systems (AFS), including adaptive driving beams (ADB)	Benefits to visibility Effects on glare Novel failure modes
Adaptive signal lighting	Possible benefits of more information Need to avoid uncoordinated proliferation of new signals
Novel signaling and marking geometries	Possible masking (especially turn signal masked by headlamp) Roles of intensity and luminance with very large, small, or unusually shaped lamps

The team involved in this project was reasonably familiar with the current literature on vehicle lighting, especially considering the involvement of the SAE Performance-Based Lighting Task Force. However, we also conducted a survey of relevant literature specifically for the purposes of the project, concentrating on the collections of papers on automotive lighting from the SAE Congress meetings in Detroit, MI from 2005 through 2008, and from the International Symposium on Automotive Lighting (ISAL) meetings in Darmstadt, Germany in 2005 and 2007 (Flannagan, Jiao, & Karbowski, 2007; Flannagan, Jiao, & Karbowski, 2008; Jiao, & Flannagan, 2005; Jiao, Flannagan, Karbowski, & Lynam, 2006; Khanh, 2007; Schlaak, 2005).

Several opportunities for making FMVSS No. 108 more performance-oriented were identified and then more fully developed and evaluated. Those opportunities were in the following areas: (1) headlighting photometry, (2) headlamp test voltage, (3) sensitivity of headlamps to vertical aim, (4) luminance of signaling and marking lamps, (5) masking of front turn signals, and (6) reliability of photometric testing (design to conform).

Major types of requirements for which we considered the possibility of using a performance-oriented approach, but for which there did not appear to be good opportunities, were: (1) the vertical and horizontal ranges of angular locations of test points for signaling and marking functions (for which changes might be appropriate, but for which there is too little research evidence to make specific recommendations), and (2) physical tests (except that performance-oriented photometric changes would apply to the photometric performance requirements of some physical tests). An analysis of possible performance-oriented approaches to the ranges of signaling and marking test points is presented in section 6 of this report.

The physical tests as a class did not appear to offer good opportunities, primarily because they are already tied very closely and appropriately to certain technologies (e.g., the abrasion issue for plastic versus glass lenses for headlamps). Most importantly, the distinctions among various types of headlamps (sealed beam, replaceable bulb, integral beam, and combination lamps) have been retained. That was done because the application of the various physical tests is tied to those four lamp types. It would be possible to reformulate the way these tests apply without reference to the four lamp types, but it would not likely reduce the complexity of describing the way the tests apply, and it would not reduce the actual complexity of the tests. For example, the rationale for applying abrasion testing for plastic lenses and not for glass lenses is reasonably clear and well accepted.

We have therefore not evaluated the feasibility of changing the current state of affairs, in which physical tests are applied based on specific characteristics of certain technologies. This means that continuing review and decision making would be required to adapt FMVSS No. 108 to possible changes in technology. Ultimately, it might be beneficial to develop a universal set of environmental tests based solely on the real-world conditions that lamps are likely to be operated in. For example, the heat conditions of mounting locations in and around the engine compartments of gasoline-powered or electrically powered vehicles could be described. However, there is currently little formal work to support such an effort. Furthermore, it is not clear, in the absence of such work, that the approach could be taken in a way that would reliably foresee all the circumstances that might have effects of future lighting technologies. For example, the heat sensitivity of LED sources is different enough from the heat sensitivity of filament sources that an attempt to design a "universal" set of physical tests before the actual use of LEDs in vehicle lighting might have missed the conditions that are important for LEDs.

However, through the SAE or other groups it might be useful to explore the possibility of working toward a set of environmental tests that would be, if not actually universal, perhaps organized on the basis of relatively general principles that could serve as guidelines for specific decisions about what and how to test.

3 Development of performance-oriented headlighting criteria

The performance-oriented photometric limits for headlighting that are evaluated in this report were derived from the current values in FMVSS No. 108, using rationales that are described in this section in enough detail to allow a reader to follow all of the significant steps. Our goal was to allow a reader to understand the overall strengths and weaknesses of the approach, but also to be able to follow the trail of photometric values from the current version of FMVSS No. 108 to the performance-oriented version. In certain cases, the translation of requirements was rather direct, while in other cases it involved relatively elaborate chains of reasoning. The full specifics of an illustrative set of performance-oriented photometric values are presented as tables in the Appendix. In this section, we describe the derivation of those values at a level of detail that is intended to be complete in itself, although the specific values in the Appendix may be helpful as a supplement to the step-by-step derivations.

The development of the headlighting criteria was based on three principles: (1) to follow as closely as possible the current photometric values in FVMSS No. 108, while (2) specifying test points relative to the vehicle rather than to individual lamps, and (3) taking advantage of computer methods for measuring photometry. As described in the Introduction, computer methods for vehicle photometry are now mature enough to allow vehicle-based photometric values to be measured objectively and reliably without the need to make actual measurements on an entire vehicle. Goniometer measurements for individual lamps, combined in software, can now provide measurement and evaluation of complete lighting systems (e.g., SAE, 2009). One consequence of this is that it can be practical to use photometric criteria that involve much larger numbers of test locations than has been traditional. Rather than requiring a certain photometric value at a single test location, it may be preferable to evaluate summary photometric values over large numbers of locations. Properly applied, this approach promises to make photometric criteria both more comprehensive and less sensitive to incidental deviations at individual test points. The photometric criteria described here involve hundreds of test locations, each potentially illuminated by several lamps, with a smaller number of critical tests that can be based on goniometer measurements of individual lamps that are interpolated and combined in software.

We first describe the derivation of requirements for the lower-beam headlighting function. This function is embodied primarily in Table II of the Appendix. The various lower-beam functions that are covered, along with the corresponding groups of points in Table II, are summarized here in Table 2. The next section covers general aspects of how we translated current photometric requirements into vehicle-based form, and subsequent sections describe the derivation of test points for each lower-beam function in turn.

Table 2. The lower-beam functions and corresponding test points in Table II of the Appendix.

Function[1]	Groups of points[2]	Number of points
Seeing light (below horizontal)	1 through 10	150
Glare control (below horizontal)	11 and 12	30
Glare control (oncoming drivers)	13 through 16	36
Glare control (preceding drivers)	17 through 24	72
Retroreflective sign lighting	25 through 31	42
Light above the traditional pattern (4-10 degrees up)	32	462
Stray up-light control (above 10 degrees)	33	1,428
Total		2,220

[1] Signaling vehicle presence could be included in this list as an additional lower-beam function, although it has not traditionally been tied to photometric test locations as closely as the functions that are included here. For details of how the lower-beam presence function is treated in the current document, please see Table 6 and the surrounding text.

[2] For each group of test points from 1 to 31, the outcome is determined by dividing the photometric value at each point by the requirement for that point and averaging the resulting ratio over all points in the group. For minima, the result must be greater than 1. For maxima, the result must be less than 1. In order to be in overall agreement with the performance-oriented system, all group results must be as required. For Groups 32 and 33, each individual point must be below the maximum.

3.1 Translating photometric requirements: General approach

The current test locations for lower-beam photometry (specifically, for Table XIX-a, lower beam pattern LB2V of FMVSS No. 108) are illustrated here in Figure 5, along with a representation of a typical roadway showing approximately where the test points and lines fall. The roadway is straight and level, and the lanes are 3.66 m [12 feet] wide. The point of view for the projection of the roadway is at the center of one lane (which could also be thought of as the midline of a vehicle centered in that lane), and at a typical headlamp mounting height (0.62 m). Thus, in terms of the approximation that is at the heart of the current lamp-based system of photometric testing, Figure 5 represents reasonably well the correspondence between the various test locations and the parts of the roadway at which they control illumination.

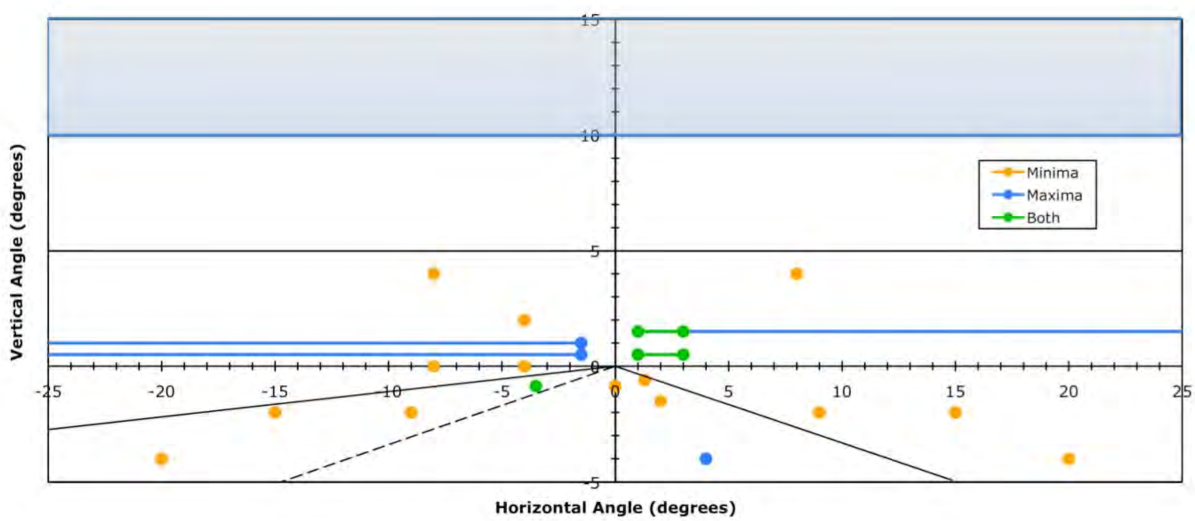

Figure 5. Photometric test locations in the current FMVSS No. 108 for lower-beam headlamps (from Table XIX-a, lower beam pattern LB2V), superimposed on a schematic roadway.

Currently, there are multiple photometric tables for headlamps in FMVSS No. 108. In addition to the variety of requirements that has grown up over the years, all photometric requirements now appear in two different formats, in the versions of the standard prior to and after the editorial rewrite (72 FR 68234, December 4, 2007). The performance-oriented photometry was developed using Table XIX-a, lower beam pattern LB2V.[3] The principles by which we made this selection were: (1) to adopt the photometric improvements for lower-beam performance that were introduced in connection with visual-optical aiming (Van Iderstine, 1997) and which had partly been developed through an extensive review of headlighting needs (Sivak, Helmers, Owens, & Flannagan, 1992; Sivak & Flannagan, 1993), (2) to use the newest of the differing requirements for upper-beam performance, and (3) to use a set of values for two-lamp rather than four-lamp systems.

The rationale for using requirements for two-lamp systems is that the performance-oriented approach naturally avoids the need to provide for possible interactions among lamps, as is done in the requirements for four-lamp systems. Unlike the current approach in FMVSS No. 108, which must provide test values for individual lamps in an attempt to control certain levels of overall system performance, the performance-oriented approach can directly establish photometric requirements for system performance independent of the number of lamps involved.

[3] This table is in the version of the standard published in the 2007 final rule, which is effective on December 1, 2012.

Perhaps the first step in translating the current photometric requirements to a vehicle-based system would be simply to double the current photometric values (which are for single lamps) and determine the positions in space around the vehicle (in three-dimensional rectangular coordinates) corresponding to the angular coordinates used in the lamp-based system. That is done in Figure 6, for the 10 current photometric minima below horizontal, which correspond to the first function listed in Table 2: *Seeing light (below horizontal).* The two-dimensional spatial locations corresponding to the photometric test angles are shown in a bird's-eye view of a straight, level roadway five lanes wide and 70 m long. The values shown in red boxes in the figure are illuminance values (in lux) for a two-lamp system that correspond to the intensity values (in candela) currently specified in FMVSS No. 108. For each point, the illuminance values are calculated by doubling the intensity values in FMVSS No. 108 and taking into account the distances involved. For example, there is currently a minimum of 15,000 cd required at 1.5 degrees down, 2.0 degrees right (relative to the axis of the headlamp). From an imaginary headlamp on the midline of a vehicle, 0.62 m above the road surface, this projects to the point shown between 20 and 30 m on the roadway. The distance from the lamp to the point on the road surface is 23.68 m, so the lux value is: 2 x 15,000 cd / $(23.68\ \text{m})^2$ = 53.5 lux (as shown in the figure).

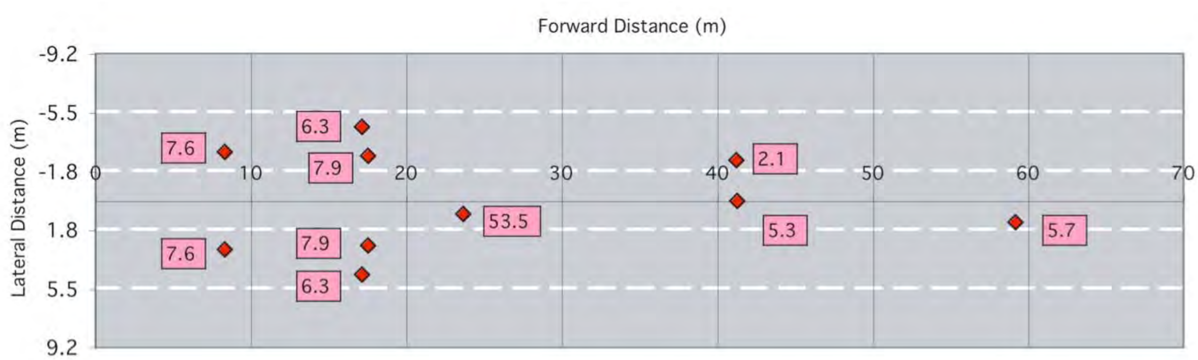

Figure 6. Photometric minima below horizontal for lower-beam headlamps in the current FMVSS No. 108 (Table XIX-a, lower beam pattern LB2V) projected onto a flat, level road surface, with corresponding lux values for a two-headlamp system. Vehicle location—defined by the forwardmost point on the vehicle midline—is 0,0 at the left of the figure.

However, the representation in Figure 6 is simplified in an important way. It does not take into account realistic ranges for the vertical and horizontal positions of headlamps. In order to translate faithfully the intent of the photometric values currently in FMVSS No. 108, it is best to use information about headlamp mounting positions prevalent at the time that the photometric values were determined. Some of the photometric values in FMVSS No. 108 are quite old, and appeared in the first Notice of Proposed Rule Making for the standard (Initial Federal Motor Vehicle Safety Standards, 1966). For example, the minimum value of 15,000 cd at 1.5D-2R was already well established in the SAE document referred to in that notice (SAE, 1965). However, it is probably misleading to think of the current values in FMVSS No. 108 as intended only for vehicle and driving conditions in the relatively distant past, at about the time that the standard itself was first established. It is arguably more appropriate to consider them in the context of the conditions that prevailed at the time of the most recent major revisions of the standard. The rationale for this is that the judgment that went into those revisions was ostensibly based on all of the information available at the time about how the photometric values fit the then-current circumstances.

The most recent major revisions of the photometric values in FMVSS No. 108 for lower-beam headlighting were made in conjunction with the introduction of visual-optical aiming in 1997 (Van Iderstine, 1997). Those changes were studied and evaluated during a series of meetings in 1995 and 1996, and much of the research that determined the major new test points was performed in the early 1990s for a project on international harmonization of lower-beam photometry (Sivak & Flannagan, 1994). The locations of the photometric test points that were added, modified, or explicitly reviewed as part of the introduction of visual-optical aiming are shown in Figure 7. All of the most critical test locations are included in that set. It therefore seems best to use information from the mid 1990s to derive the appropriate influences of the photometric limits in FMVSS No. 108, at least with regard to lower-beam headlighting. For example, we have used information about the locations of drivers' eyes and the mounting positions of headlamps from a survey that included passenger cars and light trucks and vans (LTVs) of the 1996 model year (Sivak, Flannagan, Budnik, Flannagan, & Kojima, 1996). That survey does not represent the entire fleet that was in use at the time (which would have also included vehicles manufactured several years earlier), but it provides good information about vehicles from one relevant model year, and those vehicles are probably not very different from slightly older vehicles. Also, it is a particularly good representation of vehicles that were being manufactured at the time that the changes in FMVSS No. 108 were introduced, and which therefore would be the vehicles to which the changes would first apply.

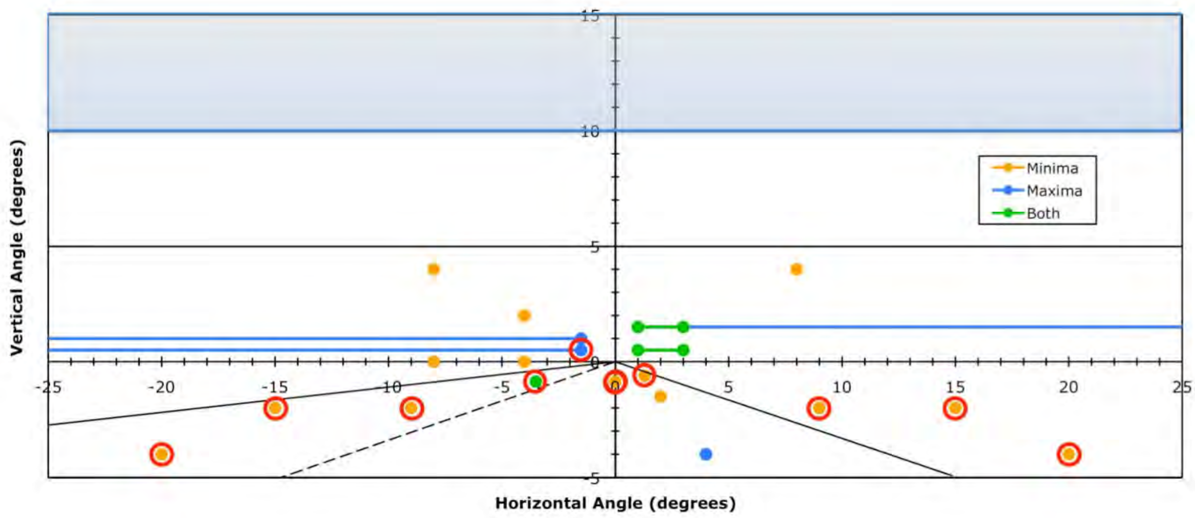

Figure 7. Photometric test locations in the current FMVSS No. 108 for lower-beam headlamps (from Table XIX-a, lower beam pattern LB2V), superimposed on a schematic roadway. Points with red circles were added, modified, or seriously reviewed during the development of visual-optical aiming in 1995-1996.

Headlamp location is taken into account in Figure 8, which is very similar to Figure 5. As in Figure 5, the view is in terms of angles from the perspective of an imaginary headlamp on the midline of a vehicle. But now the points represent not only how each angular test location would project from the observer's point of view, but also how those locations would appear (to the central observer) when projected from a realistic range of headlamp locations. Thus, each point is now a cross. (Each configuration of points in Figure 8 has a fifth point just below the central point, although the separation is not large enough to make that point clearly distinct for all of the configurations in the figure.) In each cross, the upper, lower, right, and left points were generated by locating the headlamp at a set of four positions, based on typical vehicle geometries (Sivak et al., 1996). The headlamps were located left and right of the vehicle centerline by the average of lateral separation for LTVs plus 2.0 standard deviations (resulting in positions 0.83 m left and right). They were also located vertically at the average height of a headlamp on an LTV plus 2.0 standard deviations (0.99 m), and at the average height of a headlamp on a passenger car minus 2.0 standard deviations (0.58 m). The connected configurations of points in Figure 8 thus approximately represent the spatial extents of photometric control corresponding to each angular test location in FMVSS No. 108, as those extents would appear in angular terms when viewed from a central location on a vehicle.

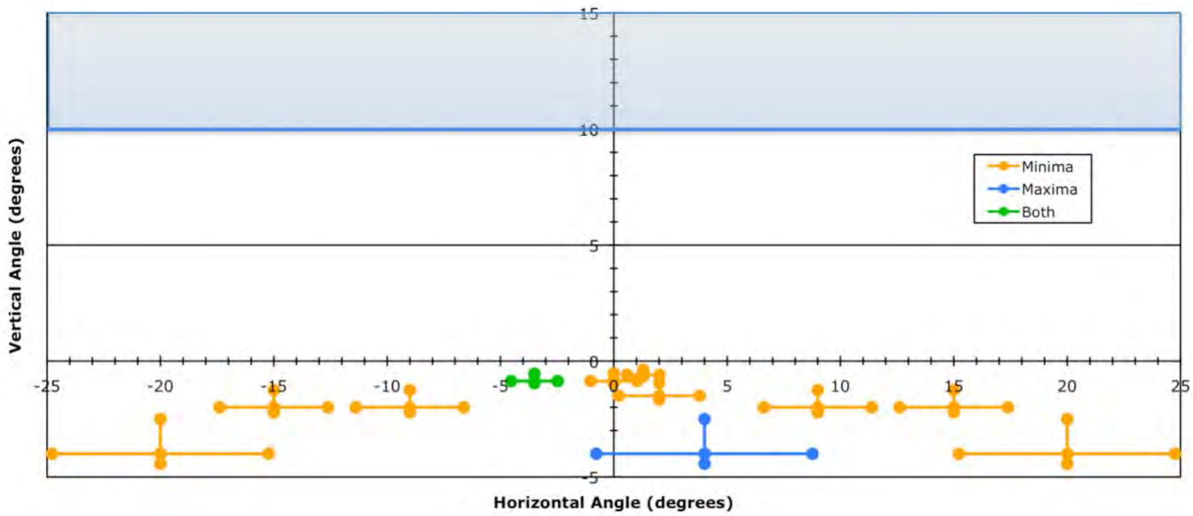

Figure 8. Projection of lower-beam test points below horizontal onto pavement, showing the spread associated with the two headlamp positions within vehicles and variation in mounting height across vehicles.

As indicated in a footnote at the end of Table II in the Appendix, most of the groups of points that we derive in the following sections are meant to be applied to headlighting systems at the level of the group. For example, for a group of 15 points there will be 15 values involved in testing (the ratios of actual headlighting output at each point to an individual photometric criterion for each point), but those ratios are averaged over all 15 points to determine whether a headlighting system meets a certain requirement. Thus, a system might fail to meet several points but those failures might be made up at other points within the same group. Only if a headlighting system does not meet an average group criterion is it considered not to meet requirements of the performance-oriented system overall. In all cases, points are grouped by similarity of function and, usually, by spatial contiguity. For the groups in the next section, the points are grouped by the test locations in the current standard from which they were derived. For glare above horizontal, the grouping is by distance from the glare source. For retroreflective sign light, the points are grouped by sign location in horizontal and vertical dimensions (i.e., a single sign viewed at varying distances by an approaching vehicle forms a group).

3.2 Translating requirements concerning seeing and glare below horizontal

In order to generate sets of roadway points corresponding to the current angular locations below horizontal in FMVSS No. 108, we used the ranges shown in Figure 8, generating several values within each range. For lateral location, we used the extreme left and right values depicted in Figure 8 and three equally spaced intermediate points: -0.830, -0.415, 0.000, 0.415, 0.830 m (using negative values to indicate lateral locations to the left of the vehicle midline). For vertical location, we used the extreme high and low lamp-height values depicted in Figure 8 and one midpoint value: 0.990, 0.785, 0.580 m (all heights above ground). Each point below horizontal in Table XIX-a, lower beam pattern LB2V of FMVSS No. 108 (including two points below horizontal with maxima, representing the second function listed in Table 2) became a group of 15 points in Table II of the Appendix. For example, the minimum at 1.5 degrees down, 2.0 degrees right corresponds to Group 4.

In order to determine illuminance values for an entire headlighting system corresponding to the intensity values for single lamps that are currently in FMVSS No. 108, we first doubled the current values and took into account distances, as was illustrated in Figure 6. However, it would be unrealistic to expect that a headlighting system spanning most of the front of a vehicle would distribute light in the same way as a single lamp. Consider the ranges of points shown in Figure 8. For each configuration of points, the left headlamp on a vehicle could be expected to meet the minimum requirement for a single lamp at the left side of each set of connected points, and the right headlamp could be expected to meet the minimum for a single lamp at the right side. But, at least with regard to the influence of the minimum requirements of a single test point, one would expect that light levels at adjacent locations in the beam pattern would be somewhat lower. (The influence of multiple angular test points, and the overall gradients that are typically seen in headlamps, can also be incorporated, but they are not used in the current analysis.) Thus, the middle of each configuration in Figure 8 could in principle receive less light from a compliant two-lamp system than the points at either side, and no point would be expected to receive as much as twice the minimum light expected from a single lamp.

The spatial extents for test points shown in Figure 8, along with information about typical gradients in headlamp beam patterns, can be used to develop predictions about the light from a typical headlighting system composed of a pair of lamps. We used information about headlamp gradients from a recent survey of U.S. headlamps (Schoettle, Sivak, Flannagan, & Kosmatka, 2004), and estimated that the average illuminance value expected for the output of a two-lamp system over ranges such as those shown in Figure 8 would be about 70% of twice the minimum for a single lamp. There are many ways to derive such a value, and we consider 70% provisional, we believe it is probably very close to most alternatives. Using the value of 70%, the requirement for average light over one of the spatial ranges shown in Figure 8 is then derived by doubling the single-lamp values and multiplying by 0.70. For example, consider the illuminance limits for the middle five points in Group 4 (23.368 lux), and recall the illuminance value corresponding to Group 4 (for the current test point at 1.5 degrees down, 2.0 degrees right) that was derived above for a mounting height of 0.62 m (53.5 lux). Because a range of mounting heights (0.990, 0.785, 0.580 m) was used in deriving the full set of photometric values, adjustments were made for the differences in distances to the pavement points corresponding to each mounting height. For example, the middle five points in Group 4 all correspond to a mounting height of 0.785 m. The adjustment for mounting height applied to the illuminance value for the 0.62 m height is therefore: 53.5 lux x $(0.620/0.785)^2$ = 33.4 lux (appropriate because the ratio of distances to the pavement points from the different mounting heights is equal to the ratio of mounting heights themselves). The system illuminance values in the Appendix were derived (within rounding error) using the factor of 0.70: 33.4 lux x 0.70 = 23.4 lux (the actual corresponding value from the Appendix is 23.368 lux). (The other ten points in Group 4 have different illuminance criteria because they represent a range of mounting heights, and some are therefore closer and some further away from the vehicle than the middle five points.)

3.3 Translating requirements concerning glare to oncoming drivers

Turning to the third function listed in Table 2, we now must consider points that are above the road surface, specifically the eyes of oncoming drivers who may be subject to headlamp glare. In order to represent the typical locations of oncoming drivers' eyes, we again used data for vehicles of the mid 1990s (Sivak et al., 1996). We considered drivers at the average eye height for passenger cars (1.11 m) and at 2.0 standard deviations above and below average (1.15 and 1.07 m). To estimate a mean lateral separation of the oncoming drivers' eyes from the midline of a glare vehicle, we used a lane width of 3.66 m [12 feet] and a lateral separation of a driver's eyes from the vehicle midline of 0.35 m (left of the midline, laterally closer to oncoming glare sources), yielding a mean lateral separation of: 3.66 m – 0.35 m = 3.31 m. For variability in lateral positions, we used an estimate of 0.29 m for the standard deviation of vehicle lateral position from a set of naturalistic driving data (LeBlanc, Sayer, Winkler, Ervin, Bogard, Devonshire et al., 2006, p. 8-13). Assuming equal and independent variability in the lateral positions of both vehicles in an oncoming encounter, the variances of the lateral positions of the individual vehicles will be additive and the standard deviation of the difference in lateral position between the two vehicles will be: $(2 \text{ x } (0.29 \text{ m})^2)^{0.5}$ = 0.41 m. For lateral locations of glare targets, we used values of ± 2 standard deviations in lateral position as well as mean lateral position: 2.49, 3.31, 4.13 m. For longitudinal vehicle separations, we used four values from a minimum separation of 15 m to a maximum separation of 120 m: 15, 30, 60, 120 m.

As with the points below horizontal that were described earlier, we used several intermediate values of these variables to produce a set of spatial locations, as shown in Table II of the Appendix, Groups 13 through 16. For photometric limits, we used procedures very similar to those described for the points below horizontal, except that, instead of using the ground as the surface on which to project the angular specifications of photometric test points, we used imaginary planes at typical driver eye heights (at the mean height of 1.11 m, and 2.0 standard deviations up and down, yielding heights of 1.15 and 1.07 m). We derived lux values corresponding to where the eye-height plane was intersected by the rightmost points of the glare-control lines shown in the upper left quadrant of Figure 5 (0.5 degrees up, 1.5 degrees left: 0.634 lux; 1.0 degrees up, 1.5 degrees left: 1.776 lux). The value of 0.634 lux results from the current FMVSS No. 108 intensity limit at 0.5 degrees up (1,000 cd) and the distance from a headlamp at an average mounting height (0.62 m) to the intersection of the 0.5-up plane with the track of an oncoming driver's eyes at a height of 1.11 m. That distance is 56.2 m. Doubling the intensity value for a pair of headlamps, and converting to illuminance at the given distance yields: (2 x 1,000 cd)/(56.2 m)^2 = 0.63 lux. Similarly, the intensity and distance for the line at 1.0 degrees up yield: (2 x 700 cd)/(28.1 m)^2 = 1.77 lux. (Both of the lux values derived here are within rounding error of the actual values as they appear in the Appendix.)

Both of these illuminance values (0.634 and 1.776 lux) are therefore limits on glare in terms of lux at the eye of a driver that are implicit in the current version of FMVSS No. 108. Interestingly, they are not the same. This is reasonable given the geometry of an approach on a straight and level road and the resulting angles at which the glare source will be seen by the oncoming driver. Glare from the lamp at 0.5 degrees up will strike the eyes of an oncoming driver at a greater distance than glare from the same lamp at 1.0 degrees up. As a consequence, the glare source will be seen by the oncoming driver at a smaller angle relative to the straight ahead for the case of 0.5 degrees up than for 1.0 degrees up. The disabling effects of glare (e.g., Vos, 2003) and the discomforting effects of glare (e.g., Schmidt-Clausen & Bindels, 1974) both fall off strongly as the angle between the glare source and the center of a person's field of view increase. We therefore assigned the derived illuminance values to the new vehicle-based test locations at the closely matched distances of 30 and 60 m (corresponding to exact distances of 28.1 and 56.2 m).

In order to extrapolate the implicit illuminance values to longer and shorter distances it is necessary to determine what model may be implicit in FMVSS No. 108 for the effects of angle on glare effects. Because of the increase in glare effects near the center of vision, the 0.634 lux value should be even lower for separations between the two vehicles greater than 60 m (corresponding to even smaller angles between the glare source and the straight ahead), and the 1.776 lux value should be higher for separations shorter than 30 m. However, these two values do not exactly fit the standard models of glare effects by angle. As a practical alternative, we therefore chose to use headlamp gradients typical of lamps from the mid 1990s as the basis for extrapolation. Sivak and colleagues (Sivak, Flannagan, Kojima, & Traube, 1997) reported median photometry for a set of headlamps from U.S. vehicles of the 1997 model year. An isocandela diagram for the median intensities from that set of lamps is shown in Figure 9. We used the median values to establish the ratios between glare that would be produced by those lamps at distances of 30 versus 15 m and at 60 versus 120 m. The rationale for using lamps typical of the 1997 model year is that those lamps represent the actual (and, perhaps, the intended) effects of the photometric requirements introduced into FMVSS No. 108 at about that time. The resulting illuminance criteria for distances of 15, 30, 60, and 120 m are: 3.109, 1.776, 0.634, and 0.281 lux.

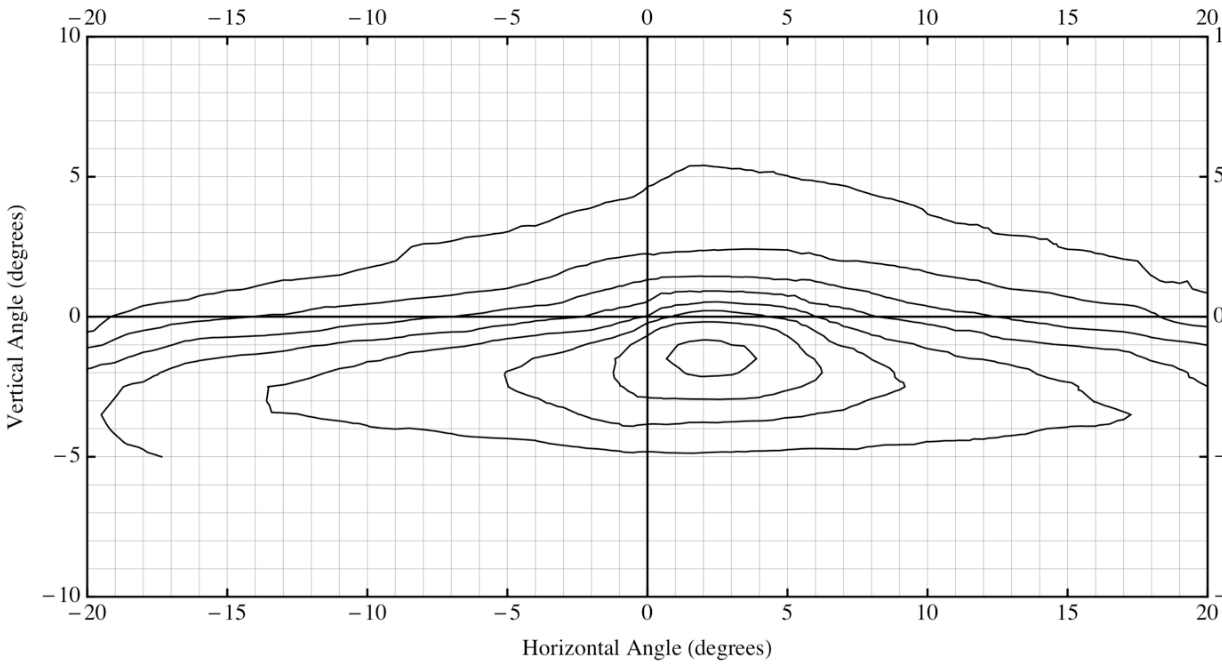

Figure 9. Isocandela diagram representing the median intensities by vertical and horizontal angle for a set of lower-beam headlamps on U.S. vehicles of the 1997 model year (candela contours are, from outermost to innermost: 150, 300, 600, 1200, 2500, 5000, 10000, 20000; data from Sivak et al., 1997).

3.4 Translating requirements concerning glare to preceding drivers

The fourth function listed in Table 2 is glare control for preceding drivers, for whom the critical lighting values are illuminance of rearview mirror positions. This was treated very much like glare for oncoming drivers, except that we used imaginary planes at typical heights for exterior rearview mirrors (at the mean height of 0.939 m, and 2.0 standard deviations up and down, yielding heights of 1.007 and 0.871 m) and interior rearview mirrors (at the mean height of 1.187 m, and 2.0 standard deviations up and down, yielding heights of 1.248 and 1.126 m). Also, the photometric values in this case were derived from the leftmost points of the glare-control lines in the upper right quadrant of Figure 5 (0.5 degrees up, 1.0 degrees right: 4.041 lux; 1.5 degrees up, 1.0 degrees right: 18.854 lux). All values for mirror locations were from measurements made on forty-three passenger cars that ranged in model year from 1989 to 1999 (Reed, Lehto, & Flannagan, 2000). The resulting test points for rearview-mirror glare are in Groups 17 through 24 of Table II in the Appendix.

3.5 Translating requirements concerning light for retroreflective signs

The fifth function in Table 2 is lighting for retroreflective signs. The main special technical issue for this function is that retroreflective sign luminance depends strongly on the angle formed by the locations of the light source, the sign, and the observer's eye (the so-called observation angle) and to a much lesser extent on the angle between a line normal to a point on the sign and a line from that point to the light source (the entrance angle). Figure 10 illustrates these two angles. The criteria for this function (Groups 25 through 31 in Table II of the Appendix) are therefore not illuminance (in lux), and instead are specified more directly as luminance values (in cd/m^2), using a minimum luminance value for signs (1.700 cd/m^2). This value is half of the minimum luminance of 3.4 cd/m^2 [1 fL] that was arrived at by Arens (1987), and it is also lower than the minimum luminance of 2.4 cd/m2 determined by Sivak, Gellatly, and Flannagan (1991). The adjustment to Arens' value is based on the current minimum intensities above horizontal at 0.5 and 1.5 degrees up (500 and 200 cd, respectively), which are about half the minimum values intensity values for those locations suggested by Arens (1,000 and 450 cd, respectively). The luminance value of 1.700 cd/m^2 is thus primarily intended to follow current FMVSS No. 108 values.

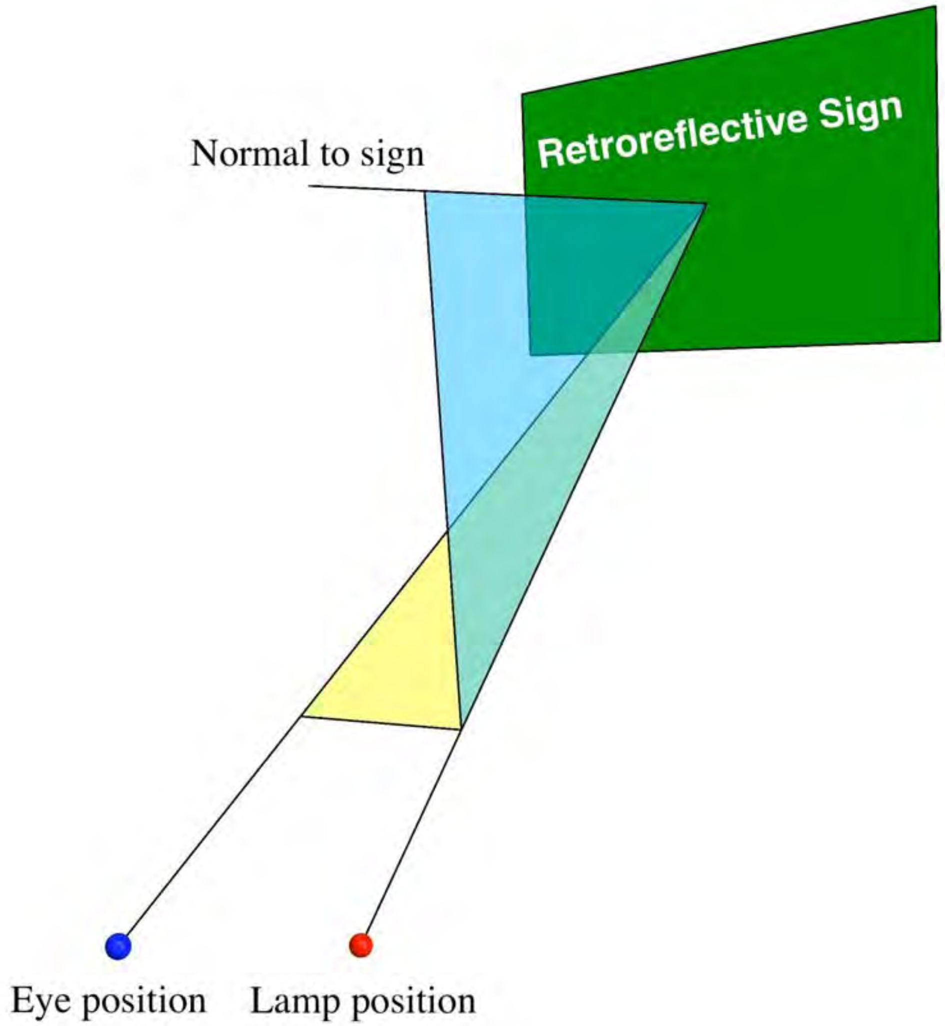

Figure 10. Two of the angles that influence the luminance of retroreflective surfaces. The observation angle (yellow) is formed by the light source, a point on the retroreflective surface, and the eye; the entrance angle (blue) is the angle between a line normal to a point on the surface and the line between that point and the light source.

In order to derive the specific test locations in Table II of the Appendix, we used the vertical and horizontal sign locations and distances that were used by Sivak, Gellatly, and Flannagan (1991), which were in turn adopted from Woltman and Szczech (1989). Those locations included a sign centered directly over the lane occupied by a vehicle. We extended this to signs one and two lanes to the left and right, using the same sign height and lane widths. Data on retroreflective efficiency for one type of sign material (encapsulated lens) as a function of observation angle were adopted from Sivak, Flannagan, and Gellatly (1993), and are reproduced as Table III of the Appendix. Retroreflective efficiency (R_A) is in units of candelas per meters squared per lux. For a given observing geometry, it is multiplied by illuminance (in lux) to yield luminance (in candelas per meters squared). Several alternatives are available for data on retroreflective efficiency. We used the set in Table III because it was available from an archival publication from the era in which the sign light minima were incorporated in FMVSS No. 108. Of the various angles that affect retroreflective performance, the performance-oriented system only makes use of observation angle. Although it would be straightforward to incorporate other variables, of which entrance angle would be the next most influential, the effects of those variables would be minor.

3.6 Translating requirements concerning light from 4°-10° up and above 10°

The final two functions in Table 2 are control of light that is close to the controlled beam pattern but at angles higher than have been considered important for seeing (4 to 10 degrees up), and control of light in areas well beyond the controlled pattern but in which uncontrolled optical features of a headlamp may scatter small amounts of light (beyond 10 degrees up). Both of these regions share the characteristic that there are no targets in them that have been identified as important for a driver to see. Indeed, the only concern in these regions has been restricting light that might be directed or scattered there. Furthermore, the main concern has not been with light that might reach identified targets at specific locations, but rather with light backscattered from rain, fog, or dust in the air. The location of the target of concern in these regions is therefore rather diffuse: the (usually) empty space through which a driver must look to see other things beyond that space.

The performance-oriented approach to photometric limits is therefore especially well suited to these concerns. In the past, because the region above 10 degrees has been addressed in terms of angular locations relative to lamps, two important circumstances of the driver's viewing situation have not been taken into account: (1) The relationship between the position of the lamp and the position of the driver's eyes strongly influences how light emitted by the lamp will affect the driver's vision. Specifically, the light directed from a lamp in an inboard direction, because it crosses a driver's view toward objects straight ahead, will much more strongly impinge on a driver's field of view than light directed in an outboard direction. (2) The effect of light on a driver's vision is determined not by light from a single lamp, but by the combination of light from all lamps that may scatter light into the region. Because the region of concern is near space through which a driver must be able to see, the angles involved will be markedly different for the lamps involved, thus making it especially important to measure light at real locations in that space. Both of these circumstances have been taken into account in the performance-oriented approach to these regions. The general strategy has been to define a regular, three-dimensional array of points in the relevant regions of space and to establish the photometric criteria as maximum illumination values that can occur at any of the individual points from the combined output of all headlighting contributors.

The location and density of the arrays of test points were established by starting with the principle that the density of coverage should be, on average, slightly denser than necessary to capture points or streaks of scattered light 2 degrees or more in extent. This was consistent with the treatment of these regions in SAE recommended practice J1735 (SAE, 2006). For both the region from 4-10 degrees and the region above 10 degrees, we established a common three-dimensional array of points that extended beyond the regions of interest and then selected points for each region based on certain geometric criteria. The grid was regular, with a spacing in all dimensions of 0.5 m. With this spacing, the angular criterion of 2.0 degrees was approximately met at a distance from the lamps of 10 m: arctan(0.5 m/ 10.0 m) = 2.86°. Although the resulting angle is somewhat greater than 2.0 degrees, in practice the points in a regular grid tend to fill in between each other from most perspectives. Furthermore, the 10 m distance was established from the front of the vehicle (near the likely location of headlamps), whereas the angles that matter are from the driver's eye location, which will normally be more than 2 m further back, thus decreasing the resulting angles (e.g., arctan(0.5 m/ 12.0 m) = 2.39).

For both the regions, from 4-10 degrees and above 10 degrees, we selected points based on two criteria: (1) Whether the points were within the proper angles—i.e., either between 4 to 10 degrees up or above 10 degrees from a typical headlamp location, and (2) whether they were within the largest driver field of view defined in FMVSS 104 (Windshield Washing and Wiping Systems), i.e., the field of view corresponding to Area A for passenger cars 1,730 mm or more in overall width (having angular limits from 18 degrees left to 56 degrees right, and 10 degrees up to 5 degrees down). The resulting groups of points appear in Table II of the Appendix, in Group 32 for the region from 4 to 10 degrees up and in Group 33 for the region above 10 degrees. The illuminance limits for the individual points are based on their distances and twice the current maximum intensity for stray up light from a single lamp. For the region above 10 degrees this was 250 cd (i.e., 2 x 125 cd). For the region between 4 and 10 degrees up, we began with the photometric maxima in the current version of FMVSS No. 108 with the highest angular locations on each side of the beam pattern (except for the 10-90 up limit): 1,400 cd at 1.5U-1R to R, and 700 cd at 1.0U-1.5L to L. We averaged these ((1,400 cd + 700 cd)/2 = 1,050 cd) and then rounded down to 1,000 cd. Because the light at issue crosses the space in front of a driver's eyes, and could be coming in any direction from any lamp, it is reasonable to combine the photometric limits for right and left. (However, these limits were clearly intended, from the perspective of an individual lamp, to be more restrictive on the left than the right.) We then doubled this value to establish limits for a headlighting system (2 x 1,000 cd = 2,000 cd).

The sections of Table II in the Appendix for light above 4° (Groups 32 and 33) are particularly long (containing 462 and 1,428 points, respectively). It may be useful to describe those points more compactly in terms of rules rather than as lists. Table 3 therefore provides a rule-based alternative that could be substituted for the material in the Appendix.

Table 3. Rules for deriving the test points for light above 4° (Groups 32 and 33)

Definition of the 3D grid:

An array of points, each defined by a set of values (*x, y, z*) is established by combining all values of:

x from 0.5 m to 10.0 m in steps of 0.5 m
y from -5.0 m to 5.0 m in steps of 0.5 m
z from 1 m to 3 m in steps of 0.5 m

Selection of points based on angles:

Angles are defined by planes rotated around an axis that is horizontal, perpendicular to the midline of the vehicle, and 0.62 m above the ground at the forward-most point of the vehicle.

For light from 4° to 10° up (Group 32), select points that are above a plane rotated 4° up and a plane rotated 10° up.
For light above 10° (Group 33), select points that are above a plane rotated 10° up.

Derivation of lux criteria for individual points:

The lux criterion for each point is derived by dividing a light intensity value in candela by the square of the distance of each point in meters from a reference point at (0, 0, 0.62). For the two zones, the intensity values are:

2,000 cd for light from 4° to 10° up (Group 32)
250 cd for light above 10° (Group 33)

3.7 Summary of lower-beam photometric test locations

An overview of the vehicle-based lower-beam requirements is provided in Figure 11, which shows the locations of the most central 867 of the 2,220 total test locations involved, as viewed from the same point of view used in earlier figures—the position of an imaginary single headlamp on the midline of the vehicle. (Almost all of the points in Table II for Groups 1 through 31 are shown in Figure 11. Many of the points for up light, in Groups 32 and 33, are outside the field of view of the figure, either vertically or horizontally.)

Figure 12 provides a view similar to the view in Figure 11, but from the point of view of a typical driver eye location. A higher proportion of the total points appear in Figure 12 (1,427 of the 2,220 total points).

Although the roles of the various groups of points are not distinguished in Figure 11 and Figure 12, those figures nevertheless highlight several interesting aspects of the performance-oriented approach. First, although the points tend to become dense near the center of the figures, there is generally evenly spread coverage of the driver's field of view (especially evident in Figure 12). The concentration of points near the middle is necessary given that that is the region in which the demands for enough light to see and for control of glare are most in conflict.

Second, there are no significant areas without coverage. In particular, the region between 4 degrees up and 10 degrees up, which has been recognized as lacking coverage in the current version of FMVSS No. 108, has been filled in.

Because both Figure 11 and Figure 12 are too crowded to allow easy inspection of individual groups of points, the next several figures present a breakdown by functions. Figure 13 presents the points below horizontal for seeing light and glare control. Figure 14 provides a view of the glare control points above horizontal, and Figure 15 provides a similar view of the points for sign light. Figure 16 and Figure 17 present the points for control of light from 4° to 10° up, and above 10° (many of those points are beyond the angular range of these figures).

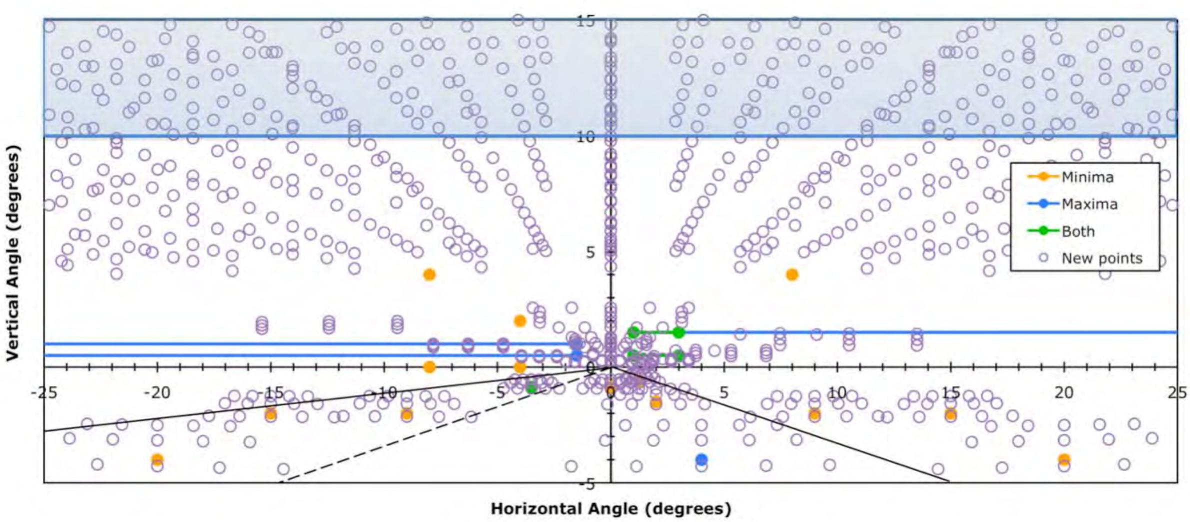

Figure 11. Locations of the most central (in this view, 867 of a total of 2,220) vehicle-based test locations for lower-beam mode in the performance-oriented system, as viewed from the center of a vehicle at typical headlamp height (0.62 m), overlaid on current lower-beam, angle-based target locations.

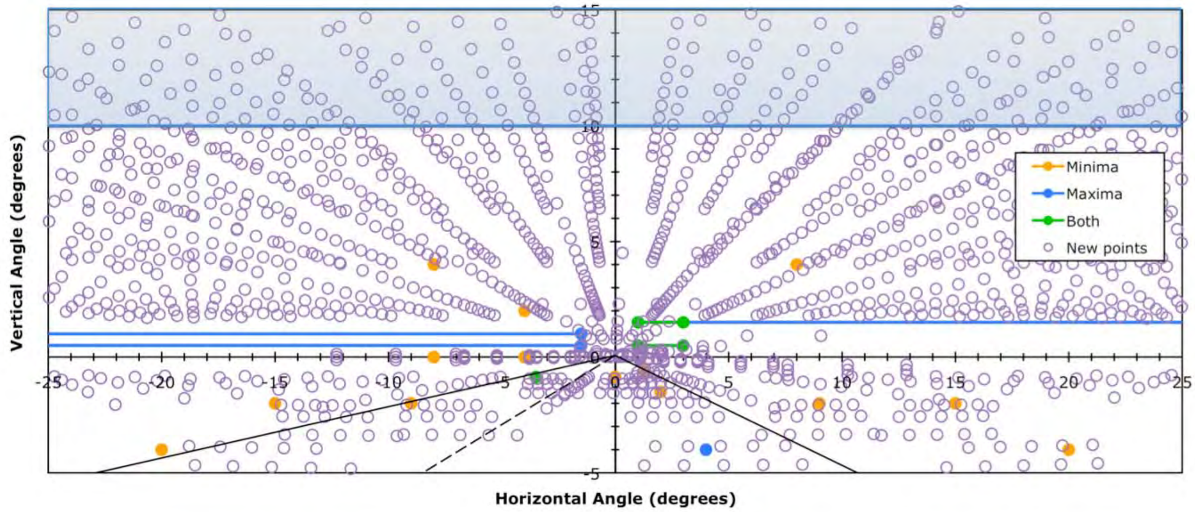

Figure 12. The locations of the most central (in this view, 1,427 of a total of 2,220) vehicle-based test locations for lower-beam mode in the performance-oriented system, as viewed from a typical driver eye position, overlaid on current lower-beam, angle-based target locations.

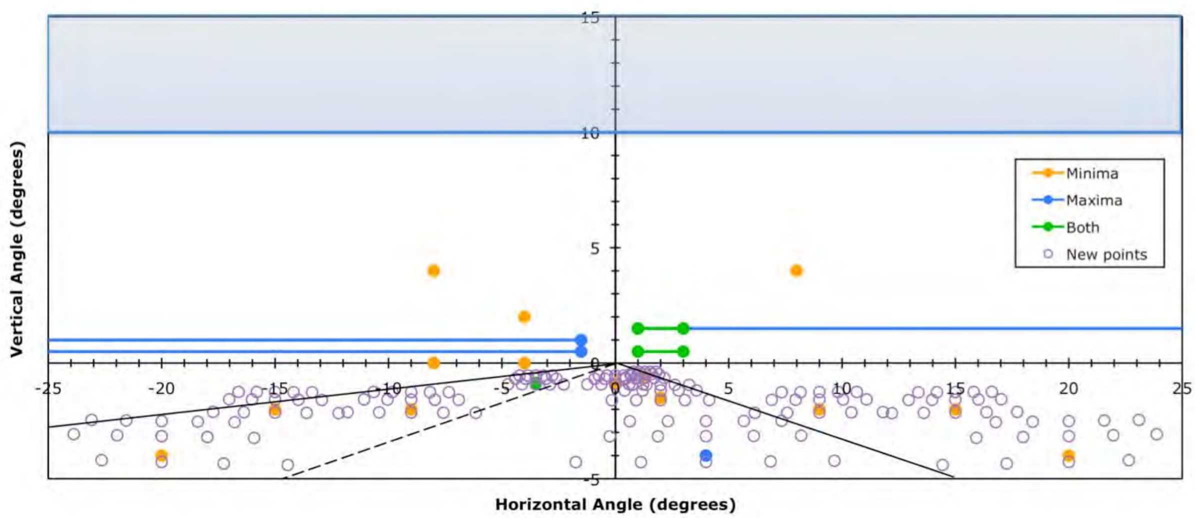

Figure 13. A subset of the test locations from Figure 11, showing locations of the new points intended to control seeing and glare light below horizontal.

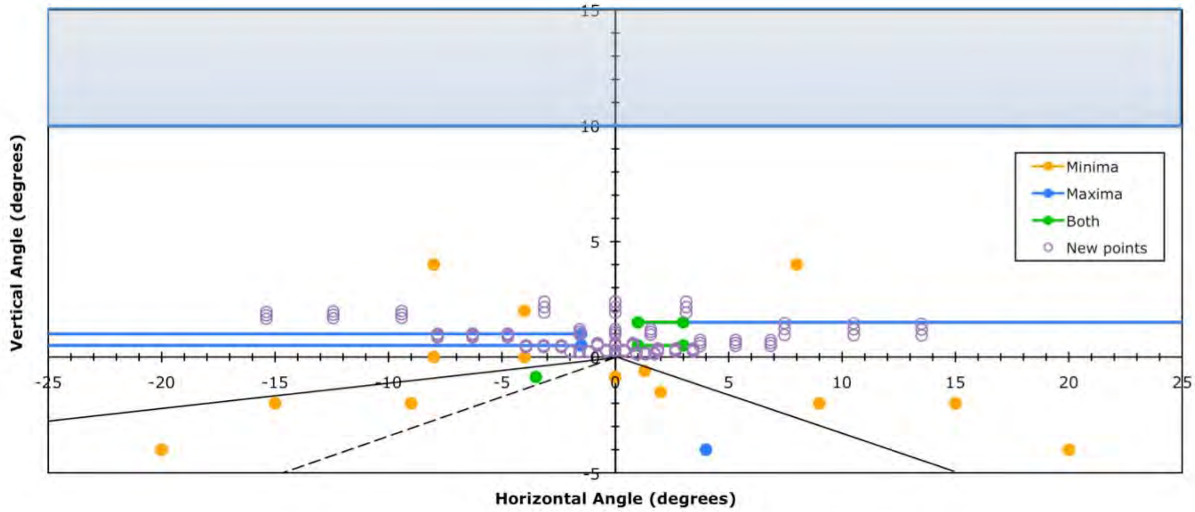

Figure 14. A subset of the test locations from Figure 11, showing locations of the new points intended to control oncoming and rearview-mirror glare.

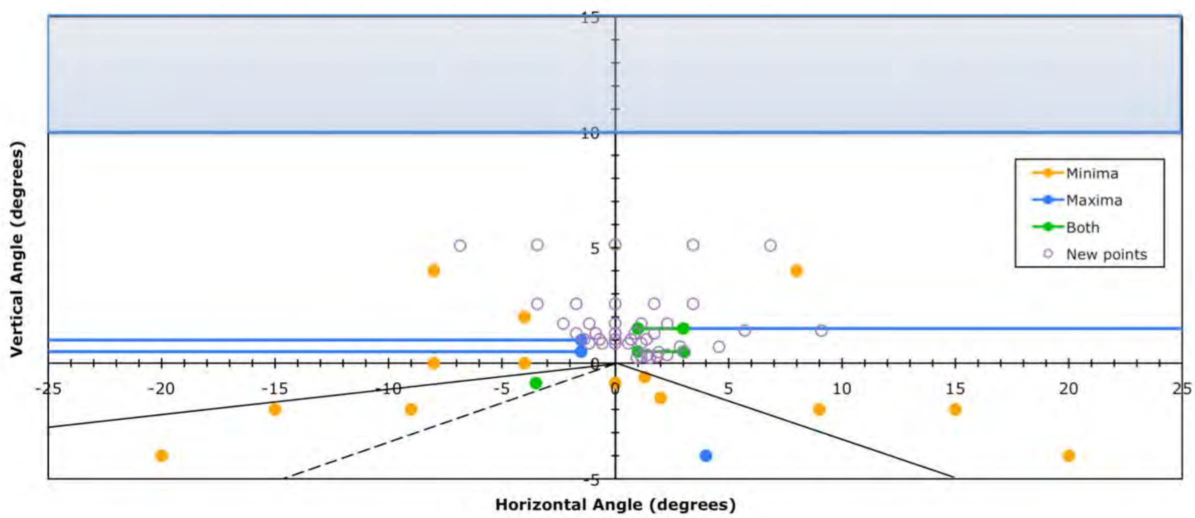

Figure 15. A subset of the test locations from Figure 11, showing locations of the new points intended to provide adequate light toward retroreflective signs.

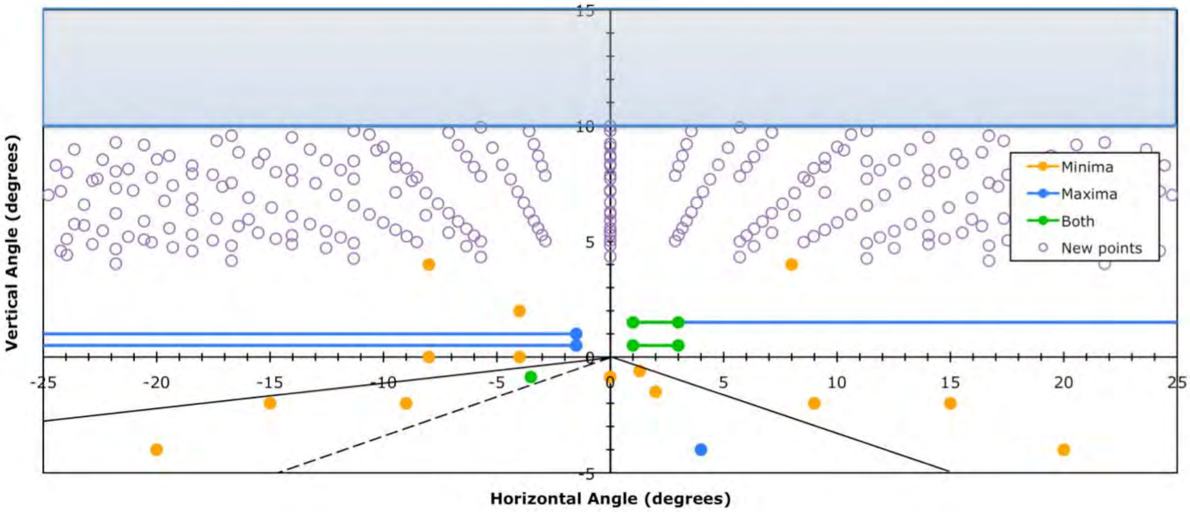

Figure 16. A subset of the test locations from Figure 11, showing locations of the new points intended to control light between 4° and 10° up.

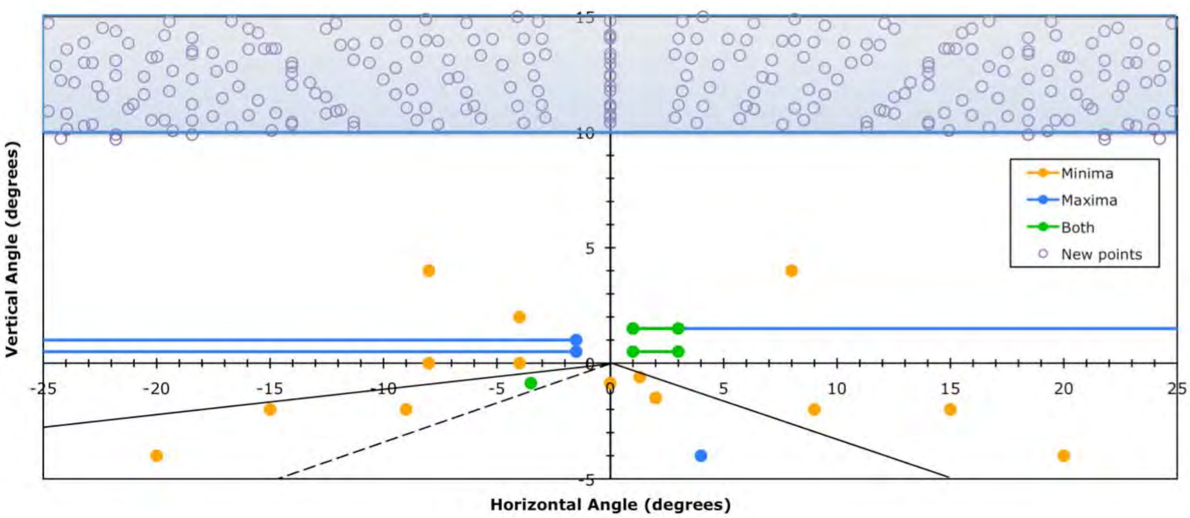

Figure 17. A subset of the test locations from Figure 11, showing locations of the new points intended to control light more than 10° up.

Figure 18 shows an overview of the test locations below horizontal. Each of the red polygons in the figure shows the area spanned by the 15 points in one of the first ten groups in Table II of the Appendix. The group numbers are shown in red in the figure next to each polygon, accompanied by the average lux criterion for each polygon (in parentheses). Two isolux contours are shown (for 10.0 and 3.0 lux) for a median two-lamp headlighting system from the 2000 model year (Schoettle et al., 2001). The isolux contours do not give enough information to determine whether the average requirement for each of the polygons is met—a full lux matrix is needed for that. However, inspection of the figure shows that the isolux contours are reasonably well aligned with the polygons and their average illuminance requirements (all criteria are in fact met for this median headlighting system). For example, the polygon for Group 1, with an average requirement over all 15 points of 2.9 lux, is mostly but not entirely within the 3-lux contour. In contrast, the polygon for Group 3, with an average requirement over all 15 points of 1.1 lux, is mostly but not entirely beyond the 3-lux contour.

One group stands out in terms of its illuminance requirement: Group 4 has a much higher average requirement (27.0 lux) than several groups that are very near it. For example, Group 2, which nearly overlaps with Group 4, has an average illuminance requirement of only 2.7 lux, one tenth of the requirement of Group 4. Individual points for these groups can be inspected in Table II of the Appendix. One of the points in Group 2 that is nearest the origin has coordinates (x, y, z) = (38.638, 0.830, 0.000) and an individual illuminance criterion of 4.220 lux. Very nearby, one of the points in Group 4 furthest from the origin has coordinates (37.784, 0.904, 0.000) and an individual illuminance criterion of 14.692 lux. Although these photometric values are substantially different, the example emphasizes that the performance-oriented test locations are designed to control average values over reasonably broad regions. The fact that the range of point locations for Group 2 lies generally much further from the vehicle than the range of point locations for Group 4 is why their photometric values are so far apart. However, Group 4 also represents a special issue in that the original photometric value on which it is based (15,000 cd at 1.5D, 2R in Table XIX-a, lower beam pattern LB2V of the current FMVSS No. 108) is itself an outlier among the current lower-beam photometric requirements. The outlier status of that test point is not immediately obvious in terms of the angles and intensity values of Table XIX-a, but it shows up clearly in Figure 6 of this report, where the corresponding transformed test point appears with a minimum pavement illuminance of 53.5 lux. We did not make an arbitrary adjustment for this point in deriving values for the performance-oriented system, and it could be argued that pavement illuminance of 53.5 lux or more is in fact a clear requirement of the current version of FMVSS No. 108, but that value is much higher than most analyses would justify at that point (e.g., Sivak et al., 1992).

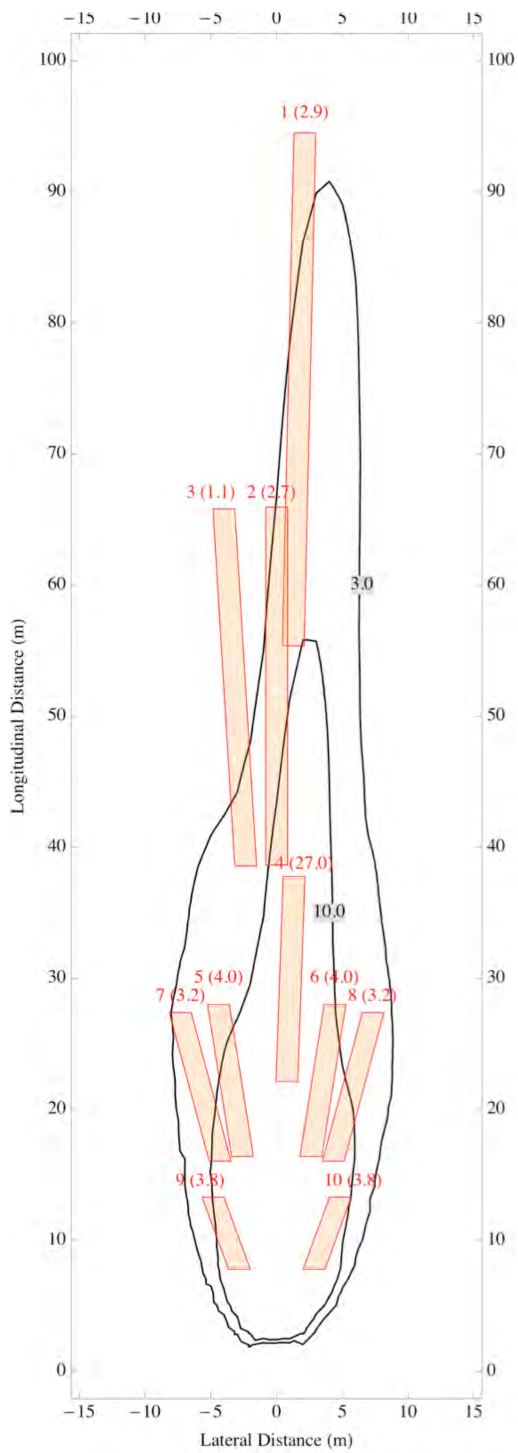

Figure 18. A bird's-eye view of the photometric minimum test regions below horizontal, as they appear on a road surface in front of a vehicle. The forward-most point on the midline of the vehicle is at the origin (0,0). Red numerals indicate the test-point group number and the minimum average lux (in parentheses) for each region; black contours represent 3.0 and 10.0 isolux lines for a current median lower-beam system.

3.8 Translating requirements concerning upper-beam headlighting

In addition to lower-beam functions, the new approach treats upper-beam functions in a vehicle-based form. Upper-beam headlighting requirements are embodied in the values shown in Table I of the Appendix, which are considerably less numerous—and also much simpler in how they are applied—than the lower-beam values in Table II. This is in keeping with the traditional relative allocation of research attention between upper and lower beams, and, most basically, is attributable to the fact that consideration of glare greatly complicates the lower-beam situation.

We derived the values in Table I from the requirements for upper-beam photometry in Table XVIII UB2 of the current version of FMVSS No. 108. The locations of those requirements are illustrated in Figure 19. The approach we used was similar to what we did for the lower-beam requirements. The main difference was that for photometric minima at and above horizontal we could not apply the rationale that we used for glare maxima or sign-light minima in the context of lower-beam headlighting. This was because there are no implicit targets (such as signs and the eyes of oncoming drivers) for the upper-beam points at and above horizontal. (For the upper-beam points below horizontal, we used intersection with the road surface, just as in the lower-beam case.)

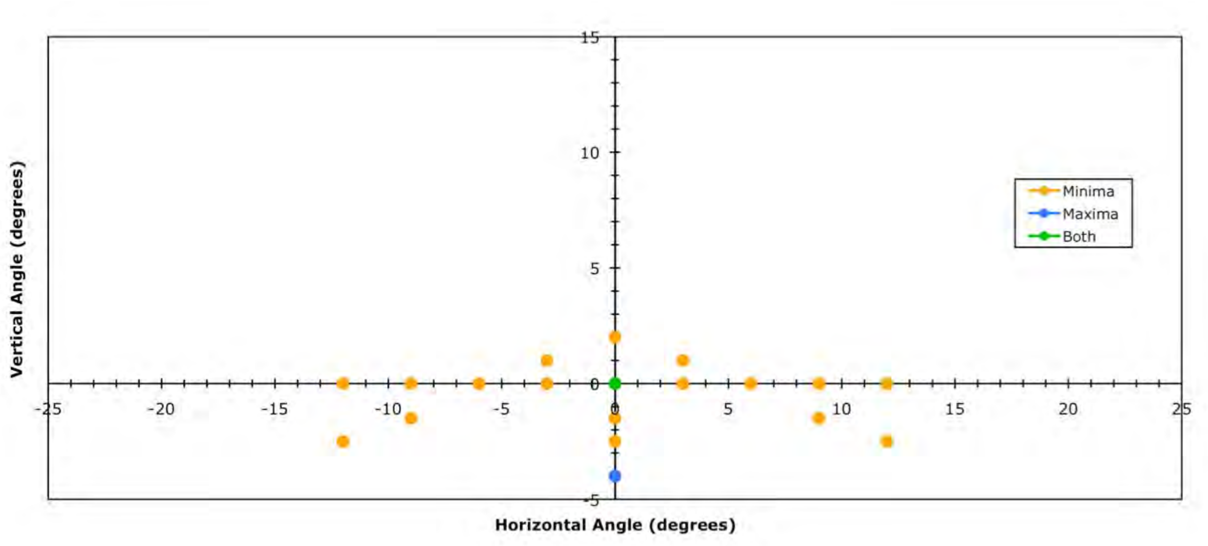

Figure 19. Photometric test locations in the current FMVSS No. 108 for upper-beam headlamps (from Table XVIII UB2).

For the points above horizontal, we derived the target points by considering a single headlamp mounted on the midline of a vehicle, and determined the distances at which the minimum required intensity for each angular location would produce a criterion illuminance level (3.0 lux, normal to the direction of propagation). For example, the upper-beam minimum of 5,000 cd at 1.0 degrees right, 3.0 degrees right corresponded to illumination of 3.0 lux at a point 40.763 m ahead of the lamp, 2.139 m to the right of the vehicle midline, and 1.333 m above the road surface (this is the third point in Table I of the Appendix). We then doubled the criterion of 3.0 lux for a single lamp to arrive at the headlighting system criterion of 6.0 lux. In practice, many different illuminance criteria would produce virtually the same results, since the intent of this procedure was simply to establish vehicle-based target locations far enough from the vehicle to reduce the effect of parallax for the two headlamp positions.

3.9 Translating requirements concerning motorcycle headlighting

Developing a performance-oriented set of photometric requirements for motorcycles presents special problems because of the substantially different options that are available for motorcycle headlighting under the current provisions of FMVSS No. 108. Motorcycles can use either half of a system for larger vehicles or a system specific to motorcycles. The main differences between these alternatives are: (1) there are no sign-light minima in the motorcycle photometry, and (2) the photometric minima below horizontal are symmetrical and considerably closer to the vehicle in the motorcycle photometry.

The contrast between the minima below horizontal is shown in Figure 20. The furthest reach for a motorcycle headlamp (assuming for illustration the same mounting heights for both lamps: 0.62 m) is 23.4 m (corresponding to an angle of 1.5° down), at each of two points, located roughly in the middle of the adjacent lanes. The furthest reach of a test point in the lane occupied by the motorcycle is 17.8 m. As shown in the figure, the motorcycle points are symmetrically located (the associated photometric values are also symmetric). In contrast, the test locations from Table XIX-a, lower beam pattern LB2V are markedly asymmetric, thus taking advantage of the lower need for glare control on the right (which also applies to motorcycles), and photometric test locations extend ahead of the vehicle to 59.2 m.

Given the substantial differences between the two systems, as partially illustrated in Figure 20, and the need to translate the current requirements into specific locations in the roadway environment of a motorcycle, a decision must be made about which system to use. It is difficult to reconcile the two systems in developing a performance-oriented approach. Given the general need for more light from headlighting systems (Perel et al., 1983; Sivak et al., 1992) it may be preferable to adopt the system with stronger photometric minima. This seems especially desirable because the two systems have the same glare limitations. In a performance-oriented approach, motorcycles could therefore use the same set of photometric test locations that have been developed for other vehicles. However, this would involve motorcycle headlamps being subject to one half of the photometric minima in Tables I and II. Because glare concerns should be based on surrounding vehicles, rather than the vehicle using the headlamps, the full values of the photometric maxima would apply directly to motorcycles.

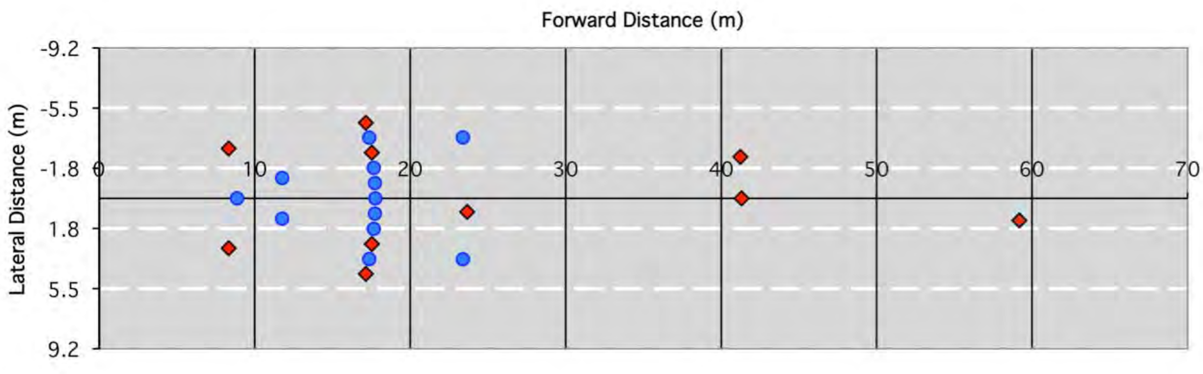

Figure 20. Pavement projections of lower-beam photometric minima below horizontal for motorcycles (blue circles) and other vehicles (Table XIX-a, lower beam pattern LB2V, red diamonds).

4 Applications of headlighting criteria to real lamps

In order to better understand the implications of the performance-oriented criteria for headlamps, we tested them using a set of headlamps sampled from recent vehicles. The set that we used consisted of the lamps for 20 vehicles from the 2004 model year (Schoettle et al., 2004). The lamps were photometered at 0.2-degree intervals from 60 degrees left to 60 degrees right, and from 10 degrees down to 10 degrees up. Although we used the photometric data to illustrate how testing works with both the current version of FMVSS No. 108 and the performance-oriented version, the photometry was actually performed in a way that was intended to best reflect lighting performance on the road, rather than for formal testing. Most importantly, after aim was set using the method appropriate to each lamp (14 were VOR, 3 were VOL, and 3 were mechanical aim), no reaim was made in an attempt to meet individual photometric limits. Because the original purpose of the photometric data was to assess potential headlighting performance in actual use, aim for the visual-optical aim lamps was set by the collective judgment of a group of three people, all of whom had extensive expertise in headlamp evaluation. The photometric values at the various test locations were interpolated in cases where points in the photometric grid did not exactly coincide with the test locations.

We first checked the lamps against the requirements of Table XIX-a, lower beam pattern LB2V[4] of the current FMVSS No. 108. With no reaim, only 5 of the 20 lamps had all locations meeting criteria. The most common location out of limits was the line at 0.5U-1R to 3 R, where 11 lamps were below the minimum of 500 cd. Five lamps were below the 0.6D-1.3R minimum of 10,000 cd. After reaiming (by up to 0.25 degrees in any direction, in software, using interpolation as needed) only 2 lamps had locations out of limits. The fact that most of the lamps met photometric limits after reaiming is not surprising, but emphasizes how critical aim can be, especially for lamps with strong gradients (which was the case for most of these lamps).

In order to explore the sensitivity of these lamps to vertical aim, all lamps were reaimed in software to a set of angles from 1 degree below to 1 degree above their initial aim settings, in 0.1-degree increments. For this test, no horizontal aiming adjustments were made, and no adjustments were made for individual test locations. The exercise was therefore different from traditional reaiming and was not intended to check agreement with requirements in the usual sense. All beam patterns were shifted in their entirety by successive 0.1-degree increments. The results are shown in Figure 21, in terms of the number of lamps at each level of aim that were below one or more photometric minima, and the number of lamps that were above one or more maxima. Individual lamps could be out of limits with both minima and maxima, at different test

[4] This table is in the version of the standard published in the 2007 final rule, which is effective on December 1, 2012.

locations, and one lamp did in fact have such a pattern of results. Note that at zero misaim (i.e., the way the lamps had been aimed for photometry), 13 lamps (65% of the 20 total lamps) exceeded at least one maximum value, and 3 lamps (15% of the 20 total lamps) were under at least one minimum value. The green dashed lines in Figure 21 represent the SAE inspection limits for headlamp vertical aim: ± 4 inches at 25 feet, corresponding to ± 0.76° (SAE, 1997). All 20 lamps are above at least one photometric maximum value before they reach the SAE limit of upward misaim (relative to the aim at which they were initially set), and most are below at least one minimum limit before reaching the SAE limit for downward misaim. For both minima and maxima, there is no vertical aim at which all 20 lamps meet all test values (i.e., without horizontal adjustments).

Further detail about the two lamps that remained out of limits after reaim is given in Table 4. These are identified as Lamps 14 and 15. One remained below the minima at two of the test points for sign light, and one remained above maximum glare test lines on the left at 0.5 and 1.0 degrees up. Lamp 14 missed the sign light values by a small amount (missing one sign point, at 2U-4L, by 14% after best reaim), but Lamp 15 was relatively far above the left-side glare limits (missing points on the glare lines at 0.5 and 1.0 degrees up on the left by 40% and 25%, respectively, after best reaim). Lamp 15 had a strong and diffuse pattern. Interestingly, it was one of the few mechanical aim lamps in the sample, meaning that the setting of its initial aim was simpler, or at least less subject to judgment, than the settings for the visual-optical aim lamps.

We also checked the 20 sample lamps against the performance-oriented criteria. As indicated in Table 4, four lamps were out of limits as initially aimed. Two of these were relatively high-mounted lamps that exceeded glare values for either rearview mirror glare (Lamp 2, mounted at 1.08 m) or oncoming glare (Lamp 20, mounted at 0.96 m). The fact that these lamps were above glare limits in the performance-oriented system, although they were within the limits of the current version of FMVSS No. 108, illustrates the major way in which we would expect the performance-oriented system to differ from the current system: lamps with high mounting locations may exceed glare limits in the performance-oriented system, which takes mounting height into account, but any effects of mounting height will not be reflected by the current system, which does not take height into account. The mechanical-aim lamp that exceeded left-side glare limits in the current system (Lamp 15) also exceeded glare limits in the performance-oriented system. One lamp that was within the limits of the current system (Lamp 7) exceeded the limits for oncoming glare in the performance-oriented system. This lamp was not particularly high mounted (0.68 m), but it had strongly failed glare limits on the left side in the current system before reaim. Inspection of the vertical gradients on the right side of this VOR lamp suggested that it may have been aimed about 0.2 degrees high during initial aiming.

Aiming it down by 0.2 degrees brought it within the limits of the performance-oriented system. The lamp that was below a minimum point for sign light in the current system (Lamp 14) met all of the sign light requirements in the performance-oriented system, although only by a small margin.

In addition to using the 20 sample lamps to test the performance-oriented system with the lamps at actual mounting locations and nominal aim, we used those lamps to explore the sensitivity of the system to changes in mounting height and misaim. The effects of misaim are shown in Figure 22, over the same range of aim that we used with the current system in Figure 21. The effects of changes in mounting height are shown in Figure 23, which shows the outcome for each lamp if it were mounted, with nominal aim, at each of a range of heights from 0.5 to 1.5 m, in steps of 0.1 m. (Although we did two parallel analyses for vertical aim, one for the current system and one for the performance-oriented system, it is in principle not possible to do a parallel analysis of mounting height for the current system, since it has no way of incorporating height.) As in Figure 21, there are dashed green lines in Figure 22 to indicate the SAE aiming limits. The result for the performance-oriented system is similar to that for the current system: all lamps exceed at least one maximum photometric limit before reaching the SAE limit for upward misaim, and most are below at least one minimum limit before reaching the SAE limit for downward misaim. Figure 23 includes dashed green lines to indicate the current minimum and maximum permitted mounting heights for headlamps in FMVSS No. 108: 22 inches (0.56 m) and 54 inches (1.37 m). All lamps exceed at least one photometric maximum when mounted at or above 1.2 m. A substantial number of lamps (5 of 20) failed photometric minima when they were just above the lower mounting height of limit of 0.56 m.

Table 4. Summary of headlamps that missed photometric limits of either the current or performance-oriented system

			Current FMVSS No. 108		Performance-oriented system	
Lamp	Aim type	Mounting height (m)	Overall within limits	Locations beyond limits	Overall within limits	Locations beyond limits
2	VOR	1.08	Yes		No	Group 17 (rearview mirror glare)
7	VOR	0.68	Yes		No	Groups 15 & 16 (oncoming glare)
14	VOR	0.70	No	Sign minimum at 2U-4L	Yes	
15	Mechanical	0.89	No	Left glare maxima at 0.5U and 1.0U	No	Groups 15 & 16 (oncoming glare)
20	VOR	0.96	Yes		No	Group 13 (oncoming glare)

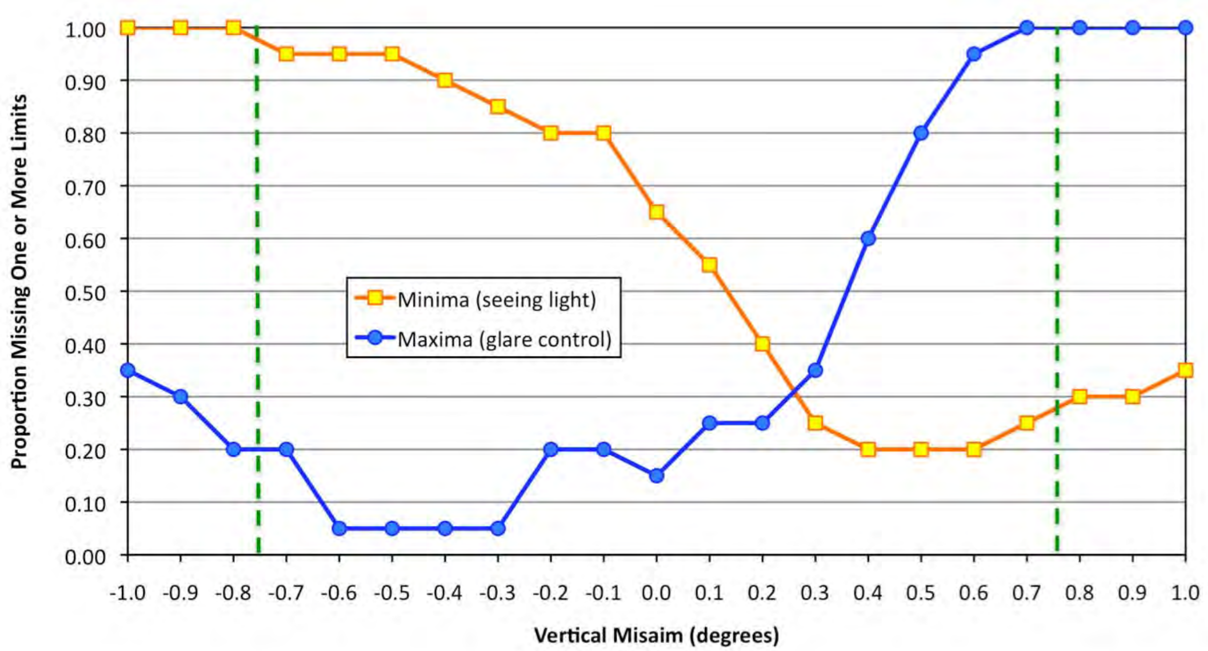

Figure 21. Proportion of lower-beam headlamps not meeting photometric minima or maxima in the current version of FMVSS No. 108, by amount of vertical misaim. The green dashed lines represent the SAE tolerance for vertical aim, ± 4 inches at 25 feet (± 0.76°).

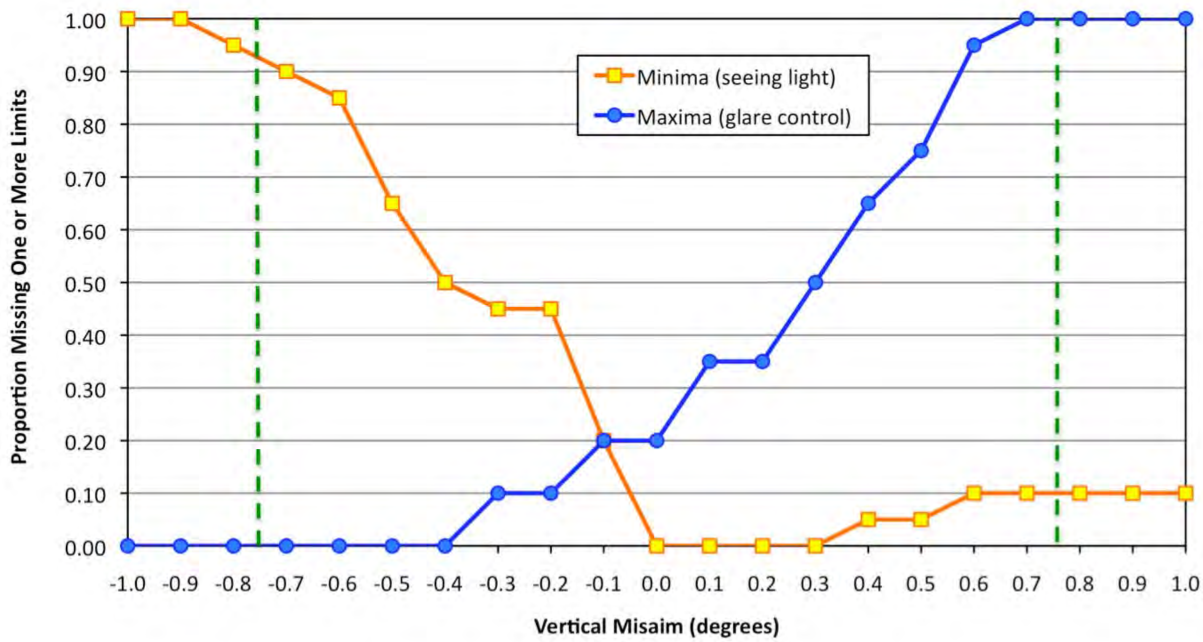

Figure 22. Proportion of lower-beam systems not meeting photometric minima or maxima in the performance-oriented system, by amount of vertical misaim (all systems at actual mounting heights). The green dashed lines represent the SAE tolerance for vertical aim, ± 4 inches at 25 feet (± 0.76°).

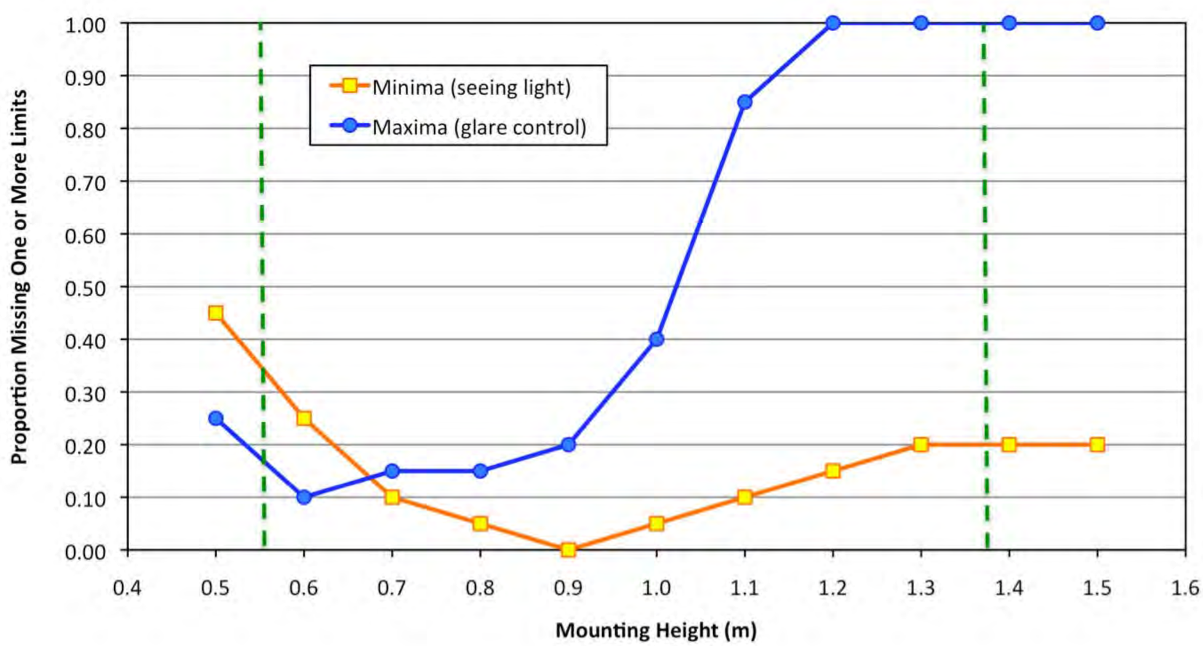

Figure 23. Proportion of lower-beam systems not meeting photometric minima or maxima in the performance-oriented system, by mounting height (all systems at nominal aim). The green dashed lines represent the current minimum and maximum mounting height for headlamps, 22 inches (0.56 m) and 54 inches (1.37 m).

Figure 24 shows the ranges over which each of the 20 individual headlamps were within the limits of the performance-oriented system as a function of aim. All lamps were within all limits for at least some range of aim, although, as previously discussed, four lamps exceeded glare maxima at their initial aim settings (shown as 0.0 in Figure 24). The ranges of aim within which all limits were met are all substantially smaller than the SAE limits (± 4 inches at 25 feet, corresponding to ± 0.76°, for a total range of 1.52°). Given the sensitivity of headlighting performance to vertical aim (Sivak, Flannagan, & Miyokawa, 1998), the more restricted ranges may be better reflections of actual performance. The ranges of aim shown in Figure 24 are summarized and discussed in a later section of this report (see Figure 29).

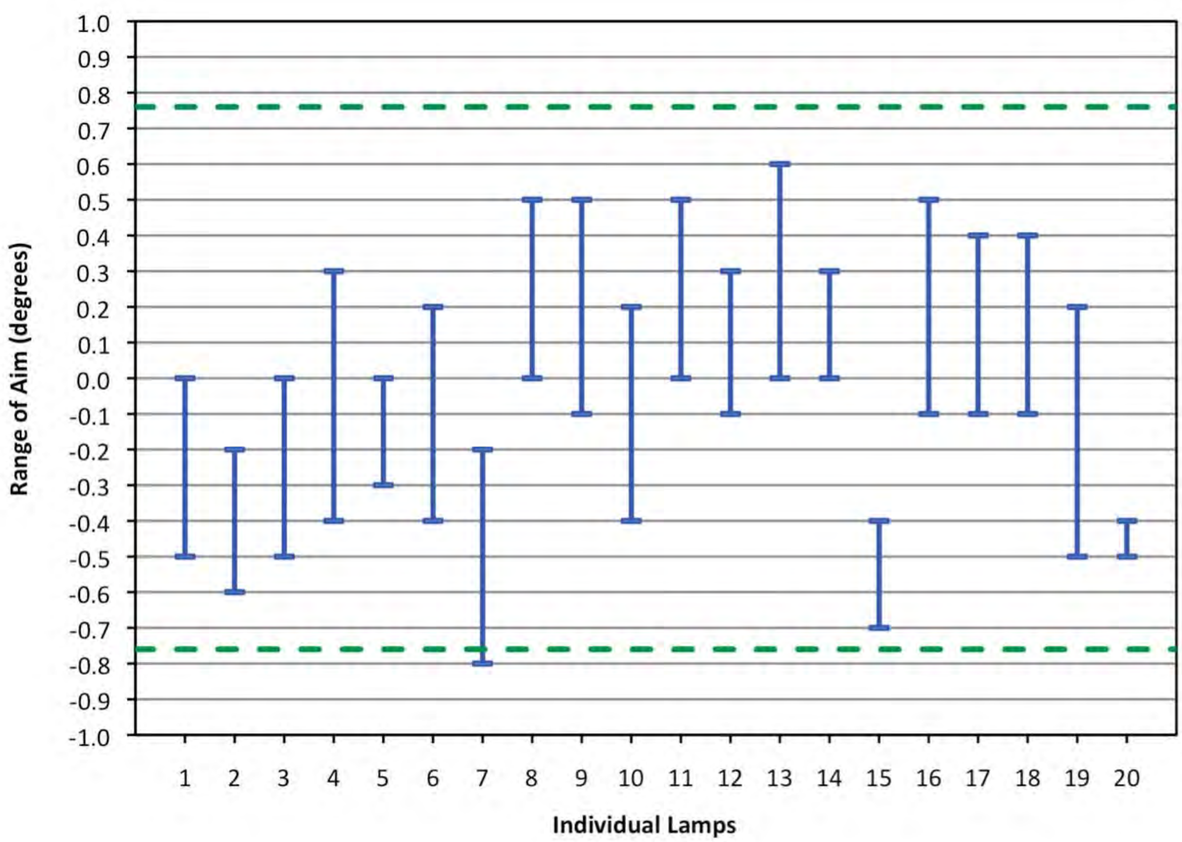

Figure 24. The ranges of vertical aim over which each of the 20 test lamps was within all limits of the performance-oriented photometry. The green dashed lines represent the SAE tolerance for vertical aim, ± 4 inches at 25 feet (± 0.76°).

5 Anticipated effects of a performance-oriented approach

Table 5 summarizes the areas in which there may be benefits from a performance-oriented approach to regulation of vehicle lighting. Details about possible effects of the performance-oriented approach in each area, and the degree to which it seems possible to achieve each type of benefit, are discussed individually in the remainder of this portion of the report.

Table 5. Summary of principal possible effects of the performance-oriented approach

	Area	Effects of the approach
1	Whole-vehicle testing	Vehicle-based criteria can be used; actual photometric procedures still involve candela matrices for individual lamps, combined in software
2	Headlamp test voltage	Probably not actual individual vehicle voltages, but possibly 13.2 V as a better single value to represent most vehicle voltages
3	Asymmetrical headlighting	Vehicle-based photometry allowing more asymmetry than the present standard, thereby allowing better tradeoff of seeing and glare
4	Headlamp mounting height	Implicit height limits based on realistic 3-D locations of test points
5	Light for retroreflective signs	Control of sign luminance incorporating the effect of observation angle
6	Adaptive frontlighting	Softened distinction between upper and lower beams; photometric limits based directly on road geometry, allowing incorporation of curvature
7	Preventing gaps in headlighting	Photometric limits based on combinations of many test points, grouped into zones, providing better coverage
8	Headlamp aim	Initial aim constrained by realistic 3-D locations of test points
9	Signal lamp luminance	Control of luminance based on actual lamp area rather than number of lighted sections
10	Front turn signal masking	Turn signal intensity requirements based on headlamp intensity at corresponding observer locations
11	Stray up light from headlamps	Control of stray up light based on the driver's field of view
12	Conform vs. design to conform	More predictable test methods involving partially redundant points, possibly allowing the elimination of the provision to design to conform

5.1 Whole-vehicle testing

Under a performance-oriented version of FMVSS No. 108, the bulk of the photometry needed to determine whether a vehicle complies could, in principle, be done on the entire vehicle within a photometric facility that would be very simple (although large and potentially expensive). For example, the lower-beam mode for headlighting as described here involves 2,220 test locations in front of a vehicle at which certain photometric values must be met. These locations were determined by considering the requirements in the current version of FMVSS No. 108 for seeing light, glare control, and sign visibility. In principle, a vehicle could be tested by placing it in a large, light-controlled room, turning on the lower-beam mode of its headlighting system, and reading the output of 2,220 light sensors that would be placed in appropriate locations in front of the vehicle and aimed at the lamps on the vehicle. Some of those sensors would be on the floor of the room; and some would be above the floor at various distances in front of the vehicle, and at various distances to the left and right of the vehicle midline.

However, in practice it would probably be more efficient to make the actual light measurements in a more traditional way, by measuring individual lamps (or "contributors") on a goniometer and combining the outputs of those lamps in software. Lamp output would be represented by traditional candela matrices, and the mounting locations and orientations of lamps would be represented by simple parameters that would allow the calculation of illuminance at any point in three-dimensional space around the vehicle. This strategy—which might be referred to as *virtual* vehicle-based photometry—would avoid the need to construct a large physical facility, and would still provide all of the benefits of actual vehicle-based photometry, since using software to combine measurements is straightforward. However, the performance-oriented approach could be used with either strategy, and the mental image of a large physical facility with multiple sensors in real three-dimensional space is a good way to convey the intent and actual effect of the approach, even if more traditional photometric methods would normally be used in practice.

A possible advantage of vehicle-based photometry is that photometric limits can be tied to the actual geometry of vehicles and the roadway. For example, in the current lamp-based system the fact that a vehicle typically has two headlamps, which are separated horizontally by about 1.2 m, is not explicitly taken into account, nor is the fact that headlamps are mounted at various heights, typically ranging from about 0.6 to 0.9 m. Those circumstances have meaningful consequences for illumination of the roadway, and the ability to take headlamp mounting locations into account in a vehicle-based system therefore may be an advantage.

There are possible ancillary benefits that go along with the precision allowed by vehicle-based photometry. Because photometric test locations in a vehicle-based system are tied to real geometry rather than a rough approximation, many more test locations can be used with greater certainty about how they will affect actual lighting performance. And because more locations can be identified, the criteria that are applied to the locations can be softened while still insuring adequate control of actual light levels in the field. Thus, in the vehicle-based system there are 2,220 test locations for the lower-beam headlighting function, versus 24 for lower-beam lamps in

Table XIX-a, lower beam pattern LB2V[5] of the current FMVSS No. 108 (although the value of 24 counts several lines and one zone as single locations). The large number of test locations and the opportunity to define overall outcomes in terms of sets of locations can, in principle, allow testing to be robust in several ways. The performance-oriented standard has been tested with photometry from a set of recent headlamps (Schoettle, Sivak, Flannagan, & Kosmatka, 2004), and the results suggest that it is in fact reasonably robust. Performance-oriented systems may offer the possibility of eliminating the technical provision for ¼-degree reaim, and even possibly the broader provision for "design to conform" rather than simply "conform."

Although the portion of the performance-oriented standard covering headlighting is largely vehicle-based, and is flexible concerning the number and arrangement of lamps contributing to the headlighting function, the approach that we have used preserves some level of control over the number and nature of lamps that can be used in headlighting. This could be done by making a distinction between what we have called "core" contributors and "secondary" contributors. The distinction is summarized in Table 6. The main idea is that, while it may be useful to allow flexibility in the placement and use of secondary or ancillary lamps—perhaps for adaptive lighting functions—there are reasons to constrain the number, nature and overall configuration of the primary lamps involved.

Table 6. Summary of distinctions between core and secondary headlighting contributors

	Type of contributor	
	Core	Secondary
Required number	1, 2, or 4	No restriction
Contribution to total light	At least 75%	No more than 25%
Aimability	Required	Not required
Maximum gradient	No restriction	0.3 over 0.5 degrees
Mounting location	Symmetrical about the vehicle midline, as close to the edges of the vehicle as practicable	No restriction

The main concerns addressed by the restrictions on core contributors are the role of headlighting in marking the width of the vehicle at night, provision for some level of redundancy across lamps and light sources, and aimability of lamps with strong gradients. Core contributors

[5] This table is in the version of the standard published in the 2007 final rule, which is effective on December 1, 2012.

are intended to be the major contributors, supplying at least 75% of the light at the required test locations. Most vehicle-based headlighting systems would likely be similar to current headlighting systems in that they would have either 2 or 4 core contributors. However, we have provided for the possibility that a headlighting system might consist of a single physical assembly. Even with such an unconventional design, the single contributor would have to be symmetrical about the midline of the vehicle, and extend as close to the edges of the vehicle as practicable. Core contributors would have to be aimable, while secondary contributors would not. In keeping with that distinction, secondary contributors would not be allowed to have strong gradients in the patterns that they themselves produce. The details of the gradient definition are based on the gradients currently typical in visual-optical aim headlamps.

The use of vehicle-based photometric criteria introduces a special challenge for replacement equipment. Because all photometric values are defined at the vehicle level, the problem of evaluating replacement equipment is more involved for the vehicle-based approach than for a more traditional lamp-based approach. The key issue is that, while all photometric tests are done on the combined output of all contributors, it may nevertheless be useful to allow individual contributors to be replaced. This introduces the difficulty of determining whether a replacement for any one of the contributors, tested by itself, would conform with the standard.

One approach to this problem would be "minus-one" vehicle-based photometry. In this approach, the vehicle manufacturer would make public, for each contributor, a description of the vehicle-based light output *without* that contributor included. This description would be in the vehicle-based coordinate system that is the heart of the vehicle-based approach. The coordinate system includes pavement targets, overhead signs, and locations that are important for glare control (eyes of oncoming drivers and rearview mirrors of preceding vehicles). While such a coordinate system involves a lot of numerical values, it is in principle a simple thing—in a single, specific format that can be handled easily in photometric software. In order to test any individual beam contributor against the overall vehicle-based photometry, the light output of the contributor would be measured by standard methods (probably using a goniometer), and the measured light output would be added into the minus-one data. The sum would then be evaluated in terms of the vehicle-based requirements.

Administratively, the minus-one photometry would be analogous to descriptions of light sources in Part 564 (or possibly to the individual physical lamp fixtures that are currently typically supplied by manufacturers in order to insure proper mounting of lamps on goniometers for testing). However, unlike the light-source data in Part 564, minus-one photometry would be very closely tied to actual light output. Thus, problems such as sensitivity to errors in the specifications of filament geometries, and the need to determine which light-source parameters are important to include in Part 564, might be naturally bypassed. Indeed, the intention of minus-one photometry is that it should be simply the best estimate of the output of all other lamps that are to be used with a certain contributor. It would be possible to bias the data in a minus-one specification and thereby affect the difficulty of meeting criteria for any single contributor. However, any such biases would be detectable by comparing a full set of actual lamps to the minus-one data.

The minus-one approach would involve the administrative burden of receiving the minus-one photometry from manufacturers and making it available. If that is not administratively possible, a variant of the approach could still work. However, rather than simply looking up the minus-one data, it would have to be estimated by photometering a reasonable sample of the other contributors involved. The output of the contributor being tested would then be added, in software, to the minus-one data set derived from the sample. In the most straightforward version of the minus-one approach, the key criterion for a replacement contributor would be simply whether it meets the photometric requirements when its photometered output is combined with the minus-one values. In that version, the minus-one values are treated as part of the standard; they are assumed to be specified rather than measured by sampling actual lamps. If those values are instead estimated from a sample of the other contributors, the outcome of a test could be influenced by the sampling error of those other contributors. In principle, the test could still be applied in the same way, but the sample size for the other contributors would have to be large. If that approach should prove impractical, one alternative would be to require that headlighting systems be tested as whole systems, and always replaced as whole systems.

5.2 Headlamp test voltage

Headlamp light output varies with vehicle voltage, a circumstance not reflected in headlamp photometry, which is done at 12.8 V. A pure performance-oriented approach to lighting certainly favors taking into account specific vehicle factors, such as the actual voltage supplied by the electrical system at the terminals of lighting equipment. The specification of voltage for photometric testing could perhaps be improved by estimating the voltage provided at the headlamp terminals by each vehicle make-model. However, voltage is not stable even within a make-model. A survey of several studies of vehicle headlamp voltage (Sivak, Flannagan, & Miyokawa, 1999) found the average estimate of the standard deviation for voltage among different vehicles to be 0.5 V. However, in the same survey, preliminary estimates of the seasonal variation in voltage within the same vehicles showed a range of about 0.4 V over the course of a year (with voltage being higher during the cold months of winter). Thus, even providing estimates of voltage for specific make-models would still leave considerable variation within vehicles unaccounted for, because of seasonal factors and perhaps other factors.

A good partial solution for selecting a realistic photometry voltage may be to continue to use a single fixed value for all vehicles, but to revise the current value of 12.8 V. The value of 13.2 V was supported as closer to typical actual vehicle voltages than 12.8 V in the survey by Sivak, Flannagan, and Miyokawa (1999), although their first recommendation was to use 12.8 V, primarily for continuity with existing practice. Their secondary recommendation of 13.2 V was based on the best estimate that could be made from the available data for a year-round average voltage (presumably varying from higher in the winter to lower in the summer). However, the data available at the time were limited, and may not reflect more recent conditions. Further data on the variation both within and between vehicle make-models in actual use would be helpful in deciding this issue. It may be that for some vehicles and some manufacturers there will be better information than in other cases about the voltage that a headlighting system will be supplied with in actual use. In such cases, it would lead to more accurate photometry if the manufacturers specified the appropriate test voltages. It would be best if this could be done in all cases, but even partial use of specific voltage values could be beneficial.

Although the recommended change from 12.8 to 13.2 V is only a 3% change in voltage, it would result in an 11% increase in photometric output from incandescent bulbs. The text-book formula for the ratio of luminous output for different voltages is the ratio of voltages to the 3.4 power: $(V_{new}/V_{old})^{3.4}$ (IES, 1984). This relationship has been demonstrated in laboratory data for headlamps with replaceable halogen bulbs (Sivak, Flannagan, Traube, & Miyokawa, 1998). Those results also demonstrated that the changes in luminous output resulting from changes in voltage are proportional throughout headlamp beam patterns. (Some questions had been raised about whether that was the case because of possible subtle changes in bulb output, resulting perhaps from differences in light output from end turns versus central portions of filaments.) The relationship between voltage and luminous output is shown graphically in Figure 25, for a range of voltages around 12.8 and 13.2 V. The luminous output at 13.2 V is 1.11 times the output at 12.8 V. Given the test results from Sivak et al., at least for the relatively small adjustment from 12.8 to 13.2 V, the IES formula appears to be reliable enough to provide a basis for adjusting the electrical characteristics of bulbs (e.g., as specified in Part 564).

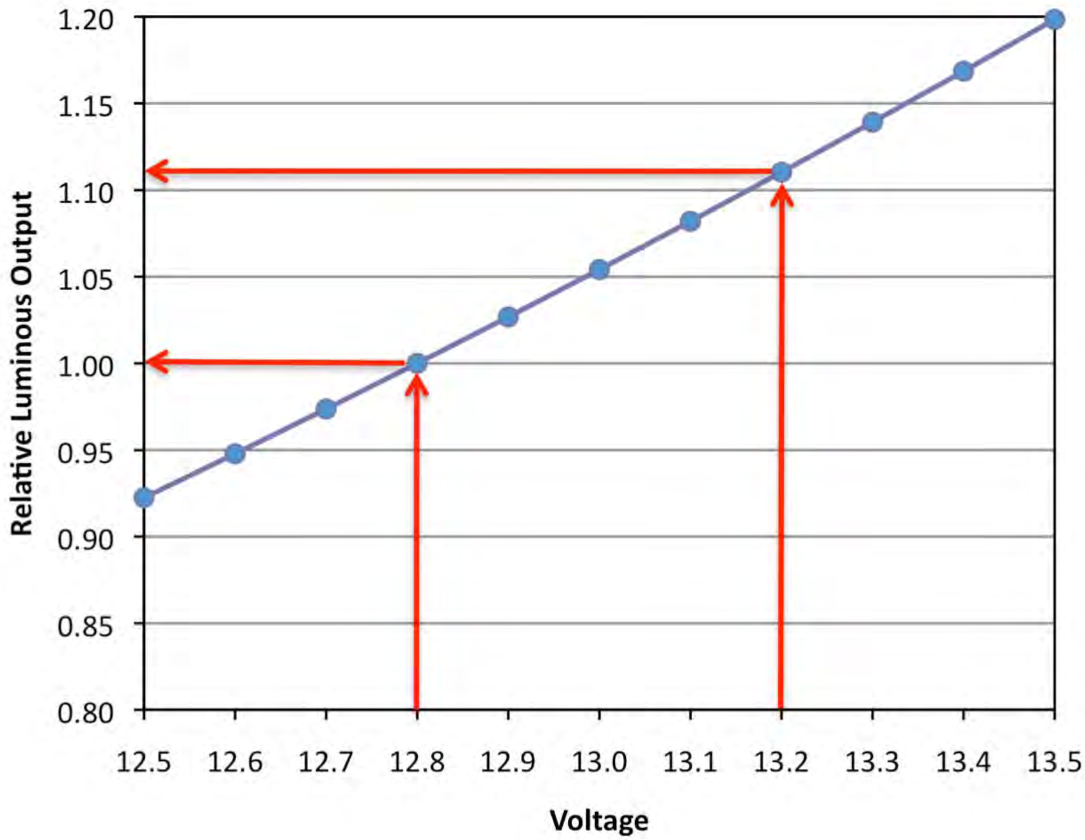

Figure 25. Relative luminous output from incandescent bulbs as a function of voltage, proportional to output at 12.8 V.

A potential problem related to test voltages is illustrated by data on supply voltages and light output from stop lamps on large trucks and trailers (Copenhaver, Guerrier, & Ching, 1990). Voltage itself is not actually an issue for photometry for lamps other than headlamps, since that photometry is based on standard flux rather than voltage, but the performance of lamps on the road will be different from that expected from laboratory photometry if real-world electrical conditions are not as they are assumed to be. Copenhaver et al. measured the voltages supplied to stop lamps, and the light output of those lamps, for a sample of 561 heavy trucks in use at sites in four states. The sample included straight trucks as well as single, double, and triple trailers. A portion of their data (for single van trailers) is shown in Figure 26 (for voltage) and Figure 27 (for photometric output). The voltages are mostly substantially lower than 12.8 V, and, as would be expected from the nonlinear relationship between voltage and light output (IES 1984), the light values for the same lamps are proportionately even lower. Most are substantially below the required minimum value of 80 cd. Copenhaver and Jones (1992) collected a similar set of data for 200 passenger vehicles from the 1986 to 1991 model years (although without direct photometric measurements), and also found many vehicles to have low voltages at the rear lamps. In order to provide an example of the light output that might be provided by lamps at the low end of the range of voltages that they measured, they identified a stop lamp that was at the 5th percentile of that range (10.42 V). Photometric testing for that lamp indicated that it would not reach photometric minima as operated on the vehicle.

The results from the Copenhaver studies are now about 20 years old, and more recent data would be useful for understanding the extent of any current practical problems. Changes in vehicle electrical systems and greater use of LEDs (with substantially lower current draws) may have improved electrical conditions for rear lighting, and signal lighting in general. However, the Copenhaver results at least illustrate the potential importance of taking into account real-world circumstances. A simple performance-oriented approach to the problem suggested by these results would be to test signal lamps as installed, or perhaps with equivalent wiring harnesses (e.g., Stephens & Bolander, 2005).

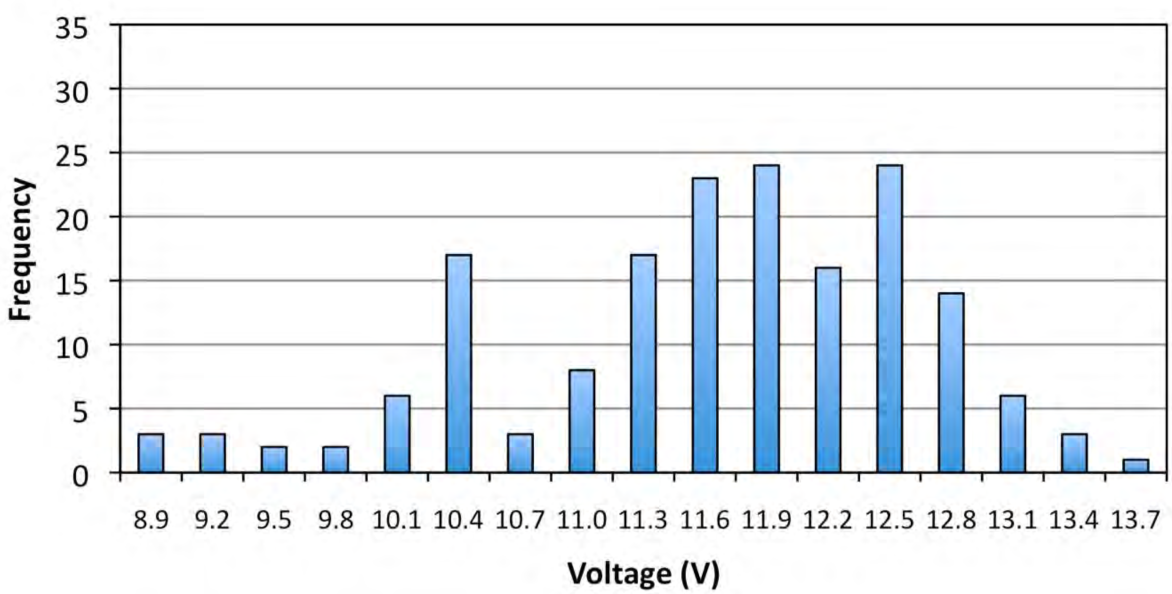

Figure 26. Voltages supplied to the stop lamps at the rear of a sample of 178 semitrailers in use (Copenhaver et al., 1990).

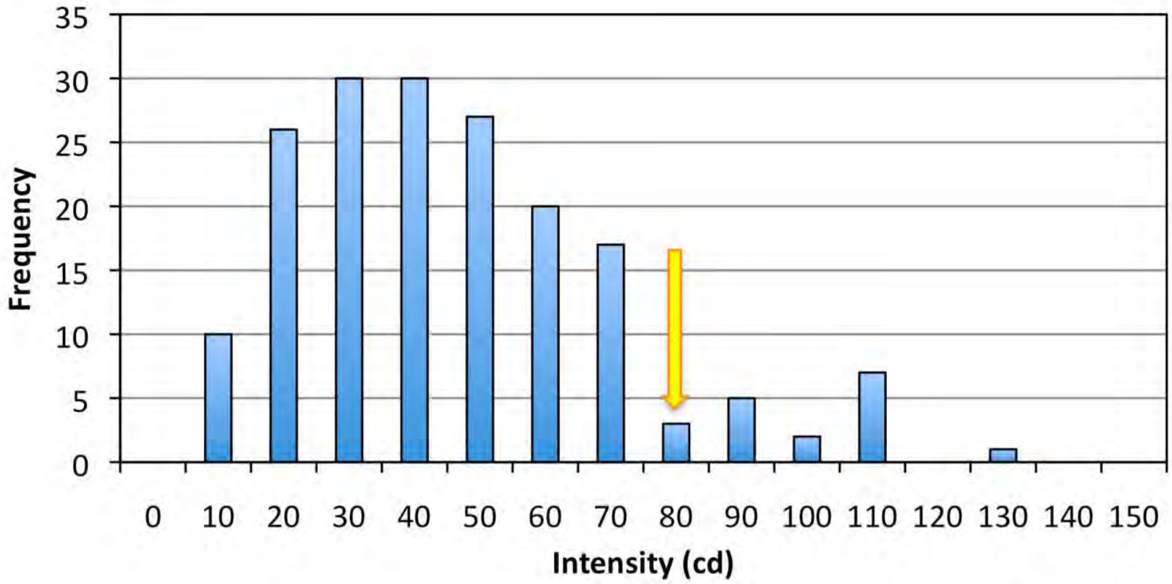

Figure 27. Intensities from the stop lamps on a sample of 178 semitrailers in use (Copenhaver et al., 1990). The yellow arrow indicates the minimum photometric requirement for these lamps at HV (80 cd), the location at which these measurements were made. (Because zonal requirements apply to these lamps, the actual minimum value for HV alone is 0.60 x 80 = 48 cd. However, because the effects of low voltage apply throughout the beam pattern, it is unlikely that other points in the zone would compensate for these low values at HV.)

5.3 Asymmetrical headlighting

Currently, the tradeoff between seeing and glare is constrained by the need for headlamps on the right and left sides of a vehicle to meet the same photometry. The performance-oriented approach would specify light output for an entire vehicle, with continuing (but reduced) constraints on symmetry. This would allow asymmetrical headlighting systems that may be able to achieve better tradeoffs between seeing light and glare. The ideal asymmetric headlighting system is yet to be defined, but it would probably involve larger left-right differences than are permitted by the current version of FMVSS No. 108. The main advantages of asymmetrical headlighting would probably come from reducing glare light from the side of the vehicle closer to the midline of the road (i.e., the driver side of the vehicle). As seen by oncoming drivers, a lamp on that side is closer in angular terms to the lane in which the oncoming drivers are traveling, and therefore closer to objects that might need to be seen in or near their own path. Because both the disability and discomfort effects of glare fall off rapidly as a function of the visual angle separating the glare source and the point that a person is fixating (Holladay, 1927; Schmidt-Clausen & Bindels, 1974), the benefits of shifting glare light from the nearer to the farther headlamp can be substantial.

The performance-oriented approach preserves some limits on the asymmetry of headlighting systems because of concerns about the function that headlamps play in marking the edges of vehicles seen from the front at night, and because of concern for some level of redundancy, so that at least some light is available in the event of the failure of one light source. The marking concern is addressed by the requirement that the core contributors involved in the lower-beam mode be arranged symmetrically and as near to the edges of the vehicle as practicable. The redundancy concern is addressed by the requirement that light in the most critical seeing region (corresponding to the points in Group 1 in Table II of the Appendix) meets 40% of the required minimum values with light originating from either side of the vehicle midline.

5.4 Headlamp mounting height

In recent years, the Society of Automotive Engineers has published reports concerning the mounting heights of headlamps on heavy vehicles (SAE, 1996) and on passenger vehicles (SAE, 2002). One of the main concerns behind these reports was glare from high-mounted headlamps. In the case of passenger vehicles, the report indicated that glare concerns limited the mounting height of headlamps to 850 mm. This is considerably lower than the current maximum for headlamp mounting height in FMVSS, which is 54 inches (1,372 mm). The current maximum is thus higher than the value arrived at by SAE by a factor of: 1,372 mm / 850 mm = 1.61.

The fundamental reason that glare can be a problem with high-mounted headlamps is that, currently, glare control limits do not take into account headlamp mounting height. If glare control limits are written in vehicle-based terms, they naturally put stronger limits on high-mounted headlamps. This permits flexibility in headlamp mounting height while still controlling glare to oncoming drivers and glare via rearview mirrors. Figure 23 provides an illustration of how this works in the performance-oriented approach. In that figure, 20 sample lamps are evaluated in terms of the performance-oriented system at hypothetical mounting heights from 0.5 to 1.5 m. None of the sample lamps meet glare-control maximum photometric limits at or above 1.2 m, and many start to exceed photometric maxima at about 1.0 m. Also, as indicated in Table 4, two of the sample lamps exceeded photometric maxima even when evaluated at their actual mounting heights (which were relatively high compared to most headlamps, at 1.08 and 0.96 m). These two lamps represent what may be the most important situation in which the current version of FMVSS No. 108 and the performance-oriented version would have different outcomes for the same lamps.

5.5 Light for retroreflective signs

Retroreflective performance is strongly dependent on the so-called observation angle (i.e., the angle formed by the positions of the light source, the retroreflective object, and the observer's eye; see Figure 10 for an illustration of this angle). For different vehicle models, this angle varies enough to substantially affect the luminances of objects such as retroreflective signs. For example, the observation angles for the driver of a passenger car viewing an overhead sign at 152 m can differ by a factor of 1.9 between two typical headlamp positions, and the resulting retroreflective efficiencies can differ by a factor of 1.8 (Sivak, Flannagan, & Gellatly, 1993). Figure 28 shows how strongly the relative luminance of retroreflective materials can fall off with small changes in observation angle, for values between 0.1° and 1.0° (based on the retroreflective efficiencies in Table III of the Appendix).

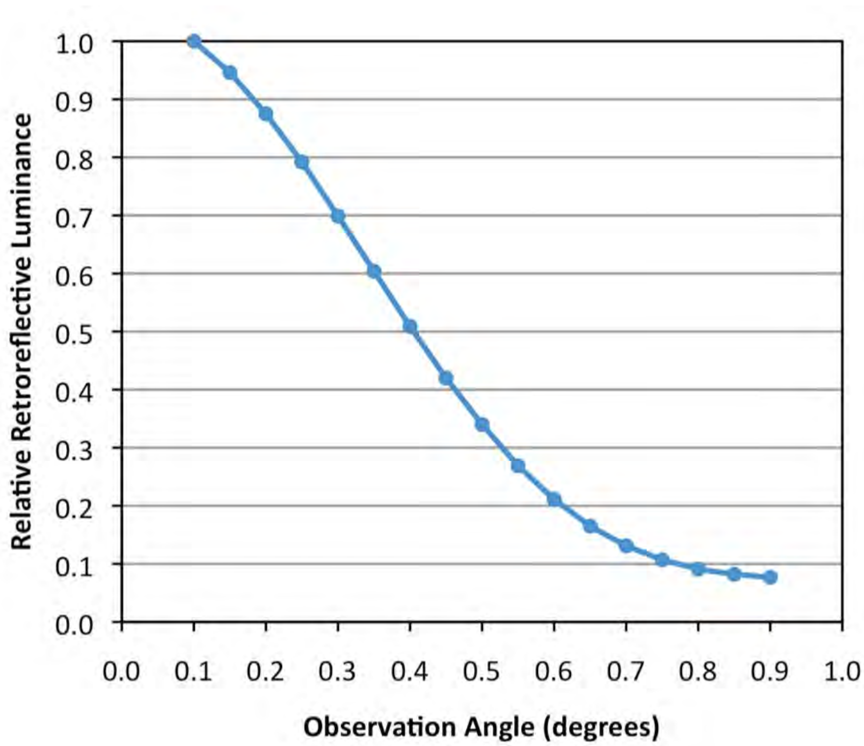

Figure 28. Relative retroreflective luminance as a function of observation angle, based on the data in Table III of the Appendix.

There could be better control of the luminance of retroreflective objects if the locations of headlamps and drivers' eyes on different vehicle models were taken into account in determining the headlighting intensity requirements for sign light. Although retroreflective efficiency is a function of several variables, observation angle is dominant in most situations. Observation angle is the only angle taken into account in the performance-oriented system, but it would be reasonably straightforward to include other angles. The key requirements are that the positions of the headlamps and the driver's eyes be known with reasonable precision.

5.6 Adaptive frontlighting

In recent years, many ideas have been discussed for adaptive headlighting. While it is difficult to anticipate all possibilities, a performance-oriented approach can be adaptable to new developments in adaptive lighting. One of the most promising recent ideas is the possibility of "glare-free" upper beams that would allow a vehicle to operate continuously in what would essentially be an upper-beam mode, even when meeting oncoming vehicles or following close behind preceding vehicles (e.g., Enders, 2001). When other vehicles are present in the headlighting pattern, parts of the pattern would be selectively eliminated just where necessary to avoid glaring the drivers of those vehicles. Because this concept greatly blurs, if not eliminates, the distinction between upper-beam and lower-beam lamps, it raises the possibility that the visual needs of drivers at night could be met without the existence of distinguishable lower-beam lamps.

In addition to providing for modified upper beams, the performance-oriented approach is also by nature compatible with many other forms of adaptive lighting. For example, because all photometric test points are tied to the geometry of a roadway, they could be used to treat curve lighting simply by incorporating the geometry of vertical or horizontal curves in the road.

5.7 Preventing gaps in headlighting

New technologies may allow increasingly precise control of light distribution from various types of lamps, including headlamps as well as signaling and marking lamps. If the economics and light characteristics of new sources (e.g., LEDs) put more of a premium on light than has previously been the case, the result could conceivably be a decrease in light in some areas. This would be analogous to the reduction in upward light from headlamps that occurred when the U.S. fleet moved away from sealed-beam headlamps in the late 1980s (Arens, 1987). That light was useful for seeing signs, but at the time it was not covered by explicit minimum requirements because it was assumed that all lamps would have at least an adequate amount of "spilled" light in that area.

The gaps between and beyond current test locations have been addressed in the new system by additional, more closely spaced locations. It may be preferable to do this in vehicle-based coordinates rather than lamp-based coordinates because specifying the locations in actual space around a vehicle rather than in angular coordinates helps insure that they have the intended effects in real space. The performance-oriented system uses considerably more points than are currently used in FMVSS No. 108 (e.g., the lower-beam function involves 2,220 test points). As illustrated in Figure 12, those points cover the driver's field of view much more completely than the traditional test points. The coverage is more complete for areas of the pavement in front of the vehicle, as well as the area from 4 to 10 degrees up, which has previously contained no test locations.

The use of multiple, closely spaced test points is similar in some ways to the use of photometric requirements based on zones in some lighting regulations, such as ECE R112 (UNECE, 2010a). Nominally, zones requirements mean that "all" points in a zone must meet a certain photometric limit. Specifying a finite, although perhaps large, number of points can have virtually the same effects, depending on how the points are chosen and how densely the photometric data are measured before interpolation. Defining points allows the photometric test methods to be more explicit, and allows more flexibility in three dimensions than traditional zones, which have normally been two-dimensional.

5.8 Headlamp aim

How headlamps are aimed, and especially how they are aimed vertically, is important for the overall effectiveness of headlighting. An analysis of the photometric consequences of the real-world ranges of various factors that affect lower-beam headlighting concluded that vertical aim was dominant, with the distant second factor being having one lamp burned out (Sivak, Flannagan, & Miyokawa, 1998). Because vertical aim is important for the overall performance of a headlighting system, a performance-oriented approach necessarily involves specifying aim in some way. Just as in the case of headlamp mounting height, this does not necessarily involve an explicit requirement, but the need to meet photometric limits at points in three-dimensional space around a vehicle means that only a certain range of aim will work. Photometric limits defined in vehicle-oriented terms might be read as implying that those limits must be met by the vehicle at the time it is sold, and that would imply, in turn, that the headlamps would have to be aimed within an appropriate tolerance at that time. Although the various causes of misaim are not fully documented, it may be that improved initial setting of aim would have substantial benefits on headlamp photometric performance. However, the state of headlamp aim is a transient setting rather than a permanent state of a vehicle. If headlamp aim was required when vehicles were sold, it might be a useful practical measure to introduce some form of temporary seal or locking measure to indicate explicitly that a lamp has been aimed.

Headlamp aim appears to be important enough that even partial measures might be helpful. Therefore, even if headlamp aiming is not required, it might be useful to require headlamps to be marked with the range of vertical aim for which they meet photometric criteria. Figure 29 shows a summary of data from Figure 24 for the ranges of vertical aim that are within criteria for a sample of 20 lamps. In all cases, the range is substantially less than the SAE limits of ± 4 inches at 25 feet (± 0.76°, corresponding to a range of 1.52°), and there is substantial variability among the lamps. Because headlighting systems appear to differ in aim tolerance, knowing the allowable range for a specific headlighting system could be useful for a vehicle owner or for anyone aiming the lamps on a specific vehicle.

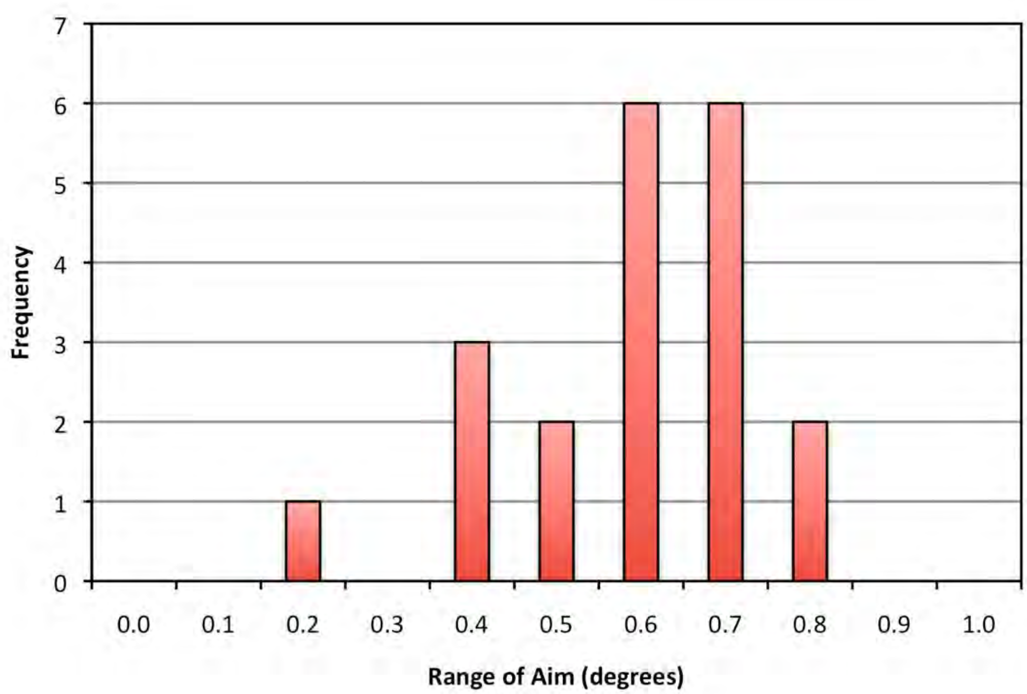

Figure 29. The distribution of angular ranges over which 20 lower-beam headlamps from the 2004 model year are within all of the photometric requirements of the performance-oriented system.

5.9 Signal lamp luminance

Currently, photometric limits are different for certain lamps based on the number of lighted sections that make up the lamp. The number of lighted sections was adopted as a surrogate measure for the lighted area of a lamp, based on assumptions about how big a lighted section would normally be, given incandescent bulbs of typical size. These assumptions my not fit well for sources such as LEDs and miniature bulbs, which can be considerably more numerous than conventional bulbs even in lamps of moderate total area. In the performance-oriented approach, measures of lighted area are substituted for number of lighted sections, thereby making this requirement independent of source type. The language follows recent SAE documents (SAE, 2005, 2007) in retaining the use of terms for multiple lighted sections but adding areas that are considered equivalent to various numbers of lighted sections. Also following the SAE documents, the equivalent areas are: less than 225 cm^2 is equivalent to one lighted section, from 225 to 450 cm^2 is equivalent to two lighted sections, and more than 450 cm^2 is equivalent to three lighted sections. More detail on the derivation of the SAE values is provided by Flannagan, Sivak, and Traube (1998). Two task forces have recently been established under the SAE Lighting Committee to develop methods for measuring the effective projected luminous lens area (EPLLA) of lamps. The approach that is being taken by these task forces is to use imaging photometers that would be used to generate photometrically calibrated images of the lamps from one or more angular positions. Those images would then be processed to determine what portion of the lamp is in fact luminous.

5.10 Masking of front turn signals

Currently, the photometric requirements for a front turn signal are determined partly by the spacing between the turn signal and a lower-beam headlamp (or auxiliary headlamp or fog lamp), but the factors by which the requirements are adjusted do not depend on the angle from which the turn signal is viewed. Because the beam patterns of lower-beam headlamps are highly directional, the actual extent to which a turn signal may be masked by glare from a headlamp depends strongly on viewing angle. Figure 30 illustrates how this would work in a typical traffic situation. Three vehicles are shown: two stopped on either side of an intersection, and a third vehicle approaching that intersection from the left. Whether the driver of the approaching vehicle is intending to turn at the intersection, either right or left, is potentially important information for the drivers of both of the stopped vehicles. It is therefore important that they both be able to see a flashing turn signal on either the right or the left side of the approaching vehicle. However, the driver to the left of the approaching vehicle (at the top of the illustration) will be exposed to substantially less glare, from both the left and right headlamps, than the driver to the right of the approaching vehicle (at the bottom of the illustration). This is because lower-beam lamps emit more light to the right, where glare to oncoming drivers is less of a concern, than to the left.

The absolute amounts of glare that each driver is exposed to, and the difference in glare levels for the right and left driver, will vary with the distance of the approaching vehicle. The most critical range of distance for seeing turn signals, in this example and in other traffic situations, depends on several variables, including vehicle speeds. Some examples of potentially critical distances, from studies that have addressed the problem of turn signal masking, are 300 feet (91.4 m) (Palmer & Kantowitz, 1994), and a series of distances: 200, 400, 600 feet (61.0, 121.9, 182.9 m) (SAE, 1978). For the situation illustrated in Figure 30, the lateral separations of the eyes of the drivers of the stopped vehicles, from the nearest (same-side) turn signal on the approaching vehicle, are 12.8 m for the stopped driver to the left and 9.8 m for the stopped driver to the right. Over the range of approach distances used in the SAE study (61.0 to 182.9 m), the angles from the axis of the same-side turn signals (and therefore also from the axis of the headlamps adjacent to those turn signals) to the eyes of the stopped drivers range from 4.0° to 11.9° for the left driver and from 2.9° to 8.5° for the right driver. Those angles cover reasonably well the horizontal range of photometric angles for turn signals, and are also within an angular range in which the light output to the left and right from a typical lower-beam headlamp is substantially asymmetrical.

Figure 31 illustrates the magnitudes of the photometric values involved at the central five test locations specified for front turn signals (-10, -5, 0, 5, 10 degrees horizontally; all at 0 degrees vertically). The upper curve shows headlamp intensities that are typical at the test points (Schoettle et al., 2001), illustrating how different the effects of masking could be for observers viewing a vehicle from the right-front versus the left-front. The lower two curves with solid symbols show the current base and augmented (x 2.5) minimum values for the turn signal as specified in FMVSS No. 108. In contrast to the headlamp intensities, the requirements for the turn signals are symmetrical. It is likely that turn signal visibility would be improved if the intensities of the turn signal in various directions, rather than remaining symmetrical, were matched to the corresponding output of the headlamp.

The performance-oriented system includes an adjustment to the factors by which the turn signal minima are increased. The amount of the adjustment was selected by assuming that the headlamp intensities involved in early SAE tests on this issue (SAE, 1984) were approximately 1,000 cd, and further assuming that the ratios between headlamp and turn signal intensities are critical for determining the visibility of the turn signal lamp. The photometric adjustment to the turn signal that is currently used (ranging from 1.5 to 2.5, depending on the type of masking lamp and spacing distance) would be itself adjusted by a factor based on the actual intensity of the headlamp divided by the assumed test intensity (1,000 cd), provided that the overall adjustment to the base minimum is ≥ 1.0. For example, consider the data in Figure 31 for the test point at horizontal and 5.0 degrees right. The headlamp output at that point is about 3,100 cd. The revised turn signal minimum would therefore be: 3,100 cd / 1,000 cd x 2.5 x 200 cd = 1,550 cd. The open triangles in Figure 31 show the corresponding values at each test point.

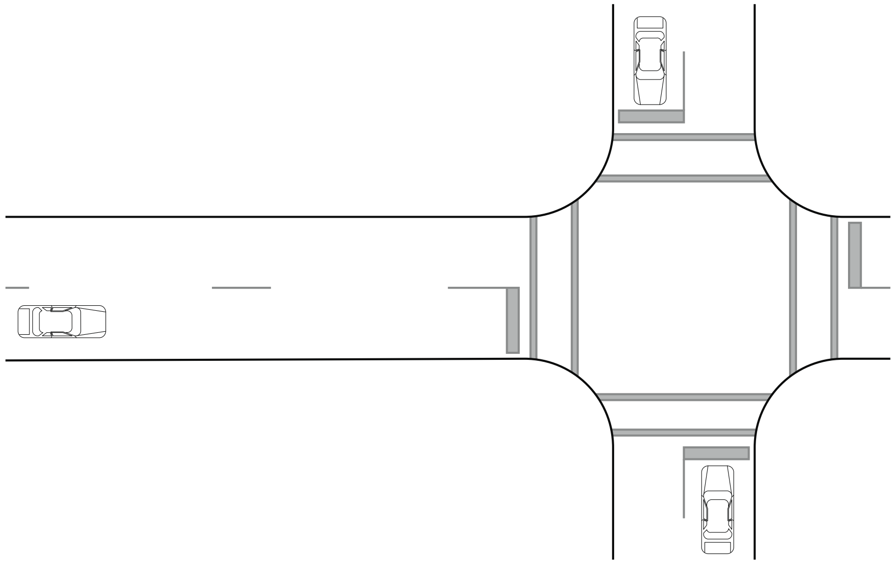

Figure 30. Two vehicles stopped at an intersection. It would often be important for the drivers of such vehicles to see the front turn signals of a third vehicle, approaching from the left.

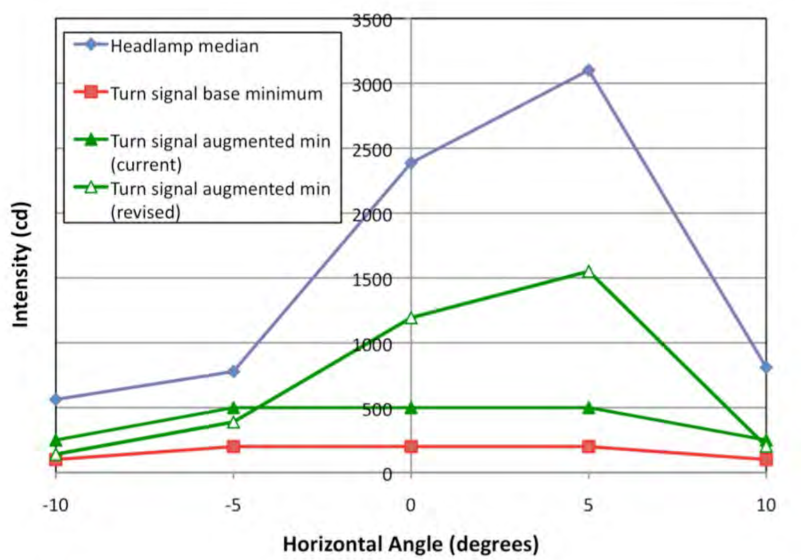

Figure 31. Front turn signal minima and typical lower-beam headlamp intensities at the central five test points for turn signals.

5.11 Stray up light from headlamps

The primary negative effects of stray light from headlamps at very high and wide angles involve backscatter from fog, rain, snow, or dust along a driver's lines of sight. Current lamp-based angles for stray light do not reflect the actual lines of sight, whereas a performance-oriented system naturally does that. For example, scatter in an inboard direction (to the left of the right lamp or to the right of the left lamp) may be more important than outboard scatter because a driver's eyes are always located between the lamps. The performance-oriented approach also allows the assessment of combined light from two or more headlamps. We have established two sets of points in front of the vehicle that populate the three-dimensional spaces corresponding to the driver's view through two angular regions: (1) a region from 4 to 10 degrees up that previously has not been explicitly controlled in FMVSS No. 108 because it was assumed to be adequately controlled by a combination of test points at lower angles and likely beam gradients, and (2) the region above 10 degrees up. The driver's view is represented by the most extensive set of viewing angles defined in FMVSS 104 (Windshield Washing and Wiping Systems). By taking into account total illuminance of each of the points in those regions, the performance-oriented approach may be better able to control light at high angles that traverses those regions, and which could be scattered back to the driver's eyes from fog, rain, snow, or dust.

5.12 Robustness of photometric tests

By using many photometric test locations and making overall outcome dependent on combinations of points rather than individual points, the performance-oriented approach may allow robust testing. The application of the performance-oriented system to sample lamps illustrated that the provision for 0.25-degree reaim that has traditionally been used in FMVSS No. 108 may not to be as important in the performance-oriented system. Only 5 of 20 lamps passed the photometric tests currently in FMVSS No. 108 without reaim, but 16 of the 20 lamps passed the new tests, and the ones that failed appeared to fail for valid reasons.

The performance-oriented system may also make practical the use of a provision to "conform" rather than "design to conform" to the new criteria. The possible robustness of the new system is illustrated in Figure 32, which shows how well the 20 sample lamps meet a current FMVSS No. 108 test point (the 15,000 cd minimum at 1.5 degrees down, 2.0 degrees right), as well as with a corresponding set of points in the new system (Group 4 in Table II of the Appendix). In both versions of the requirement, all 20 lamps meet the minimum value. This is shown by the fact that all bars in the histograms are at levels of 1.0 or more times the minimum photometric requirements. However, the outcomes for the lamps under the current system (shown by the red bars) are more marginal, with more lamps falling near the criterion than under the performance-oriented system (shown by the blue bars). For example, there are only two lamps that are under 1.5 times the minimum requirement under the performance-oriented system, whereas most of the lamps (11) are below 1.5 times the minimum under the current system.

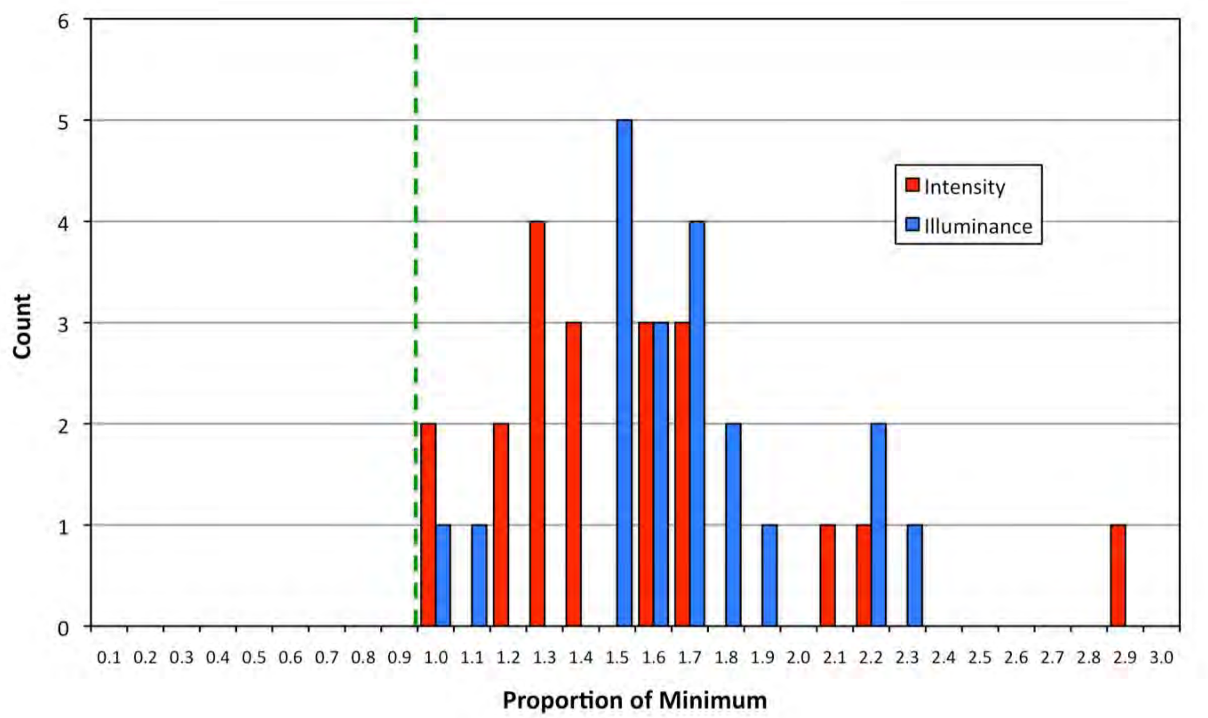

Figure 32. Current (intensity) and vehicle-based (illuminance) limits for a set of 20 headlamps from the 2004 model year (based on the point 1.5 D, 2.0 R).

6 Signal lamp locations and test angles

The vertical ranges of photometric test locations for signaling and marking lamps (including front and rear turn signals, tail lamps, stop lamps, parking lamps, and side marker lamps) extend from 10 degrees up to 10 degrees down; and there are visibility requirements further out, at 15 degrees up and down. There are provisions to reduce the down-angle extent to 5 degrees down for lamps that are mounted less than 750 mm high. That height corresponds roughly to the boundary between mounting heights of front and rear turn signals. We recently surveyed the mounting locations of various automotive lamps on passenger vehicles of the 2002 model year (Schoettle, Sivak, & Nakata, 2002). The averages and standard deviations of the mounting heights of front and rear turn signals were as follows: 0.66 m mean and 0.07 m standard deviation for front, and 0.86 m mean and 0.05 standard deviation for rear. The normal distributions based on these values are shown in Figure 33. Based on these distributions, one would expect that front turn signals would usually not have requirements below 5 degrees, while rear turn signals usually would. The distinction fits well with these key signal lamps.

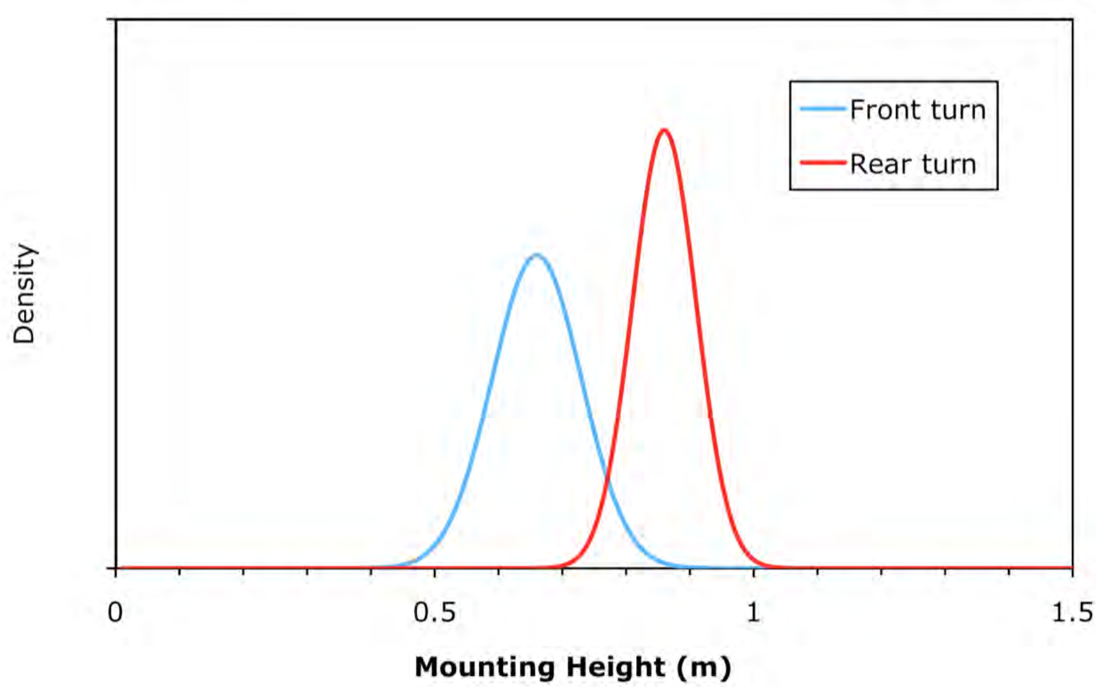

Figure 33. Distributions of heights for front and rear turn signals on vehicles of the 2002 model year.

However, in practice the mounting heights of these lamps may not be as important for determining their required angular ranges as roadway geometry. Figure 34 illustrates the ranges of distances on flat and level pavement corresponding to test points at 5 and 10 degrees down for various mounting heights. All of the distances are extremely short, and virtually all down angles for these lamps correspond to points below the eyes of a driver. However, based on vertical curvature, the roadway situations in which various up or down angles are important may not be very different for lamps of various mounting heights. The ranges of distances shown in Figure 34 illustrate how mounting height can affect "near field" circumstances (which, for the most part, are nevertheless not of great concern), but "far field" differences (which may be of greater concern) will generally not be affected by mounting height, but probably will be markedly affected by changes in roadway vertical curvature.

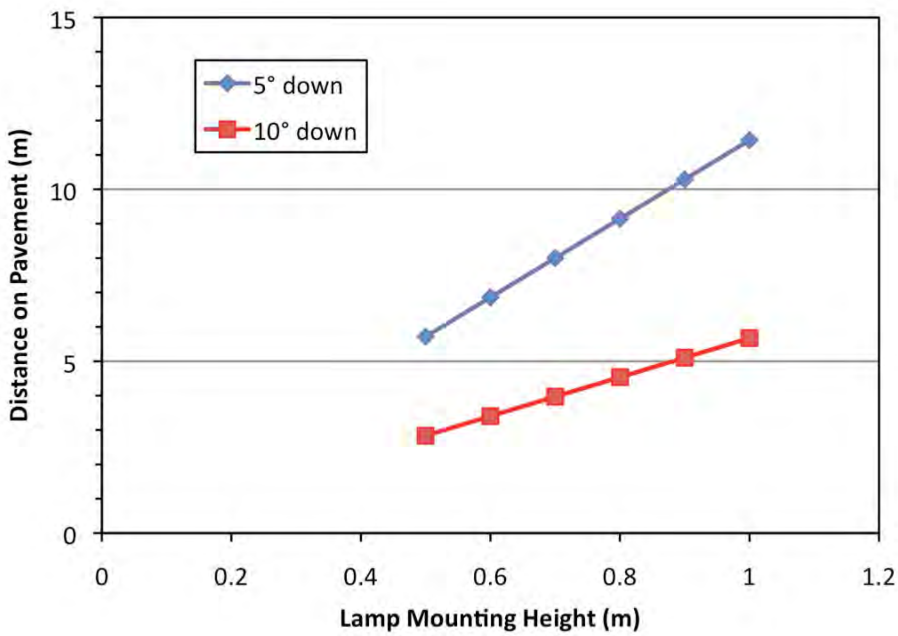

Figure 34. Distances on pavement corresponding to test angles of 5 and 10 degrees down for lamps over a range of mounting heights.

Causal observation suggests that it may be unlikely to encounter changes in roadway geometry abrupt enough to place the eyes of a rearward driver as low as 10 or even 5 degrees below the axis of a stop lamp on a preceding vehicle. The circumstances needed for a driver's eyes to be located at such low angles would appear to require abrupt changes in the pitch of a road, so that a lead vehicle would be pitched down by, for example, 5 degrees relative to the average pitch of the road between the lead vehicle and the rearward driver. However, we are not aware of any formal evidence on this issue. Standards for roadway vertical curvature are based on a simplified model of that curvature, using parabolic curves (AASHTO, 2004), and that idealization may not capture some extreme situations on roads that are not up to ideal standards.

In order to illustrate this issue, we conducted a small pilot study on roads in Washtenaw County, Michigan. The sampling was very informal and biased toward what we believed to be abrupt changes in road curvature or pitch. We placed a video camera on the back of a vehicle, between the stop lamps, and recorded the rearward scene as the vehicle was driven over relatively hilly roads. The resulting data should not be considered serious measurements of typical roads, and certainly do not represent a systematic sample of any well-defined set of roads. The data should be considered only an illustration of the kind of data that a more elaborate study might collect. We digitized the locations of the eyes of drivers who appeared in the video and translated those locations into angular terms relative to the camera (and relative to the axes of the rear lamps on the test vehicle). The resulting pilot data are shown in Figure 35. With strong cautions about the weak quality of these data, we believe that this small pilot study does suggest that it may be difficult to find situations in which the eyes of a rearward driver are at very low angles relative to rear lamps. It appeared to be easier to find cases in which a driver's eyes were at relatively high angles, on sags. However, it would be very difficult for a survey to capture the full range of vertical curvatures that probably exists. It may be that, even if they are rare, situations can be found in which down angles of 5 degrees or more occur.

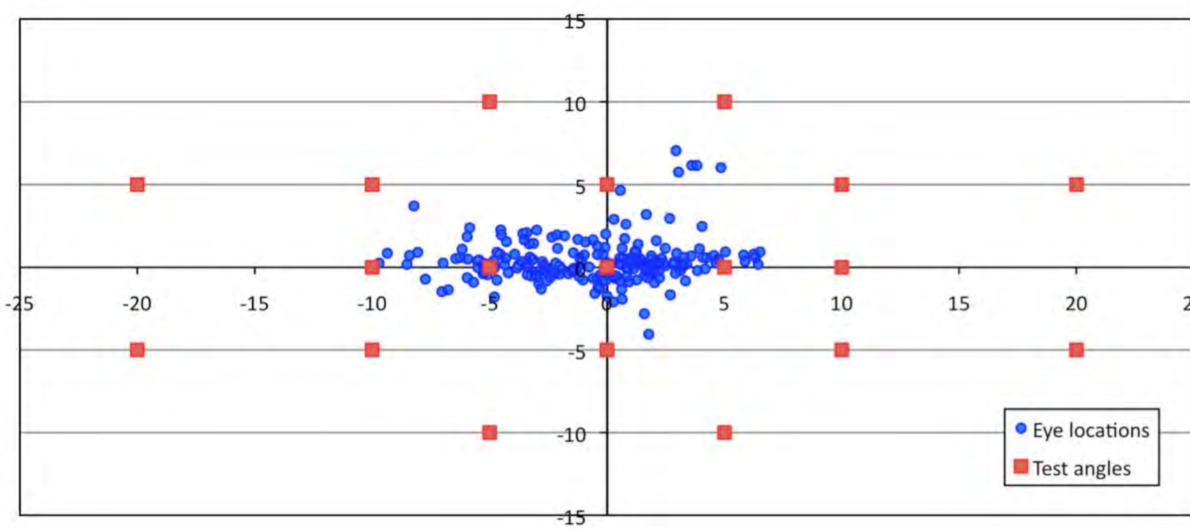

Figure 35. A small set of pilot data for rearward driver eye positions from the perspective of a point midway between the left and right stop lamps, sampled informally from roads with abrupt changes in vertical curvature in Washtenaw County, Michigan.

The lack of clear data on the angular locations of rearward drivers' eyes makes it difficult to apply the performance-oriented approach to photometric test points for signaling and marking lamps. However, a partial approach to performance-oriented test points already exists in the form of the provision for reducing the down angles for lamps mounted less than 750 mm above the road surface. A geometric analysis of the locations of drivers' eyes relative to lamps at a range of mounting heights demonstrates how this provision works. Figure 36 shows a typical situation, for two stop lamps located 1.32 m apart, 0.85 m high (Schoettle, Sivak, & Nakata, 2002), and viewed by a rearward driver with an eye location 1.11 m high and 0.35 m from the centerline of his or her own vehicle (Sivak, Flannagan, Budnik et al., 1996), with both vehicles on a straight and level road. The figure shows the angular positions of the midpoint between the driver's eyes from the perspectives of the left and right stop lamps. Because the stop lamps are mounted lower than the driver's eyes, the locations are all at upward angles. The points in the figure show the angular positions of the eyes at a series of distances between the vehicles (measured from bumper to bumper) ranging from 1 m (the highest and widest angles) to 50 m (the small angles near the middle of the figure). For the typical situation, the eye locations are well separated from the low test points at 5 and 10 degrees down. However, the permitted locations for stop lamps span a substantial range, from 15 to 72 inches (0.381 to 1.83 m). We next turn to that range of locations.

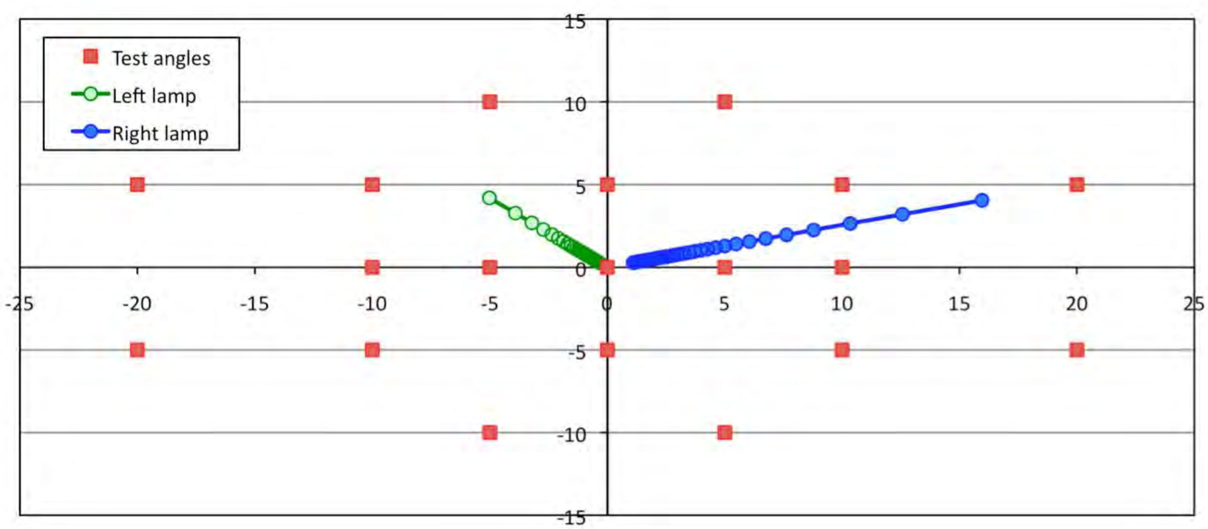

Figure 36. The position of a rearward driver's cyclopean eye point from the perspectives of left and right stop lamps on a typical passenger car for a series of distances on a straight and level road ranging from 1 to 50 m, measured from bumper to bumper, shown in the context of the angles for photometric test points.

Figure 37 shows eye locations of a rearward driver relative to stop lamps at a series of five mounting heights, evenly spanning the permitted range for stop lamps: 0.381, 0.743, 1.11, 1.47, 1.83 m. (Appropriately, the middle value matches a typical driver eye height and the value just below that just qualifies for the reduction in down test angles for lamps mounted below 0.75 m). The resulting range of eye locations corresponds reasonably well with the locations of the test points. That suggests that, for the full permitted range of mounting heights, the range of test points is just about right. However, for a stop lamp of known height, the range of test points extends too far vertically (assuming a straight and level road, in lieu of real data on driver eye locations similar in form to the pilot data in Figure 35). Specifically, lamps mounted at 0.74 and 0.38 m correspond to the second highest and highest lines of points in Figure 37, respectively. Although such lamps would not be required to meet test points at 10 degrees down, those locations are not close even to the points at 5 degrees down. Without clearer data on the effects of roadway vertical curves, it is difficult to know how much of a margin to build into these test points, but it appears that the provision to reduce down-angle tests for lamps mounted lower than 0.75 m could be extended both in terms of how many test points are modified and in terms of how low lamps have to be in order to be affected. Our recommendation on this issue is that better data about vertical curvature of roadways is needed, and that, while reductions in the extent of vertical test points are likely to be appropriate, no changes can be made with confidence without such information.

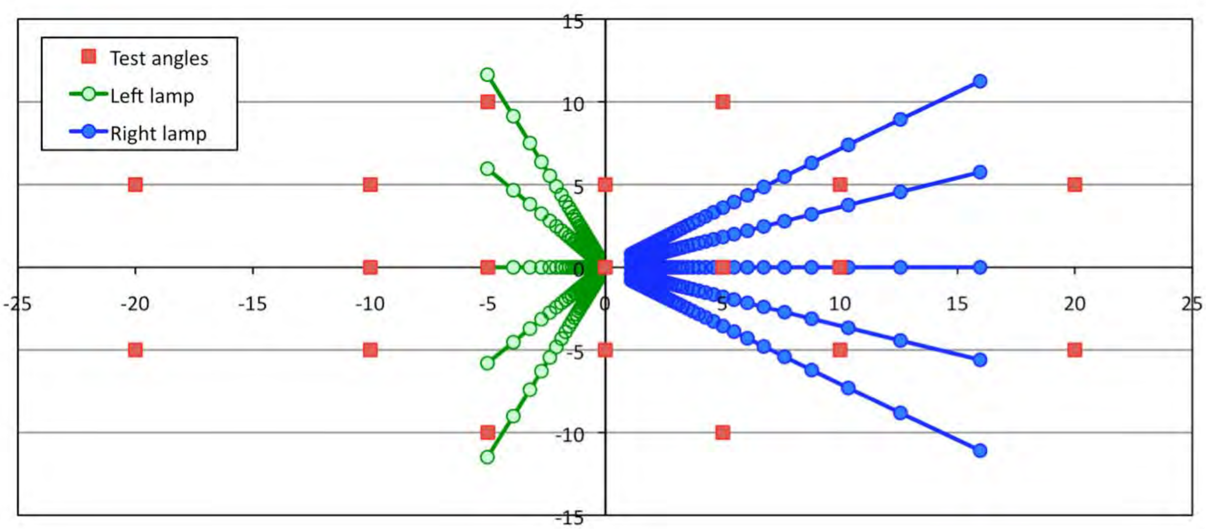

Figure 37. Similar to Figure 36, but for a series of five pairs of stop lamps mounted in even increments from the lowest to highest permitted mounting heights (0.38, 0.74, 1.11, 1.47 and 1.83 m).

7 Photometric methods for implementation

The ranges of photometry needed to cover the performance-oriented test locations depend to some extent on where lamps are mounted on the vehicle. For example, if headlamps are mounted relatively high, lower angles need to be photometered for those lamps in order to provide coverage of light toward points on the pavement. The angles required are straightforward to calculate from vehicle geometry and the locations of the test points themselves (as given in the Appendix). However, it is also easy to specify reasonable default ranges of photometry that will cover the great majority of headlighting systems.

Figure 38 shows the ranges of photometry needed to cover all 2,220 test locations for lower-beam headlighting, for lamps mounted almost anywhere headlamps are typically found: from a minimum height, based on the mean headlamp height for passenger cars minus two standard deviations (0.58 m), to a maximum height, based on the mean headlamp height for light trucks and vans plus two standard deviations (0.99 m), and laterally out to the width of headlamp pairs on light trucks and vans plus two standard deviations (± 0.83 m from the vehicle midline) (all data from Sivak et al., 1996).

The central test points are covered by a rectangular candela matrix extending ± 30 degrees horizontally and from 8 degrees down to 6 degrees up (indicated by the red box in Figure 38). This region should be scanned at 0.2-degree intervals to provide accurate measurement of the strong gradients that are likely to be present there. The region needed for the 4-10 up points is virtually a subset of the region needed for the points above 10 degrees (indicated by the blue and green boxes in Figure 38, respectively). A single set of points extending ± 86 degrees horizontally and from 1 to 78 degrees up can therefore be used for all of the points in both of these higher ranges. That region can be scanned at 1.0-degree intervals without missing significant streaks or other high-scattered light. That resolution is the same as specified in a current SAE draft of J1383 (SAE, under review).

Figure 39 shows the range of photometry needed to cover all 20 test locations for upper-beam headlighting for the same range of headlamp mounting locations used for Figure 38. The required candela matrix extends ± 16 degrees horizontally and from 7 degrees down to 3 degrees up. This region should be scanned at 0.2-degree intervals.

The ranges shown in Figure 38 and Figure 39 are sufficient to cover all of the performance-oriented photometric test locations for virtually all current vehicles. However, for most vehicles more restricted ranges would be sufficient. Given that the locations of headlamps can be known for specific vehicles, the angular ranges of all of the test points relative to those locations are straightforward to calculate. In particular, the ranges of photometry for the regions above 4 degrees would not normally need to be as wide as shown, because most light directed toward outboard locations is not of interest.

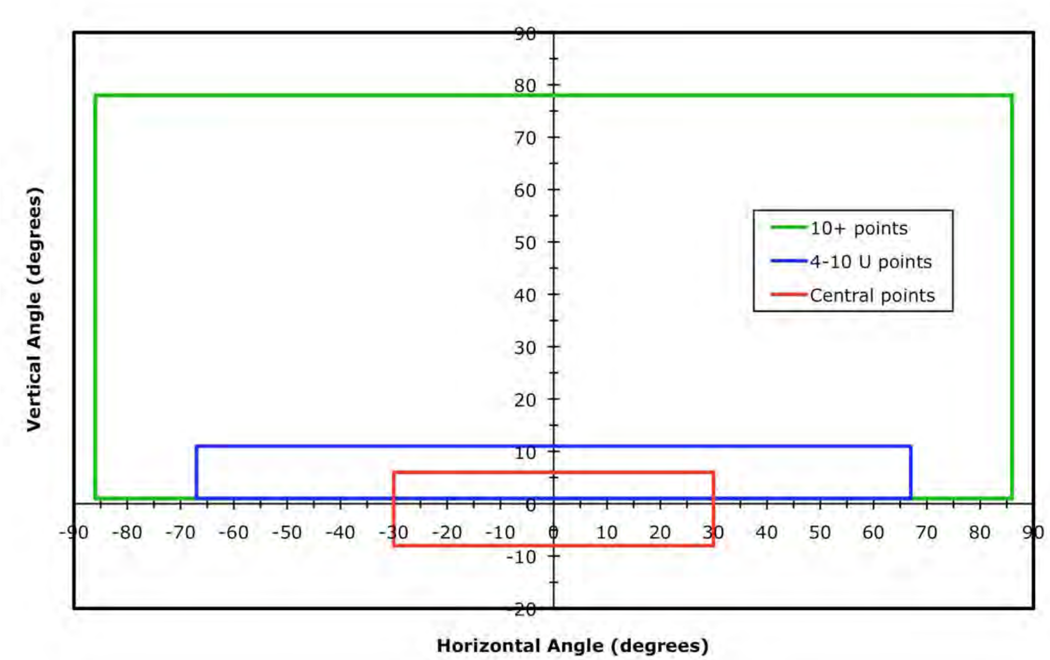

Figure 38. Rectangular regions for candela matrices sufficient to calculate total illuminance at the identified sets of test points for lower-beam mode in the performance-oriented system.

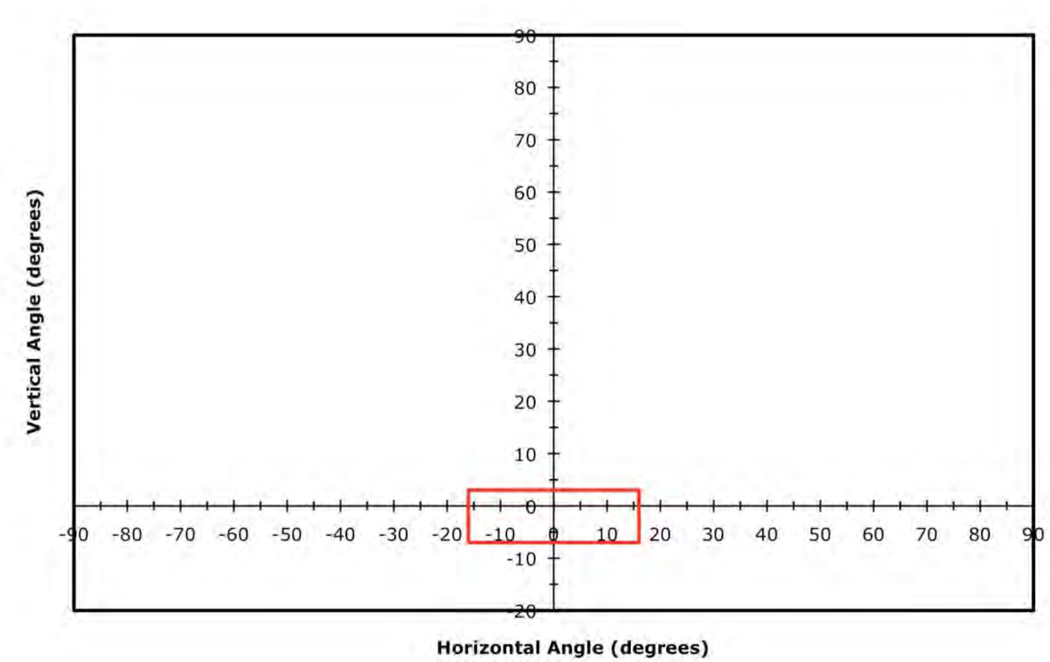

Figure 39. A rectangular region for a candela matrix sufficient to calculate total illuminance at all of the test points for upper-beam mode in the performance-oriented system.

8 Software useful for implementation

The headlighting portions of the performance-oriented version of FMVSS No. 108, as embodied in the photometric values in the Appendix, are currently implemented in code that is easily run on most computer platforms. The software takes as input candela matrices and variables that describe lamp locations, and provides as output both pass/fail information as well as various background variables that may be useful in understanding how and why certain headlighting systems pass or fail. We have developed and used the software throughout the work on the performance-oriented system. Many of the results described in this report for how the performance-oriented approach applies to current lamps were obtained by using the software. Ultimately, the software may be useful for explaining the performance-oriented changes in FMVSS No. 108, and in testing outcomes with actual lighting systems. The software is not necessary to implement a performance-oriented approach; the tables of illustrative photometric values in the Appendix determine the performance-oriented photometry. However, anyone wanting to check a lighting system against the performance-oriented version would very likely have to develop software much like the code that we have developed and used. Using the code can be particularly helpful for the bookkeeping aspects of some of the more involved parts of the system, such as evaluating and combining the outcomes of large numbers of test points, combining the light from multiple lamps, and taking into account the geometry involved in calculating the luminance of retroreflective signs.

9 Summary

9.1 State of the performance-oriented approach

The new approaches to regulation in FMVSS No. 108 that are described and analyzed in this report appear to offer several potential benefits. In the domain of signaling and marking lamps, lamp area and luminance could be directly addressed rather than being controlled through the surrogate of number of lighted sections. In the domain of headlighting, the approach for photometric testing of headlighting is fully vehicle-based. This has several consequences: headlamp mounting height is taken into account and controlled in a natural and graded fashion, the effects of headlamp aim are quantified and can be reported to vehicle owners and to people who maintain headlighting systems, and the control of headlamp glare is more closely tied to the actual geometries of vehicles and encounters between vehicles in traffic. Because the locations of the photometric test points for headlamps are based on real geometry instead of approximate angles, and because the photometric values used in testing reflect the combined output of all lamps rather than single lamps, the relationship of the test points to desired lighting functions is better defined. A large number of precisely located test points can therefore be established, grouped into coherent sets, and tested against summary criteria for those sets. Because criteria are applied to groups of points rather than individual points, the outcomes of the photometric tests can be relatively robust. The large number of test points provide more extensive coverage than the current test locations, leaving no significant gaps between test locations, and the combination of points for testing makes it less likely that a headlighting system would meet or not meet the criteria based on small irregularities in light output in the immediate location of a single test point.

9.2 Issues for the future

There are several issues for which a performance-oriented solution might be beneficial, but for which there is currently not enough research knowledge or practical knowledge to support a clear approach. One of these issues is the geometry of test points for signaling and marking lamps. The partial analysis that we have been able to develop for that issue suggests that those points may be more extensive than necessary, particularly at low angles. However, not enough is known about road geometry and the angles from which drivers may view those lamps to make a definitive recommendation about how to change the angles.

Another area involves the physical tests for headlighting devices. The approach presented here essentially preserves the intricate logic of physical test requirements for three types of contributors, based on the previously established types of headlamps: sealed beams, integral beams, and replaceable bulb lamps. No photometric requirements are different among those types of beam contributors, but the distinction is preserved because it is used in determining how the physical tests apply. A truly performance-oriented approach for physical testing could involve establishing a universal set of physical tests, based closely on the conditions that lamps are subjected to in real use. If such a universal set could be constructed, it could in principle make it unnecessary to revise physical tests when new technologies, which may have different sensitivities to environmental conditions, are introduced (e.g., differences in heat effects on LED and incandescent sources). However, such an approach would at least require a major research effort and might not prove useful in practice, given the large number of possible differences in sensitivity to environmental conditions.

A closely related set of issues involves the possible treatment of new forms of adaptive headlighting, such as so-called adaptive driving beams (e.g., Dreier & Rosenhan, 2009; Schmidt, Kalze, & Irmscher, 2009). Suggestions for how to regulate such systems were recently submitted by the Groupe de Travail "Bruxelles 1952" (GTB) to the Working Party on Lighting and Light-Signaling (GRE) of the United Nations Economic Commission for Europe (UNECE, 2010b). The suggested approach involved performance-oriented elements, including a test drive on a course chosen to include a mix of real road types (urban, motorway, country). The performance-oriented system described here could be extended to create virtual test drives for such systems by introducing varying road geometries and dynamic encounters with other road users (motorized vehicles, bicycles, and pedestrians). The basis for adding such elements to software headlighting evaluations is well established (e.g., Mortimer & Becker, 1973; Bhise et al., 1977).

Finally, even in the case of requirements for which we believed there was an adequate research basis to formulate a performance-oriented version, many of the specifics described in this report could be further evaluated and revised. Prominent possibilities include: (1) revising the test points for headlighting photometry to provide better coverage of all portions of roadways, and (2) refining the combination rules used with those test points to establish the best balance between full coverage and ensuring that the test outcomes are not overly sensitive to small deviations. The performance-oriented headlighting photometry as described here was tested with a set of recent headlighting systems, and the results were reasonably favorable. However, perhaps the most valuable extension of this work would be to supplement that testing with a large number of current or proposed headlighting systems.

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Appendix: Illustrative Photometric Values

This appendix presents tables with illustrative values for (1) upper beam photometry, (2) lower beam photometry, and (3) criterion retroreflective performance for sign materials. In the tables presented in this appendix, we have used a level of precision for numerical values that is in many cases higher than necessary (e.g., distances here are rounded to mm although cm would probably be good enough). We have done this for two reasons. First, it insures that precision is high enough in all cases while keeping consistent conventions throughout. Second, it may allow easier detection of errors, which seems useful in work such as this, which involves many new derivations based on existing photometric or geometric values. For most practical purposes we see no reason not to round down to somewhat lower precision. For perhaps the best balance of useful precision, common conventions, and editorial or esthetic consistency, we would suggest cm for distance, and single decimal digits for all of the photometric values (lux, cd/m^2, and $cd/m^2/lux$).

Table I: Photometry requirements for upper beam mode

Test location (m)			Illuminance (lux)	
x	y	z	Minimum	Maximum
22.347	0.000	1.401	6.000	
40.763	-2.139	1.333	6.000	
40.763	2.139	1.333	6.000	
115.470	0.000	0.620	6.000	
70.614	-3.706	0.620	6.000	
70.614	3.706	0.620	6.000	
40.601	-4.291	0.620	6.000	
40.601	4.291	0.620	6.000	
31.233	-5.009	0.620	6.000	
31.233	5.009	0.620	6.000	
21.872	-4.753	0.620	6.000	
21.872	4.753	0.620	6.000	
23.677	0.000	0.000	17.838	
23.385	-3.704	0.000	7.135	
23.385	3.704	0.000	7.135	
14.200	0.000	0.000	24.795	
13.890	-2.952	0.000	9.918	
13.890	2.952	0.000	9.918	
8.866	0.000	0.000		305.292
158.114	0.000	0.620		6.000

Test locations are referenced to the ground level at the forwardmost point of the vehicle, on the vehicle midline. Conventions for location variables are: x is distance ahead of the reference point, y is lateral distance with positive values toward the right from the driver's point of view, and z is height above the ground.

Table II: Photometry requirements for lower beam mode

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
1	94.510	2.975	0.000	1.567		
1	94.510	2.560	0.000	1.567		
1	94.510	2.145	0.000	1.567		
1	94.510	1.730	0.000	1.567		
1	94.510	1.315	0.000	1.567		
1	74.940	2.531	0.000	2.492		
1	74.940	2.116	0.000	2.492		
1	74.940	1.701	0.000	2.492		
1	74.940	1.286	0.000	2.492		
1	74.940	0.871	0.000	2.492		
1	55.370	2.087	0.000	4.564		
1	55.370	1.672	0.000	4.564		
1	55.370	1.257	0.000	4.564		
1	55.370	0.842	0.000	4.564		
1	55.370	0.427	0.000	4.564		
2	65.952	0.830	0.000	1.448		
2	65.952	0.415	0.000	1.448		
2	65.952	0.000	0.000	1.448		
2	65.952	-0.415	0.000	1.448		
2	65.952	-0.830	0.000	1.448		
2	52.295	0.830	0.000	2.304		
2	52.295	0.415	0.000	2.304		
2	52.295	0.000	0.000	2.304		
2	52.295	-0.415	0.000	2.304		
2	52.295	-0.830	0.000	2.304		
2	38.638	0.830	0.000	4.220		
2	38.638	0.415	0.000	4.220		
2	38.638	0.000	0.000	4.220		
2	38.638	-0.415	0.000	4.220		
2	38.638	-0.830	0.000	4.220		
3	65.829	-3.196	0.000	0.579		
3	65.829	-3.611	0.000	0.579		
3	65.829	-4.026	0.000	0.579		
3	65.829	-4.441	0.000	0.579		
3	65.829	-4.856	0.000	0.579		
3	52.198	-2.363	0.000	0.921		
3	52.198	-2.778	0.000	0.921		
3	52.198	-3.193	0.000	0.921		
3	52.198	-3.608	0.000	0.921		
3	52.198	-4.023	0.000	0.921		
3	38.566	-1.529	0.000	1.688		
3	38.566	-1.944	0.000	1.688		
3	38.566	-2.359	0.000	1.688		
3	38.566	-2.774	0.000	1.688		
3	38.566	-3.189	0.000	1.688		
4	37.784	2.149	0.000	14.692		
4	37.784	1.734	0.000	14.692		

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
4	37.784	1.319	0.000	14.692		
4	37.784	0.904	0.000	14.692		
4	37.784	0.489	0.000	14.692		
4	29.960	1.876	0.000	23.368		
4	29.960	1.461	0.000	23.368		
4	29.960	1.046	0.000	23.368		
4	29.960	0.631	0.000	23.368		
4	29.960	0.216	0.000	23.368		
4	22.136	1.603	0.000	42.805		
4	22.136	1.188	0.000	42.805		
4	22.136	0.773	0.000	42.805		
4	22.136	0.358	0.000	42.805		
4	22.136	-0.057	0.000	42.805		
5	28.001	-3.605	0.000	2.177		
5	28.001	-4.020	0.000	2.177		
5	28.001	-4.435	0.000	2.177		
5	28.001	-4.850	0.000	2.177		
5	28.001	-5.265	0.000	2.177		
5	22.203	-2.687	0.000	3.463		
5	22.203	-3.102	0.000	3.463		
5	22.203	-3.517	0.000	3.463		
5	22.203	-3.932	0.000	3.463		
5	22.203	-4.347	0.000	3.463		
5	16.405	-1.768	0.000	6.344		
5	16.405	-2.183	0.000	6.344		
5	16.405	-2.598	0.000	6.344		
5	16.405	-3.013	0.000	6.344		
5	16.405	-3.428	0.000	6.344		
6	28.001	5.265	0.000	2.177		
6	28.001	4.850	0.000	2.177		
6	28.001	4.435	0.000	2.177		
6	28.001	4.020	0.000	2.177		
6	28.001	3.605	0.000	2.177		
6	22.203	4.347	0.000	3.463		
6	22.203	3.932	0.000	3.463		
6	22.203	3.517	0.000	3.463		
6	22.203	3.102	0.000	3.463		
6	22.203	2.687	0.000	3.463		
6	16.405	3.428	0.000	6.344		
6	16.405	3.013	0.000	6.344		
6	16.405	2.598	0.000	6.344		
6	16.405	2.183	0.000	6.344		
6	16.405	1.768	0.000	6.344		
7	27.384	-6.507	0.000	1.742		
7	27.384	-6.922	0.000	1.742		
7	27.384	-7.337	0.000	1.742		

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
7	27.384	-7.752	0.000	1.742		
7	27.384	-8.167	0.000	1.742		
7	21.713	-4.988	0.000	2.770		
7	21.713	-5.403	0.000	2.770		
7	21.713	-5.818	0.000	2.770		
7	21.713	-6.233	0.000	2.770		
7	21.713	-6.648	0.000	2.770		
7	16.043	-3.469	0.000	5.075		
7	16.043	-3.884	0.000	5.075		
7	16.043	-4.299	0.000	5.075		
7	16.043	-4.714	0.000	5.075		
7	16.043	-5.129	0.000	5.075		
8	27.384	8.167	0.000	1.742		
8	27.384	7.752	0.000	1.742		
8	27.384	7.337	0.000	1.742		
8	27.384	6.922	0.000	1.742		
8	27.384	6.507	0.000	1.742		
8	21.713	6.648	0.000	2.770		
8	21.713	6.233	0.000	2.770		
8	21.713	5.818	0.000	2.770		
8	21.713	5.403	0.000	2.770		
8	21.713	4.988	0.000	2.770		
8	16.043	5.129	0.000	5.075		
8	16.043	4.714	0.000	5.075		
8	16.043	4.299	0.000	5.075		
8	16.043	3.884	0.000	5.075		
8	16.043	3.469	0.000	5.075		
9	13.304	-4.012	0.000	2.095		
9	13.304	-4.427	0.000	2.095		
9	13.304	-4.842	0.000	2.095		
9	13.304	-5.257	0.000	2.095		
9	13.304	-5.672	0.000	2.095		
9	10.549	-3.010	0.000	3.333		
9	10.549	-3.425	0.000	3.333		
9	10.549	-3.840	0.000	3.333		
9	10.549	-4.255	0.000	3.333		
9	10.549	-4.670	0.000	3.333		
9	7.794	-2.007	0.000	6.105		
9	7.794	-2.422	0.000	6.105		
9	7.794	-2.837	0.000	6.105		
9	7.794	-3.252	0.000	6.105		
9	7.794	-3.667	0.000	6.105		
10	13.304	5.672	0.000	2.095		
10	13.304	5.257	0.000	2.095		
10	13.304	4.842	0.000	2.095		
10	13.304	4.427	0.000	2.095		
10	13.304	4.012	0.000	2.095		
10	10.549	4.670	0.000	3.333		

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
10	10.549	4.255	0.000	3.333		
10	10.549	3.840	0.000	3.333		
10	10.549	3.425	0.000	3.333		
10	10.549	3.010	0.000	3.333		
10	7.794	3.667	0.000	6.105		
10	7.794	3.252	0.000	6.105		
10	7.794	2.837	0.000	6.105		
10	7.794	2.422	0.000	6.105		
10	7.794	2.007	0.000	6.105		
11	65.829	-3.196	0.000		5.518	
11	65.829	-3.611	0.000		5.518	
11	65.829	-4.026	0.000		5.518	
11	65.829	-4.441	0.000		5.518	
11	65.829	-4.856	0.000		5.518	
11	52.198	-2.363	0.000		8.776	
11	52.198	-2.778	0.000		8.776	
11	52.198	-3.193	0.000		8.776	
11	52.198	-3.608	0.000		8.776	
11	52.198	-4.023	0.000		8.776	
11	38.566	-1.529	0.000		16.076	
11	38.566	-1.944	0.000		16.076	
11	38.566	-2.359	0.000		16.076	
11	38.566	-2.774	0.000		16.076	
11	38.566	-3.189	0.000		16.076	
12	14.123	1.818	0.000		124.726	
12	14.123	1.403	0.000		124.726	
12	14.123	0.988	0.000		124.726	
12	14.123	0.573	0.000		124.726	
12	14.123	0.158	0.000		124.726	
12	11.199	1.613	0.000		198.376	
12	11.199	1.198	0.000		198.376	
12	11.199	0.783	0.000		198.376	
12	11.199	0.368	0.000		198.376	
12	11.199	-0.047	0.000		198.376	
12	8.274	1.409	0.000		363.389	
12	8.274	0.994	0.000		363.389	
12	8.274	0.579	0.000		363.389	
12	8.274	0.164	0.000		363.389	
12	8.274	-0.251	0.000		363.389	
13	15.000	-4.128	1.070		3.109	
13	15.000	-3.308	1.070		3.109	
13	15.000	-2.488	1.070		3.109	
13	15.000	-4.128	1.110		3.109	
13	15.000	-3.308	1.110		3.109	
13	15.000	-2.488	1.110		3.109	
13	15.000	-4.128	1.150		3.109	
13	15.000	-3.308	1.150		3.109	
13	15.000	-2.488	1.150		3.109	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
14	30.000	-4.128	1.070		1.776	
14	30.000	-3.308	1.070		1.776	
14	30.000	-2.488	1.070		1.776	
14	30.000	-4.128	1.110		1.776	
14	30.000	-3.308	1.110		1.776	
14	30.000	-2.488	1.110		1.776	
14	30.000	-4.128	1.150		1.776	
14	30.000	-3.308	1.150		1.776	
14	30.000	-2.488	1.150		1.776	
15	60.000	-4.128	1.070		0.634	
15	60.000	-3.308	1.070		0.634	
15	60.000	-2.488	1.070		0.634	
15	60.000	-4.128	1.110		0.634	
15	60.000	-3.308	1.110		0.634	
15	60.000	-2.488	1.110		0.634	
15	60.000	-4.128	1.150		0.634	
15	60.000	-3.308	1.150		0.634	
15	60.000	-2.488	1.150		0.634	
16	120.000	-4.128	1.070		0.281	
16	120.000	-3.308	1.070		0.281	
16	120.000	-2.488	1.070		0.281	
16	120.000	-4.128	1.110		0.281	
16	120.000	-3.308	1.110		0.281	
16	120.000	-2.488	1.110		0.281	
16	120.000	-4.128	1.150		0.281	
16	120.000	-3.308	1.150		0.281	
16	120.000	-2.488	1.150		0.281	
17	15.000	1.965	0.871		18.854	
17	15.000	2.785	0.871		18.854	
17	15.000	3.605	0.871		18.854	
17	15.000	1.965	0.939		18.854	
17	15.000	2.785	0.939		18.854	
17	15.000	3.605	0.939		18.854	
17	15.000	1.965	1.007		18.854	
17	15.000	2.785	1.007		18.854	
17	15.000	3.605	1.007		18.854	
18	30.000	1.965	0.871		18.854	
18	30.000	2.785	0.871		18.854	
18	30.000	3.605	0.871		18.854	
18	30.000	1.965	0.939		18.854	
18	30.000	2.785	0.939		18.854	
18	30.000	3.605	0.939		18.854	
18	30.000	1.965	1.007		18.854	
18	30.000	2.785	1.007		18.854	
18	30.000	3.605	1.007		18.854	
19	60.000	1.965	0.871		4.041	
19	60.000	2.785	0.871		4.041	
19	60.000	3.605	0.871		4.041	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
19	60.000	1.965	0.939		4.041	
19	60.000	2.785	0.939		4.041	
19	60.000	3.605	0.939		4.041	
19	60.000	1.965	1.007		4.041	
19	60.000	2.785	1.007		4.041	
19	60.000	3.605	1.007		4.041	
20	120.000	1.965	0.871		4.041	
20	120.000	2.785	0.871		4.041	
20	120.000	3.605	0.871		4.041	
20	120.000	1.965	0.939		4.041	
20	120.000	2.785	0.939		4.041	
20	120.000	3.605	0.939		4.041	
20	120.000	1.965	1.007		4.041	
20	120.000	2.785	1.007		4.041	
20	120.000	3.605	1.007		4.041	
21	15.000	-0.820	1.126		18.854	
21	15.000	0.000	1.126		18.854	
21	15.000	0.820	1.126		18.854	
21	15.000	-0.820	1.187		18.854	
21	15.000	0.000	1.187		18.854	
21	15.000	0.820	1.187		18.854	
21	15.000	-0.820	1.248		18.854	
21	15.000	0.000	1.248		18.854	
21	15.000	0.820	1.248		18.854	
22	30.000	-0.820	1.126		18.854	
22	30.000	0.000	1.126		18.854	
22	30.000	0.820	1.126		18.854	
22	30.000	-0.820	1.187		18.854	
22	30.000	0.000	1.187		18.854	
22	30.000	0.820	1.187		18.854	
22	30.000	-0.820	1.248		18.854	
22	30.000	0.000	1.248		18.854	
22	30.000	0.820	1.248		18.854	
23	60.000	-0.820	1.126		4.041	
23	60.000	0.000	1.126		4.041	
23	60.000	0.820	1.126		4.041	
23	60.000	-0.820	1.187		4.041	
23	60.000	0.000	1.187		4.041	
23	60.000	0.820	1.187		4.041	
23	60.000	-0.820	1.248		4.041	
23	60.000	0.000	1.248		4.041	
23	60.000	0.820	1.248		4.041	
24	120.000	-0.820	1.126		4.041	
24	120.000	0.000	1.126		4.041	
24	120.000	0.820	1.126		4.041	
24	120.000	-0.820	1.187		4.041	
24	120.000	0.000	1.187		4.041	
24	120.000	0.820	1.187		4.041	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
24	120.000	-0.820	1.248		4.041	
24	120.000	0.000	1.248		4.041	
24	120.000	0.820	1.248		4.041	
25	365.760	-7.315	6.096			1.700
25	304.800	-7.315	6.096			1.700
25	243.840	-7.315	6.096			1.700
25	182.880	-7.315	6.096			1.700
25	121.920	-7.315	6.096			1.700
25	60.960	-7.315	6.096			1.700
26	365.760	-3.658	6.096			1.700
26	304.800	-3.658	6.096			1.700
26	243.840	-3.658	6.096			1.700
26	182.880	-3.658	6.096			1.700
26	121.920	-3.658	6.096			1.700
26	60.960	-3.658	6.096			1.700
27	365.760	0.000	6.096			1.700
27	304.800	0.000	6.096			1.700
27	243.840	0.000	6.096			1.700
27	182.880	0.000	6.096			1.700
27	121.920	0.000	6.096			1.700
27	60.960	0.000	6.096			1.700
28	365.760	3.658	6.096			1.700
28	304.800	3.658	6.096			1.700
28	243.840	3.658	6.096			1.700
28	182.880	3.658	6.096			1.700
28	121.920	3.658	6.096			1.700
28	60.960	3.658	6.096			1.700
29	365.760	7.315	6.096			1.700
29	304.800	7.315	6.096			1.700
29	243.840	7.315	6.096			1.700
29	182.880	7.315	6.096			1.700
29	121.920	7.315	6.096			1.700
29	60.960	7.315	6.096			1.700
30	365.760	6.096	2.134			1.700
30	304.800	6.096	2.134			1.700
30	243.840	6.096	2.134			1.700
30	182.880	6.096	2.134			1.700
30	121.920	6.096	2.134			1.700
30	60.960	6.096	2.134			1.700
31	365.760	9.754	2.134			1.700
31	304.800	9.754	2.134			1.700
31	243.840	9.754	2.134			1.700
31	182.880	9.754	2.134			1.700
31	121.920	9.754	2.134			1.700
31	60.960	9.754	2.134			1.700
32	2.500	-5.000	1.000		63.706	
32	2.500	-4.500	1.000		75.063	
32	2.500	-4.000	1.000		89.308	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
32	2.500	-3.500	1.000		107.271	
32	2.500	-3.000	1.000		129.917	
32	2.500	-2.500	1.000		158.173	
32	2.500	-2.000	1.000		192.411	
32	2.500	-1.500	1.000		231.364	
32	2.500	-1.000	1.000		270.475	
32	2.500	-0.500	1.000		301.005	
32	2.500	0.000	1.000		312.774	
32	2.500	0.500	1.000		301.005	
32	2.500	1.000	1.000		270.475	
32	2.500	1.500	1.000		231.364	
32	2.500	2.000	1.000		192.411	
32	2.500	2.500	1.000		158.173	
32	2.500	3.000	1.000		129.917	
32	2.500	3.500	1.000		107.271	
32	2.500	4.000	1.000		89.308	
32	2.500	4.500	1.000		75.063	
32	2.500	5.000	1.000		63.706	
32	3.000	-5.000	1.000		58.575	
32	3.000	-4.500	1.000		68.040	
32	3.000	-4.000	1.000		79.541	
32	3.000	-3.500	1.000		93.482	
32	3.000	-3.000	1.000		110.227	
32	3.000	-2.500	1.000		129.917	
32	3.000	-2.000	1.000		152.156	
32	3.000	-1.500	1.000		175.525	
32	3.000	-1.000	1.000		197.153	
32	3.000	-0.500	1.000		212.893	
32	3.000	0.000	1.000		218.713	
32	3.000	0.500	1.000		212.893	
32	3.000	1.000	1.000		197.153	
32	3.000	1.500	1.000		175.525	
32	3.000	2.000	1.000		152.156	
32	3.000	2.500	1.000		129.917	
32	3.000	3.000	1.000		110.227	
32	3.000	3.500	1.000		93.482	
32	3.000	4.000	1.000		79.541	
32	3.000	4.500	1.000		68.040	
32	3.000	5.000	1.000		58.575	
32	3.500	-5.000	1.000		53.484	
32	3.500	-4.500	1.000		61.266	
32	3.500	-4.000	1.000		70.436	
32	3.500	-3.500	1.000		81.154	
32	3.500	-3.000	1.000		93.482	
32	3.500	-2.500	1.000		107.271	
32	3.500	-2.000	1.000		121.993	
32	3.500	-1.500	1.000		136.571	
32	3.500	-1.000	1.000		149.316	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
32	3.500	-0.500	1.000		158.173	
32	3.500	0.000	1.000		161.363	
32	3.500	0.500	1.000		158.173	
32	3.500	1.000	1.000		149.316	
32	3.500	1.500	1.000		136.571	
32	3.500	2.000	1.000		121.993	
32	3.500	2.500	1.000		107.271	
32	3.500	3.000	1.000		93.482	
32	3.500	3.500	1.000		81.154	
32	3.500	4.000	1.000		70.436	
32	3.500	4.500	1.000		61.266	
32	3.500	5.000	1.000		53.484	
32	4.000	-5.000	1.000		48.609	
32	4.000	-4.500	1.000		54.954	
32	4.000	-4.000	1.000		62.219	
32	4.000	-3.500	1.000		70.436	
32	4.000	-3.000	1.000		79.541	
32	4.000	-2.500	1.000		89.308	
32	4.000	-2.000	1.000		99.283	
32	4.000	-1.500	1.000		108.729	
32	4.000	-1.000	1.000		116.656	
32	4.000	-0.500	1.000		121.993	
32	4.000	0.000	1.000		123.882	
32	4.000	0.500	1.000		121.993	
32	4.000	1.000	1.000		116.656	
32	4.000	1.500	1.000		108.729	
32	4.000	2.000	1.000		99.283	
32	4.000	2.500	1.000		89.308	
32	4.000	3.000	1.000		79.541	
32	4.000	3.500	1.000		70.436	
32	4.000	4.000	1.000		62.219	
32	4.000	4.500	1.000		54.954	
32	4.000	5.000	1.000		48.609	
32	4.500	-5.000	1.000		44.058	
32	4.500	-4.500	1.000		49.207	
32	4.500	-4.000	1.000		54.954	
32	4.500	-3.500	1.000		61.266	
32	4.500	-3.000	1.000		68.040	
32	4.500	-2.500	1.000		75.063	
32	4.500	-2.000	1.000		81.986	
32	4.500	-1.500	1.000		88.322	
32	4.500	-1.000	1.000		93.482	
32	4.500	-0.500	1.000		96.879	
32	4.500	0.000	1.000		98.066	
32	4.500	0.500	1.000		96.879	
32	4.500	1.000	1.000		93.482	
32	4.500	1.500	1.000		88.322	
32	4.500	2.000	1.000		81.986	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
32	4.500	2.500	1.000		75.063	
32	4.500	3.000	1.000		68.040	
32	4.500	3.500	1.000		61.266	
32	4.500	4.000	1.000		54.954	
32	4.500	4.500	1.000		49.207	
32	4.500	5.000	1.000		44.058	
32	5.000	-5.000	1.000		39.885	
32	5.000	-5.000	1.500		39.390	
32	5.000	-4.500	1.000		44.058	
32	5.000	-4.500	1.500		43.455	
32	5.000	-4.000	1.000		48.609	
32	5.000	-4.000	1.500		47.876	
32	5.000	-3.500	1.000		53.484	
32	5.000	-3.500	1.500		52.598	
32	5.000	-3.000	1.000		58.575	
32	5.000	-3.000	1.500		57.514	
32	5.000	-2.500	1.000		63.706	
32	5.000	-2.500	1.500		62.452	
32	5.000	-2.000	1.000		68.624	
32	5.000	-2.000	1.500		67.172	
32	5.000	-1.500	1.000		73.008	
32	5.000	-1.500	1.500		71.366	
32	5.000	-1.000	1.000		76.498	
32	5.000	-1.000	1.500		74.698	
32	5.000	-0.500	1.000		78.758	
32	5.000	-0.500	1.500		76.851	
32	5.000	0.000	1.000		79.541	
32	5.000	0.000	1.500		77.596	
32	5.000	0.500	1.000		78.758	
32	5.000	0.500	1.500		76.851	
32	5.000	1.000	1.000		76.498	
32	5.000	1.000	1.500		74.698	
32	5.000	1.500	1.000		73.008	
32	5.000	1.500	1.500		71.366	
32	5.000	2.000	1.000		68.624	
32	5.000	2.000	1.500		67.172	
32	5.000	2.500	1.000		63.706	
32	5.000	2.500	1.500		62.452	
32	5.000	3.000	1.000		58.575	
32	5.000	3.000	1.500		57.514	
32	5.000	3.500	1.000		53.484	
32	5.000	3.500	1.500		52.598	
32	5.000	4.000	1.000		48.609	
32	5.000	4.000	1.500		47.876	
32	5.000	4.500	1.000		44.058	
32	5.000	4.500	1.500		43.455	
32	5.000	5.000	1.000		39.885	
32	5.000	5.000	1.500		39.390	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
32	5.500	-5.000	1.500		35.699	
32	5.500	-4.500	1.500		39.006	
32	5.500	-4.000	1.500		42.531	
32	5.500	-3.500	1.500		46.217	
32	5.500	-3.000	1.500		49.970	
32	5.500	-2.500	1.500		53.656	
32	5.500	-2.000	1.500		57.103	
32	5.500	-1.500	1.500		60.106	
32	5.500	-1.000	1.500		62.452	
32	5.500	-0.500	1.500		63.950	
32	5.500	0.000	1.500		64.465	
32	5.500	0.500	1.500		63.950	
32	5.500	1.000	1.500		62.452	
32	5.500	1.500	1.500		60.106	
32	5.500	2.000	1.500		57.103	
32	5.500	2.500	1.500		53.656	
32	5.500	3.000	1.500		49.970	
32	5.500	3.500	1.500		46.217	
32	5.500	4.000	1.500		42.531	
32	5.500	4.500	1.500		39.006	
32	5.500	5.000	1.500		35.699	
32	6.000	-5.000	1.500		32.376	
32	6.000	-4.500	1.500		35.073	
32	6.000	-4.000	1.500		37.897	
32	6.000	-3.500	1.500		40.796	
32	6.000	-3.000	1.500		43.693	
32	6.000	-2.500	1.500		46.485	
32	6.000	-2.000	1.500		49.050	
32	6.000	-1.500	1.500		51.250	
32	6.000	-1.000	1.500		52.946	
32	6.000	-0.500	1.500		54.018	
32	6.000	0.000	1.500		54.386	
32	6.000	0.500	1.500		54.018	
32	6.000	1.000	1.500		52.946	
32	6.000	1.500	1.500		51.250	
32	6.000	2.000	1.500		49.050	
32	6.000	2.500	1.500		46.485	
32	6.000	3.000	1.500		43.693	
32	6.000	3.500	1.500		40.796	
32	6.000	4.000	1.500		37.897	
32	6.000	4.500	1.500		35.073	
32	6.000	5.000	1.500		32.376	
32	6.500	-5.000	1.500		29.401	
32	6.500	-4.500	1.500		31.608	
32	6.500	-4.000	1.500		33.884	
32	6.500	-3.500	1.500		36.183	
32	6.500	-3.000	1.500		38.443	
32	6.500	-2.500	1.500		40.589	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
32	6.500	-2.000	1.500		42.531	
32	6.500	-1.500	1.500		44.175	
32	6.500	-1.000	1.500		45.429	
32	6.500	-0.500	1.500		46.217	
32	6.500	0.000	1.500		46.485	
32	6.500	0.500	1.500		46.217	
32	6.500	1.000	1.500		45.429	
32	6.500	1.500	1.500		44.175	
32	6.500	2.000	1.500		42.531	
32	6.500	2.500	1.500		40.589	
32	6.500	3.000	1.500		38.443	
32	6.500	3.500	1.500		36.183	
32	6.500	4.000	1.500		33.884	
32	6.500	4.500	1.500		31.608	
32	6.500	5.000	1.500		29.401	
32	7.000	-5.000	1.500		26.747	
32	7.000	-4.500	1.500		28.561	
32	7.000	-4.000	1.500		30.407	
32	7.000	-3.500	1.500		32.245	
32	7.000	-3.000	1.500		34.028	
32	7.000	-2.500	1.500		35.699	
32	7.000	-2.000	1.500		37.192	
32	7.000	-1.500	1.500		38.443	
32	7.000	-1.000	1.500		39.390	
32	7.000	-0.500	1.500		39.980	
32	7.000	0.000	1.500		40.181	
32	7.000	0.500	1.500		39.980	
32	7.000	1.000	1.500		39.390	
32	7.000	1.500	1.500		38.443	
32	7.000	2.000	1.500		37.192	
32	7.000	2.500	1.500		35.699	
32	7.000	3.000	1.500		34.028	
32	7.000	3.500	1.500		32.245	
32	7.000	4.000	1.500		30.407	
32	7.000	4.500	1.500		28.561	
32	7.000	5.000	1.500		26.747	
32	7.500	-5.000	1.500		24.383	
32	7.500	-4.500	1.500		25.882	
32	7.500	-4.000	1.500		27.388	
32	7.500	-3.500	1.500		28.871	
32	7.500	-3.000	1.500		30.292	
32	7.500	-2.500	1.500		31.608	
32	7.500	-2.000	1.500		32.774	
32	7.500	-1.500	1.500		33.741	
32	7.500	-1.000	1.500		34.468	
32	7.500	-0.500	1.500		34.920	
32	7.500	0.000	1.500		35.073	
32	7.500	0.500	1.500		34.920	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
32	7.500	1.000	1.500		34.468	
32	7.500	1.500	1.500		33.741	
32	7.500	2.000	1.500		32.774	
32	7.500	2.500	1.500		31.608	
32	7.500	3.000	1.500		30.292	
32	7.500	3.500	1.500		28.871	
32	7.500	4.000	1.500		27.388	
32	7.500	4.500	1.500		25.882	
32	7.500	5.000	1.500		24.383	
32	8.000	-5.000	1.500		22.278	
32	8.000	-5.000	2.000		22.001	
32	8.000	-4.500	1.500		23.523	
32	8.000	-4.500	2.000		23.214	
32	8.000	-4.000	1.500		24.760	
32	8.000	-4.000	2.000		24.419	
32	8.000	-3.500	1.500		25.966	
32	8.000	-3.500	2.000		25.590	
32	8.000	-3.000	1.500		27.110	
32	8.000	-3.000	2.000		26.701	
32	8.000	-2.500	1.500		28.159	
32	8.000	-2.500	2.000		27.718	
32	8.000	-2.000	1.500		29.081	
32	8.000	-2.000	2.000		28.611	
32	8.000	-1.500	1.500		29.840	
32	8.000	-1.500	2.000		29.345	
32	8.000	-1.000	1.500		30.407	
32	8.000	-1.000	2.000		29.893	
32	8.000	-0.500	1.500		30.758	
32	8.000	-0.500	2.000		30.232	
32	8.000	0.000	1.500		30.876	
32	8.000	0.000	2.000		30.347	
32	8.000	0.500	1.500		30.758	
32	8.000	0.500	2.000		30.232	
32	8.000	1.000	1.500		30.407	
32	8.000	1.000	2.000		29.893	
32	8.000	1.500	1.500		29.840	
32	8.000	1.500	2.000		29.345	
32	8.000	2.000	1.500		29.081	
32	8.000	2.000	2.000		28.611	
32	8.000	2.500	1.500		28.159	
32	8.000	2.500	2.000		27.718	
32	8.000	3.000	1.500		27.110	
32	8.000	3.000	2.000		26.701	
32	8.000	3.500	1.500		25.966	
32	8.000	3.500	2.000		25.590	
32	8.000	4.000	1.500		24.760	
32	8.000	4.000	2.000		24.419	
32	8.000	4.500	1.500		23.523	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
32	8.000	4.500	2.000		23.214	
32	8.000	5.000	1.500		22.278	
32	8.000	5.000	2.000		22.001	
32	8.500	-5.000	1.500		20.403	
32	8.500	-5.000	2.000		20.171	
32	8.500	-4.500	1.500		21.442	
32	8.500	-4.500	2.000		21.185	
32	8.500	-4.000	1.500		22.466	
32	8.500	-4.000	2.000		22.184	
32	8.500	-3.500	1.500		23.454	
32	8.500	-3.500	2.000		23.147	
32	8.500	-3.000	1.500		24.383	
32	8.500	-3.000	2.000		24.052	
32	8.500	-2.500	1.500		25.229	
32	8.500	-2.500	2.000		24.874	
32	8.500	-2.000	1.500		25.966	
32	8.500	-2.000	2.000		25.590	
32	8.500	-1.500	1.500		26.569	
32	8.500	-1.500	2.000		26.177	
32	8.500	-1.000	1.500		27.018	
32	8.500	-1.000	2.000		26.612	
32	8.500	-0.500	1.500		27.295	
32	8.500	-0.500	2.000		26.880	
32	8.500	0.000	1.500		27.388	
32	8.500	0.000	2.000		26.971	
32	8.500	0.500	1.500		27.295	
32	8.500	0.500	2.000		26.880	
32	8.500	1.000	1.500		27.018	
32	8.500	1.000	2.000		26.612	
32	8.500	1.500	1.500		26.569	
32	8.500	1.500	2.000		26.177	
32	8.500	2.000	1.500		25.966	
32	8.500	2.000	2.000		25.590	
32	8.500	2.500	1.500		25.229	
32	8.500	2.500	2.000		24.874	
32	8.500	3.000	1.500		24.383	
32	8.500	3.000	2.000		24.052	
32	8.500	3.500	1.500		23.454	
32	8.500	3.500	2.000		23.147	
32	8.500	4.000	1.500		22.466	
32	8.500	4.000	2.000		22.184	
32	8.500	4.500	1.500		21.442	
32	8.500	4.500	2.000		21.185	
32	8.500	5.000	1.500		20.403	
32	8.500	5.000	2.000		20.171	
32	9.000	-5.000	1.500		18.731	
32	9.000	-5.000	2.000		18.535	
32	9.000	-4.500	1.500		19.603	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
32	9.000	-4.500	2.000		19.388	
32	9.000	-4.000	1.500		20.455	
32	9.000	-4.000	2.000		20.222	
32	9.000	-3.500	1.500		21.271	
32	9.000	-3.500	2.000		21.018	
32	9.000	-3.000	1.500		22.033	
32	9.000	-3.000	2.000		21.762	
32	9.000	-2.500	1.500		22.721	
32	9.000	-2.500	2.000		22.433	
32	9.000	-2.000	1.500		23.317	
32	9.000	-2.000	2.000		23.014	
32	9.000	-1.500	1.500		23.803	
32	9.000	-1.500	2.000		23.487	
32	9.000	-1.000	1.500		24.162	
32	9.000	-1.000	2.000		23.837	
32	9.000	-0.500	1.500		24.383	
32	9.000	-0.500	2.000		24.052	
32	9.000	0.000	1.500		24.458	
32	9.000	0.000	2.000		24.124	
32	9.000	0.500	1.500		24.383	
32	9.000	0.500	2.000		24.052	
32	9.000	1.000	1.500		24.162	
32	9.000	1.000	2.000		23.837	
32	9.000	1.500	1.500		23.803	
32	9.000	1.500	2.000		23.487	
32	9.000	2.000	1.500		23.317	
32	9.000	2.000	2.000		23.014	
32	9.000	2.500	1.500		22.721	
32	9.000	2.500	2.000		22.433	
32	9.000	3.000	1.500		22.033	
32	9.000	3.000	2.000		21.762	
32	9.000	3.500	1.500		21.271	
32	9.000	3.500	2.000		21.018	
32	9.000	4.000	1.500		20.455	
32	9.000	4.000	2.000		20.222	
32	9.000	4.500	1.500		19.603	
32	9.000	4.500	2.000		19.388	
32	9.000	5.000	1.500		18.731	
32	9.000	5.000	2.000		18.535	
32	9.500	-5.000	1.500		17.238	
32	9.500	-5.000	2.000		17.071	
32	9.500	-4.500	1.500		17.974	
32	9.500	-4.500	2.000		17.793	
32	9.500	-4.000	1.500		18.687	
32	9.500	-4.000	2.000		18.492	
32	9.500	-3.500	1.500		19.366	
32	9.500	-3.500	2.000		19.156	
32	9.500	-3.000	1.500		19.995	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
32	9.500	-3.000	2.000		19.772	
32	9.500	-2.500	1.500		20.560	
32	9.500	-2.500	2.000		20.324	
32	9.500	-2.000	1.500		21.047	
32	9.500	-2.000	2.000		20.800	
32	9.500	-1.500	1.500		21.442	
32	9.500	-1.500	2.000		21.185	
32	9.500	-1.000	1.500		21.733	
32	9.500	-1.000	2.000		21.470	
32	9.500	-0.500	1.500		21.912	
32	9.500	-0.500	2.000		21.644	
32	9.500	0.000	1.500		21.972	
32	9.500	0.000	2.000		21.703	
32	9.500	0.500	1.500		21.912	
32	9.500	0.500	2.000		21.644	
32	9.500	1.000	1.500		21.733	
32	9.500	1.000	2.000		21.470	
32	9.500	1.500	1.500		21.442	
32	9.500	1.500	2.000		21.185	
32	9.500	2.000	1.500		21.047	
32	9.500	2.000	2.000		20.800	
32	9.500	2.500	1.500		20.560	
32	9.500	2.500	2.000		20.324	
32	9.500	3.000	1.500		19.995	
32	9.500	3.000	2.000		19.772	
32	9.500	3.500	1.500		19.366	
32	9.500	3.500	2.000		19.156	
32	9.500	4.000	1.500		18.687	
32	9.500	4.000	2.000		18.492	
32	9.500	4.500	1.500		17.974	
32	9.500	4.500	2.000		17.793	
32	9.500	5.000	1.500		17.238	
32	9.500	5.000	2.000		17.071	
32	10.000	-5.000	1.500		15.901	
32	10.000	-5.000	2.000		15.760	
32	10.000	-4.500	1.500		16.526	
32	10.000	-4.500	2.000		16.373	
32	10.000	-4.000	1.500		17.127	
32	10.000	-4.000	2.000		16.963	
32	10.000	-3.500	1.500		17.695	
32	10.000	-3.500	2.000		17.520	
32	10.000	-3.000	1.500		18.219	
32	10.000	-3.000	2.000		18.034	
32	10.000	-2.500	1.500		18.687	
32	10.000	-2.500	2.000		18.492	
32	10.000	-2.000	1.500		19.089	
32	10.000	-2.000	2.000		18.885	
32	10.000	-1.500	1.500		19.413	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
32	10.000	-1.500	2.000		19.202	
32	10.000	-1.000	1.500		19.651	
32	10.000	-1.000	2.000		19.436	
32	10.000	-0.500	1.500		19.797	
32	10.000	-0.500	2.000		19.578	
32	10.000	0.000	1.500		19.846	
32	10.000	0.000	2.000		19.626	
32	10.000	0.500	1.500		19.797	
32	10.000	0.500	2.000		19.578	
32	10.000	1.000	1.500		19.651	
32	10.000	1.000	2.000		19.436	
32	10.000	1.500	1.500		19.413	
32	10.000	1.500	2.000		19.202	
32	10.000	2.000	1.500		19.089	
32	10.000	2.000	2.000		18.885	
32	10.000	2.500	1.500		18.687	
32	10.000	2.500	2.000		18.492	
32	10.000	3.000	1.500		18.219	
32	10.000	3.000	2.000		18.034	
32	10.000	3.500	1.500		17.695	
32	10.000	3.500	2.000		17.520	
32	10.000	4.000	1.500		17.127	
32	10.000	4.000	2.000		16.963	
32	10.000	4.500	1.500		16.526	
32	10.000	4.500	2.000		16.373	
32	10.000	5.000	1.500		15.901	
32	10.000	5.000	2.000		15.760	
33	0.500	-5.000	1.000		9.845	
33	0.500	-5.000	1.500		9.606	
33	0.500	-5.000	2.000		9.207	
33	0.500	-5.000	2.500		8.685	
33	0.500	-5.000	3.000		8.087	
33	0.500	-4.500	1.000		12.110	
33	0.500	-4.500	1.500		11.751	
33	0.500	-4.500	2.000		11.159	
33	0.500	-4.500	2.500		10.402	
33	0.500	-4.500	3.000		9.555	
33	0.500	-4.000	1.000		15.249	
33	0.500	-4.000	1.500		14.685	
33	0.500	-4.000	2.000		13.771	
33	0.500	-4.000	2.500		12.636	
33	0.500	-4.000	3.000		11.408	
33	0.500	-3.500	1.000		19.772	
33	0.500	-3.500	1.500		18.833	
33	0.500	-3.500	2.000		17.356	
33	0.500	-3.500	2.500		15.591	
33	0.500	-3.500	3.000		13.763	
33	0.500	-3.000	1.000		26.612	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	0.500	-3.000	1.500		24.939	
33	0.500	-3.000	2.000		22.413	
33	0.500	-3.000	2.500		19.555	
33	0.500	-3.000	3.000		16.762	
33	0.500	-2.500	1.000		37.626	
33	0.500	-2.500	1.500		34.367	
33	0.500	-2.500	2.000		29.746	
33	0.500	-2.500	2.500		24.914	
33	0.500	-2.500	3.000		20.552	
33	0.500	-2.000	1.000		56.891	
33	0.500	-2.000	1.500		49.757	
33	0.500	-2.000	2.000		40.621	
33	0.500	-2.000	2.500		32.116	
33	0.500	-2.000	3.000		25.216	
33	0.500	-1.500	1.000		94.539	
33	0.500	-1.500	1.500		76.350	
33	0.500	-1.500	2.000		56.761	
33	0.500	-1.500	2.500		41.429	
33	0.500	-1.500	3.000		30.621	
33	0.500	-1.000	1.000		179.289	
33	0.500	-1.000	1.500		123.493	
33	0.500	-1.000	2.000		79.254	
33	0.500	-1.000	2.500		52.253	
33	0.500	-1.000	3.000		36.156	
33	0.500	-0.500	1.000		387.958	
33	0.500	-0.500	1.500		196.171	
33	0.500	-0.500	2.000		103.976	
33	0.500	-0.500	2.500		61.967	
33	0.500	-0.500	3.000		40.555	
33	0.500	0.000	1.000		633.874	
33	0.500	0.000	1.500		244.045	
33	0.500	0.000	2.000		116.042	
33	0.500	0.000	2.500		66.061	
33	0.500	0.000	3.000		42.270	
33	0.500	0.500	1.000		387.958	
33	0.500	0.500	1.500		196.171	
33	0.500	0.500	2.000		103.976	
33	0.500	0.500	2.500		61.967	
33	0.500	0.500	3.000		40.555	
33	0.500	1.000	1.000		179.289	
33	0.500	1.000	1.500		123.493	
33	0.500	1.000	2.000		79.254	
33	0.500	1.000	2.500		52.253	
33	0.500	1.000	3.000		36.156	
33	0.500	1.500	1.000		94.539	
33	0.500	1.500	1.500		76.350	
33	0.500	1.500	2.000		56.761	
33	0.500	1.500	2.500		41.429	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	0.500	1.500	3.000		30.621	
33	0.500	2.000	1.000		56.891	
33	0.500	2.000	1.500		49.757	
33	0.500	2.000	2.000		40.621	
33	0.500	2.000	2.500		32.116	
33	0.500	2.000	3.000		25.216	
33	0.500	2.500	1.000		37.626	
33	0.500	2.500	1.500		34.367	
33	0.500	2.500	2.000		29.746	
33	0.500	2.500	2.500		24.914	
33	0.500	2.500	3.000		20.552	
33	0.500	3.000	1.000		26.612	
33	0.500	3.000	1.500		24.939	
33	0.500	3.000	2.000		22.413	
33	0.500	3.000	2.500		19.555	
33	0.500	3.000	3.000		16.762	
33	0.500	3.500	1.000		19.772	
33	0.500	3.500	1.500		18.833	
33	0.500	3.500	2.000		17.356	
33	0.500	3.500	2.500		15.591	
33	0.500	3.500	3.000		13.763	
33	0.500	4.000	1.000		15.249	
33	0.500	4.000	1.500		14.685	
33	0.500	4.000	2.000		13.771	
33	0.500	4.000	2.500		12.636	
33	0.500	4.000	3.000		11.408	
33	0.500	4.500	1.000		12.110	
33	0.500	4.500	1.500		11.751	
33	0.500	4.500	2.000		11.159	
33	0.500	4.500	2.500		10.402	
33	0.500	4.500	3.000		9.555	
33	0.500	5.000	1.000		9.845	
33	0.500	5.000	1.500		9.606	
33	0.500	5.000	2.000		9.207	
33	0.500	5.000	2.500		8.685	
33	0.500	5.000	3.000		8.087	
33	1.000	-5.000	1.000		9.562	
33	1.000	-5.000	1.500		9.337	
33	1.000	-5.000	2.000		8.959	
33	1.000	-5.000	2.500		8.465	
33	1.000	-5.000	3.000		7.895	
33	1.000	-4.500	1.000		11.685	
33	1.000	-4.500	1.500		11.351	
33	1.000	-4.500	2.000		10.797	
33	1.000	-4.500	2.500		10.087	
33	1.000	-4.500	3.000		9.289	
33	1.000	-4.000	1.000		14.582	
33	1.000	-4.000	1.500		14.065	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	1.000	-4.000	2.000		13.224	
33	1.000	-4.000	2.500		12.175	
33	1.000	-4.000	3.000		11.031	
33	1.000	-3.500	1.000		18.665	
33	1.000	-3.500	1.500		17.826	
33	1.000	-3.500	2.000		16.497	
33	1.000	-3.500	2.500		14.895	
33	1.000	-3.500	3.000		13.217	
33	1.000	-3.000	1.000		24.644	
33	1.000	-3.000	1.500		23.203	
33	1.000	-3.000	2.000		21.001	
33	1.000	-3.000	2.500		18.471	
33	1.000	-3.000	3.000		15.960	
33	1.000	-2.500	1.000		33.809	
33	1.000	-2.500	1.500		31.155	
33	1.000	-2.500	2.000		27.309	
33	1.000	-2.500	2.500		23.182	
33	1.000	-2.500	3.000		19.358	
33	1.000	-2.000	1.000		48.597	
33	1.000	-2.000	1.500		43.295	
33	1.000	-2.000	2.000		36.209	
33	1.000	-2.000	2.500		29.293	
33	1.000	-2.000	3.000		23.442	
33	1.000	-1.500	1.000		73.651	
33	1.000	-1.500	1.500		62.121	
33	1.000	-1.500	2.000		48.502	
33	1.000	-1.500	2.500		36.849	
33	1.000	-1.500	3.000		28.045	
33	1.000	-1.000	1.000		116.583	
33	1.000	-1.000	1.500		90.110	
33	1.000	-1.000	2.000		64.030	
33	1.000	-1.000	2.500		45.172	
33	1.000	-1.000	3.000		32.618	
33	1.000	-0.500	1.000		179.289	
33	1.000	-0.500	1.500		123.493	
33	1.000	-0.500	2.000		79.254	
33	1.000	-0.500	2.500		52.253	
33	1.000	-0.500	3.000		36.156	
33	1.000	0.000	1.000		218.455	
33	1.000	0.000	1.500		140.893	
33	1.000	0.000	2.000		86.076	
33	1.000	0.000	2.500		55.134	
33	1.000	0.000	3.000		37.513	
33	1.000	0.500	1.000		179.289	
33	1.000	0.500	1.500		123.493	
33	1.000	0.500	2.000		79.254	
33	1.000	0.500	2.500		52.253	
33	1.000	0.500	3.000		36.156	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	1.000	1.000	1.000		116.583	
33	1.000	1.000	1.500		90.110	
33	1.000	1.000	2.000		64.030	
33	1.000	1.000	2.500		45.172	
33	1.000	1.000	3.000		32.618	
33	1.000	1.500	1.000		73.651	
33	1.000	1.500	1.500		62.121	
33	1.000	1.500	2.000		48.502	
33	1.000	1.500	2.500		36.849	
33	1.000	1.500	3.000		28.045	
33	1.000	2.000	1.000		48.597	
33	1.000	2.000	1.500		43.295	
33	1.000	2.000	2.000		36.209	
33	1.000	2.000	2.500		29.293	
33	1.000	2.000	3.000		23.442	
33	1.000	2.500	1.000		33.809	
33	1.000	2.500	1.500		31.155	
33	1.000	2.500	2.000		27.309	
33	1.000	2.500	2.500		23.182	
33	1.000	2.500	3.000		19.358	
33	1.000	3.000	1.000		24.644	
33	1.000	3.000	1.500		23.203	
33	1.000	3.000	2.000		21.001	
33	1.000	3.000	2.500		18.471	
33	1.000	3.000	3.000		15.960	
33	1.000	3.500	1.000		18.665	
33	1.000	3.500	1.500		17.826	
33	1.000	3.500	2.000		16.497	
33	1.000	3.500	2.500		14.895	
33	1.000	3.500	3.000		13.217	
33	1.000	4.000	1.000		14.582	
33	1.000	4.000	1.500		14.065	
33	1.000	4.000	2.000		13.224	
33	1.000	4.000	2.500		12.175	
33	1.000	4.000	3.000		11.031	
33	1.000	4.500	1.000		11.685	
33	1.000	4.500	1.500		11.351	
33	1.000	4.500	2.000		10.797	
33	1.000	4.500	2.500		10.087	
33	1.000	4.500	3.000		9.289	
33	1.000	5.000	1.000		9.562	
33	1.000	5.000	1.500		9.337	
33	1.000	5.000	2.000		8.959	
33	1.000	5.000	2.500		8.465	
33	1.000	5.000	3.000		7.895	
33	1.500	-5.000	1.000		9.126	
33	1.500	-5.000	1.500		8.921	
33	1.500	-5.000	2.000		8.575	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	1.500	-5.000	2.500		8.121	
33	1.500	-5.000	3.000		7.595	
33	1.500	-4.500	1.000		11.040	
33	1.500	-4.500	1.500		10.741	
33	1.500	-4.500	2.000		10.244	
33	1.500	-4.500	2.500		9.603	
33	1.500	-4.500	3.000		8.876	
33	1.500	-4.000	1.000		13.591	
33	1.500	-4.000	1.500		13.141	
33	1.500	-4.000	2.000		12.404	
33	1.500	-4.000	2.500		11.476	
33	1.500	-4.000	3.000		10.454	
33	1.500	-3.500	1.000		17.071	
33	1.500	-3.500	1.500		16.367	
33	1.500	-3.500	2.000		15.240	
33	1.500	-3.500	2.500		13.862	
33	1.500	-3.500	3.000		12.398	
33	1.500	-3.000	1.000		21.941	
33	1.500	-3.000	1.500		20.791	
33	1.500	-3.000	2.000		19.005	
33	1.500	-3.000	2.500		16.910	
33	1.500	-3.000	3.000		14.780	
33	1.500	-2.500	1.000		28.920	
33	1.500	-2.500	1.500		26.956	
33	1.500	-2.500	2.000		24.028	
33	1.500	-2.500	2.500		20.774	
33	1.500	-2.500	3.000		17.650	
33	1.500	-2.000	1.000		39.097	
33	1.500	-2.000	1.500		35.590	
33	1.500	-2.000	2.000		30.658	
33	1.500	-2.000	2.500		25.551	
33	1.500	-2.000	3.000		20.983	
33	1.500	-1.500	1.000		53.828	
33	1.500	-1.500	1.500		47.399	
33	1.500	-1.500	2.000		39.036	
33	1.500	-1.500	2.500		31.116	
33	1.500	-1.500	3.000		24.596	
33	1.500	-1.000	1.000		73.651	
33	1.500	-1.000	1.500		62.121	
33	1.500	-1.000	2.000		48.502	
33	1.500	-1.000	2.500		36.849	
33	1.500	-1.000	3.000		28.045	
33	1.500	-0.500	1.000		94.539	
33	1.500	-0.500	1.500		76.350	
33	1.500	-0.500	2.000		56.761	
33	1.500	-0.500	2.500		41.429	
33	1.500	-0.500	3.000		30.621	
33	1.500	0.000	1.000		104.410	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	1.500	0.000	1.500		82.661	
33	1.500	0.000	2.000		60.177	
33	1.500	0.000	2.500		43.220	
33	1.500	0.000	3.000		31.588	
33	1.500	0.500	1.000		94.539	
33	1.500	0.500	1.500		76.350	
33	1.500	0.500	2.000		56.761	
33	1.500	0.500	2.500		41.429	
33	1.500	0.500	3.000		30.621	
33	1.500	1.000	1.000		73.651	
33	1.500	1.000	1.500		62.121	
33	1.500	1.000	2.000		48.502	
33	1.500	1.000	2.500		36.849	
33	1.500	1.000	3.000		28.045	
33	1.500	1.500	1.000		53.828	
33	1.500	1.500	1.500		47.399	
33	1.500	1.500	2.000		39.036	
33	1.500	1.500	2.500		31.116	
33	1.500	1.500	3.000		24.596	
33	1.500	2.000	1.000		39.097	
33	1.500	2.000	1.500		35.590	
33	1.500	2.000	2.000		30.658	
33	1.500	2.000	2.500		25.551	
33	1.500	2.000	3.000		20.983	
33	1.500	2.500	1.000		28.920	
33	1.500	2.500	1.500		26.956	
33	1.500	2.500	2.000		24.028	
33	1.500	2.500	2.500		20.774	
33	1.500	2.500	3.000		17.650	
33	1.500	3.000	1.000		21.941	
33	1.500	3.000	1.500		20.791	
33	1.500	3.000	2.000		19.005	
33	1.500	3.000	2.500		16.910	
33	1.500	3.000	3.000		14.780	
33	1.500	3.500	1.000		17.071	
33	1.500	3.500	1.500		16.367	
33	1.500	3.500	2.000		15.240	
33	1.500	3.500	2.500		13.862	
33	1.500	3.500	3.000		12.398	
33	1.500	4.000	1.000		13.591	
33	1.500	4.000	1.500		13.141	
33	1.500	4.000	2.000		12.404	
33	1.500	4.000	2.500		11.476	
33	1.500	4.000	3.000		10.454	
33	1.500	4.500	1.000		11.040	
33	1.500	4.500	1.500		10.741	
33	1.500	4.500	2.000		10.244	
33	1.500	4.500	2.500		9.603	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	1.500	4.500	3.000		8.876	
33	1.500	5.000	1.000		9.126	
33	1.500	5.000	1.500		8.921	
33	1.500	5.000	2.000		8.575	
33	1.500	5.000	2.500		8.121	
33	1.500	5.000	3.000		7.595	
33	2.000	-5.000	1.000		8.578	
33	2.000	-5.000	1.500		8.396	
33	2.000	-5.000	2.000		8.089	
33	2.000	-5.000	2.500		7.684	
33	2.000	-5.000	3.000		7.212	
33	2.000	-4.500	1.000		10.248	
33	2.000	-4.500	1.500		9.990	
33	2.000	-4.500	2.000		9.559	
33	2.000	-4.500	2.500		8.998	
33	2.000	-4.500	3.000		8.357	
33	2.000	-4.000	1.000		12.410	
33	2.000	-4.000	1.500		12.034	
33	2.000	-4.000	2.000		11.413	
33	2.000	-4.000	2.500		10.623	
33	2.000	-4.000	3.000		9.741	
33	2.000	-3.500	1.000		15.249	
33	2.000	-3.500	1.500		14.685	
33	2.000	-3.500	2.000		13.771	
33	2.000	-3.500	2.500		12.636	
33	2.000	-3.500	3.000		11.408	
33	2.000	-3.000	1.000		19.020	
33	2.000	-3.000	1.500		18.150	
33	2.000	-3.000	2.000		16.774	
33	2.000	-3.000	2.500		15.120	
33	2.000	-3.000	3.000		13.394	
33	2.000	-2.500	1.000		24.051	
33	2.000	-2.500	1.500		22.677	
33	2.000	-2.500	2.000		20.569	
33	2.000	-2.500	2.500		18.136	
33	2.000	-2.500	3.000		15.709	
33	2.000	-2.000	1.000		30.696	
33	2.000	-2.000	1.500		28.492	
33	2.000	-2.000	2.000		25.241	
33	2.000	-2.000	2.500		21.674	
33	2.000	-2.000	3.000		18.296	
33	2.000	-1.500	1.000		39.097	
33	2.000	-1.500	1.500		35.590	
33	2.000	-1.500	2.000		30.658	
33	2.000	-1.500	2.500		25.551	
33	2.000	-1.500	3.000		20.983	
33	2.000	-1.000	1.000		48.597	
33	2.000	-1.000	1.500		43.295	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	2.000	-1.000	2.000		36.209	
33	2.000	-1.000	2.500		29.293	
33	2.000	-1.000	3.000		23.442	
33	2.000	-0.500	1.000		56.891	
33	2.000	-0.500	1.500		49.757	
33	2.000	-0.500	2.000		40.621	
33	2.000	-0.500	2.500		32.116	
33	2.000	-0.500	3.000		25.216	
33	2.000	0.000	1.000		60.322	
33	2.000	0.000	1.500		52.363	
33	2.000	0.000	2.000		42.341	
33	2.000	0.000	2.500		33.181	
33	2.000	0.000	3.000		25.868	
33	2.000	0.500	1.000		56.891	
33	2.000	0.500	1.500		49.757	
33	2.000	0.500	2.000		40.621	
33	2.000	0.500	2.500		32.116	
33	2.000	0.500	3.000		25.216	
33	2.000	1.000	1.000		48.597	
33	2.000	1.000	1.500		43.295	
33	2.000	1.000	2.000		36.209	
33	2.000	1.000	2.500		29.293	
33	2.000	1.000	3.000		23.442	
33	2.000	1.500	1.000		39.097	
33	2.000	1.500	1.500		35.590	
33	2.000	1.500	2.000		30.658	
33	2.000	1.500	2.500		25.551	
33	2.000	1.500	3.000		20.983	
33	2.000	2.000	1.000		30.696	
33	2.000	2.000	1.500		28.492	
33	2.000	2.000	2.000		25.241	
33	2.000	2.000	2.500		21.674	
33	2.000	2.000	3.000		18.296	
33	2.000	2.500	1.000		24.051	
33	2.000	2.500	1.500		22.677	
33	2.000	2.500	2.000		20.569	
33	2.000	2.500	2.500		18.136	
33	2.000	2.500	3.000		15.709	
33	2.000	3.000	1.000		19.020	
33	2.000	3.000	1.500		18.150	
33	2.000	3.000	2.000		16.774	
33	2.000	3.000	2.500		15.120	
33	2.000	3.000	3.000		13.394	
33	2.000	3.500	1.000		15.249	
33	2.000	3.500	1.500		14.685	
33	2.000	3.500	2.000		13.771	
33	2.000	3.500	2.500		12.636	
33	2.000	3.500	3.000		11.408	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	2.000	4.000	1.000		12.410	
33	2.000	4.000	1.500		12.034	
33	2.000	4.000	2.000		11.413	
33	2.000	4.000	2.500		10.623	
33	2.000	4.000	3.000		9.741	
33	2.000	4.500	1.000		10.248	
33	2.000	4.500	1.500		9.990	
33	2.000	4.500	2.000		9.559	
33	2.000	4.500	2.500		8.998	
33	2.000	4.500	3.000		8.357	
33	2.000	5.000	1.000		8.578	
33	2.000	5.000	1.500		8.396	
33	2.000	5.000	2.000		8.089	
33	2.000	5.000	2.500		7.684	
33	2.000	5.000	3.000		7.212	
33	2.500	-5.000	1.500		7.807	
33	2.500	-5.000	2.000		7.540	
33	2.500	-5.000	2.500		7.187	
33	2.500	-5.000	3.000		6.772	
33	2.500	-4.500	1.500		9.166	
33	2.500	-4.500	2.000		8.801	
33	2.500	-4.500	2.500		8.324	
33	2.500	-4.500	3.000		7.773	
33	2.500	-4.000	1.500		10.858	
33	2.500	-4.000	2.000		10.350	
33	2.500	-4.000	2.500		9.696	
33	2.500	-4.000	3.000		8.956	
33	2.500	-3.500	1.500		12.971	
33	2.500	-3.500	2.000		12.252	
33	2.500	-3.500	2.500		11.346	
33	2.500	-3.500	3.000		10.346	
33	2.500	-3.000	1.500		15.601	
33	2.500	-3.000	2.000		14.574	
33	2.500	-3.000	2.500		13.309	
33	2.500	-3.000	3.000		11.953	
33	2.500	-2.500	1.500		18.833	
33	2.500	-2.500	2.000		17.356	
33	2.500	-2.500	2.500		15.591	
33	2.500	-2.500	3.000		13.763	
33	2.500	-2.000	1.500		22.677	
33	2.500	-2.000	2.000		20.569	
33	2.500	-2.000	2.500		18.136	
33	2.500	-2.000	3.000		15.709	
33	2.500	-1.500	1.500		26.956	
33	2.500	-1.500	2.000		24.028	
33	2.500	-1.500	2.500		20.774	
33	2.500	-1.500	3.000		17.650	
33	2.500	-1.000	1.500		31.155	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	2.500	-1.000	2.000		27.309	
33	2.500	-1.000	2.500		23.182	
33	2.500	-1.000	3.000		19.358	
33	2.500	-0.500	1.500		34.367	
33	2.500	-0.500	2.000		29.746	
33	2.500	-0.500	2.500		24.914	
33	2.500	-0.500	3.000		20.552	
33	2.500	0.000	1.500		35.590	
33	2.500	0.000	2.000		30.658	
33	2.500	0.000	2.500		25.551	
33	2.500	0.000	3.000		20.983	
33	2.500	0.500	1.500		34.367	
33	2.500	0.500	2.000		29.746	
33	2.500	0.500	2.500		24.914	
33	2.500	0.500	3.000		20.552	
33	2.500	1.000	1.500		31.155	
33	2.500	1.000	2.000		27.309	
33	2.500	1.000	2.500		23.182	
33	2.500	1.000	3.000		19.358	
33	2.500	1.500	1.500		26.956	
33	2.500	1.500	2.000		24.028	
33	2.500	1.500	2.500		20.774	
33	2.500	1.500	3.000		17.650	
33	2.500	2.000	1.500		22.677	
33	2.500	2.000	2.000		20.569	
33	2.500	2.000	2.500		18.136	
33	2.500	2.000	3.000		15.709	
33	2.500	2.500	1.500		18.833	
33	2.500	2.500	2.000		17.356	
33	2.500	2.500	2.500		15.591	
33	2.500	2.500	3.000		13.763	
33	2.500	3.000	1.500		15.601	
33	2.500	3.000	2.000		14.574	
33	2.500	3.000	2.500		13.309	
33	2.500	3.000	3.000		11.953	
33	2.500	3.500	1.500		12.971	
33	2.500	3.500	2.000		12.252	
33	2.500	3.500	2.500		11.346	
33	2.500	3.500	3.000		10.346	
33	2.500	4.000	1.500		10.858	
33	2.500	4.000	2.000		10.350	
33	2.500	4.000	2.500		9.696	
33	2.500	4.000	3.000		8.956	
33	2.500	4.500	1.500		9.166	
33	2.500	4.500	2.000		8.801	
33	2.500	4.500	2.500		8.324	
33	2.500	4.500	3.000		7.773	
33	2.500	5.000	1.500		7.807	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	2.500	5.000	2.000		7.540	
33	2.500	5.000	2.500		7.187	
33	2.500	5.000	3.000		6.772	
33	3.000	-5.000	1.500		7.189	
33	3.000	-5.000	2.000		6.963	
33	3.000	-5.000	2.500		6.661	
33	3.000	-5.000	3.000		6.303	
33	3.000	-4.500	1.500		8.327	
33	3.000	-4.500	2.000		8.025	
33	3.000	-4.500	2.500		7.626	
33	3.000	-4.500	3.000		7.160	
33	3.000	-4.000	1.500		9.700	
33	3.000	-4.000	2.000		9.292	
33	3.000	-4.000	2.500		8.761	
33	3.000	-4.000	3.000		8.153	
33	3.000	-3.500	1.500		11.351	
33	3.000	-3.500	2.000		10.797	
33	3.000	-3.500	2.500		10.087	
33	3.000	-3.500	3.000		9.289	
33	3.000	-3.000	1.500		13.316	
33	3.000	-3.000	2.000		12.560	
33	3.000	-3.000	2.500		11.609	
33	3.000	-3.000	3.000		10.564	
33	3.000	-2.500	1.500		15.601	
33	3.000	-2.500	2.000		14.574	
33	3.000	-2.500	2.500		13.309	
33	3.000	-2.500	3.000		11.953	
33	3.000	-2.000	1.500		18.150	
33	3.000	-2.000	2.000		16.774	
33	3.000	-2.000	2.500		15.120	
33	3.000	-2.000	3.000		13.394	
33	3.000	-1.500	1.500		20.791	
33	3.000	-1.500	2.000		19.005	
33	3.000	-1.500	2.500		16.910	
33	3.000	-1.500	3.000		14.780	
33	3.000	-1.000	1.500		23.203	
33	3.000	-1.000	2.000		21.001	
33	3.000	-1.000	2.500		18.471	
33	3.000	-1.000	3.000		15.960	
33	3.000	-0.500	1.500		24.939	
33	3.000	-0.500	2.000		22.413	
33	3.000	-0.500	2.500		19.555	
33	3.000	-0.500	3.000		16.762	
33	3.000	0.000	1.500		25.577	
33	3.000	0.000	2.000		22.927	
33	3.000	0.000	2.500		19.945	
33	3.000	0.000	3.000		17.048	
33	3.000	0.500	1.500		24.939	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	3.000	0.500	2.000		22.413	
33	3.000	0.500	2.500		19.555	
33	3.000	0.500	3.000		16.762	
33	3.000	1.000	1.500		23.203	
33	3.000	1.000	2.000		21.001	
33	3.000	1.000	2.500		18.471	
33	3.000	1.000	3.000		15.960	
33	3.000	1.500	1.500		20.791	
33	3.000	1.500	2.000		19.005	
33	3.000	1.500	2.500		16.910	
33	3.000	1.500	3.000		14.780	
33	3.000	2.000	1.500		18.150	
33	3.000	2.000	2.000		16.774	
33	3.000	2.000	2.500		15.120	
33	3.000	2.000	3.000		13.394	
33	3.000	2.500	1.500		15.601	
33	3.000	2.500	2.000		14.574	
33	3.000	2.500	2.500		13.309	
33	3.000	2.500	3.000		11.953	
33	3.000	3.000	1.500		13.316	
33	3.000	3.000	2.000		12.560	
33	3.000	3.000	2.500		11.609	
33	3.000	3.000	3.000		10.564	
33	3.000	3.500	1.500		11.351	
33	3.000	3.500	2.000		10.797	
33	3.000	3.500	2.500		10.087	
33	3.000	3.500	3.000		9.289	
33	3.000	4.000	1.500		9.700	
33	3.000	4.000	2.000		9.292	
33	3.000	4.000	2.500		8.761	
33	3.000	4.000	3.000		8.153	
33	3.000	4.500	1.500		8.327	
33	3.000	4.500	2.000		8.025	
33	3.000	4.500	2.500		7.626	
33	3.000	4.500	3.000		7.160	
33	3.000	5.000	1.500		7.189	
33	3.000	5.000	2.000		6.963	
33	3.000	5.000	2.500		6.661	
33	3.000	5.000	3.000		6.303	
33	3.500	-5.000	1.500		6.575	
33	3.500	-5.000	2.000		6.385	
33	3.500	-5.000	2.500		6.130	
33	3.500	-5.000	3.000		5.826	
33	3.500	-4.500	1.500		7.513	
33	3.500	-4.500	2.000		7.267	
33	3.500	-4.500	2.500		6.938	
33	3.500	-4.500	3.000		6.551	
33	3.500	-4.000	1.500		8.613	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	3.500	-4.000	2.000		8.291	
33	3.500	-4.000	2.500		7.865	
33	3.500	-4.000	3.000		7.372	
33	3.500	-3.500	1.500		9.891	
33	3.500	-3.500	2.000		9.468	
33	3.500	-3.500	2.500		8.918	
33	3.500	-3.500	3.000		8.288	
33	3.500	-3.000	1.500		11.351	
33	3.500	-3.000	2.000		10.797	
33	3.500	-3.000	2.500		10.087	
33	3.500	-3.000	3.000		9.289	
33	3.500	-2.500	1.500		12.971	
33	3.500	-2.500	2.000		12.252	
33	3.500	-2.500	2.500		11.346	
33	3.500	-2.500	3.000		10.346	
33	3.500	-2.000	1.500		14.685	
33	3.500	-2.000	2.000		13.771	
33	3.500	-2.000	2.500		12.636	
33	3.500	-2.000	3.000		11.408	
33	3.500	-1.500	1.500		16.367	
33	3.500	-1.500	2.000		15.240	
33	3.500	-1.500	2.500		13.862	
33	3.500	-1.500	3.000		12.398	
33	3.500	-1.000	1.500		17.826	
33	3.500	-1.000	2.000		16.497	
33	3.500	-1.000	2.500		14.895	
33	3.500	-1.000	3.000		13.217	
33	3.500	-0.500	1.500		18.833	
33	3.500	-0.500	2.000		17.356	
33	3.500	-0.500	2.500		15.591	
33	3.500	-0.500	3.000		13.763	
33	3.500	0.000	1.500		19.195	
33	3.500	0.000	2.000		17.662	
33	3.500	0.000	2.500		15.838	
33	3.500	0.000	3.000		13.955	
33	3.500	0.500	1.500		18.833	
33	3.500	0.500	2.000		17.356	
33	3.500	0.500	2.500		15.591	
33	3.500	0.500	3.000		13.763	
33	3.500	1.000	1.500		17.826	
33	3.500	1.000	2.000		16.497	
33	3.500	1.000	2.500		14.895	
33	3.500	1.000	3.000		13.217	
33	3.500	1.500	1.500		16.367	
33	3.500	1.500	2.000		15.240	
33	3.500	1.500	2.500		13.862	
33	3.500	1.500	3.000		12.398	
33	3.500	2.000	1.500		14.685	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	3.500	2.000	2.000		13.771	
33	3.500	2.000	2.500		12.636	
33	3.500	2.000	3.000		11.408	
33	3.500	2.500	1.500		12.971	
33	3.500	2.500	2.000		12.252	
33	3.500	2.500	2.500		11.346	
33	3.500	2.500	3.000		10.346	
33	3.500	3.000	1.500		11.351	
33	3.500	3.000	2.000		10.797	
33	3.500	3.000	2.500		10.087	
33	3.500	3.000	3.000		9.289	
33	3.500	3.500	1.500		9.891	
33	3.500	3.500	2.000		9.468	
33	3.500	3.500	2.500		8.918	
33	3.500	3.500	3.000		8.288	
33	3.500	4.000	1.500		8.613	
33	3.500	4.000	2.000		8.291	
33	3.500	4.000	2.500		7.865	
33	3.500	4.000	3.000		7.372	
33	3.500	4.500	1.500		7.513	
33	3.500	4.500	2.000		7.267	
33	3.500	4.500	2.500		6.938	
33	3.500	4.500	3.000		6.551	
33	3.500	5.000	1.500		6.575	
33	3.500	5.000	2.000		6.385	
33	3.500	5.000	2.500		6.130	
33	3.500	5.000	3.000		5.826	
33	4.000	-5.000	1.500		5.985	
33	4.000	-5.000	2.000		5.827	
33	4.000	-5.000	2.500		5.614	
33	4.000	-5.000	3.000		5.357	
33	4.000	-4.500	1.500		6.752	
33	4.000	-4.500	2.000		6.552	
33	4.000	-4.500	2.500		6.284	
33	4.000	-4.500	3.000		5.965	
33	4.000	-4.000	1.500		7.628	
33	4.000	-4.000	2.000		7.374	
33	4.000	-4.000	2.500		7.035	
33	4.000	-4.000	3.000		6.638	
33	4.000	-3.500	1.500		8.613	
33	4.000	-3.500	2.000		8.291	
33	4.000	-3.500	2.500		7.865	
33	4.000	-3.500	3.000		7.372	
33	4.000	-3.000	1.500		9.700	
33	4.000	-3.000	2.000		9.292	
33	4.000	-3.000	2.500		8.761	
33	4.000	-3.000	3.000		8.153	
33	4.000	-2.500	1.500		10.858	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	4.000	-2.500	2.000		10.350	
33	4.000	-2.500	2.500		9.696	
33	4.000	-2.500	3.000		8.956	
33	4.000	-2.000	1.500		12.034	
33	4.000	-2.000	2.000		11.413	
33	4.000	-2.000	2.500		10.623	
33	4.000	-2.000	3.000		9.741	
33	4.000	-1.500	1.500		13.141	
33	4.000	-1.500	2.000		12.404	
33	4.000	-1.500	2.500		11.476	
33	4.000	-1.500	3.000		10.454	
33	4.000	-1.000	1.500		14.065	
33	4.000	-1.000	2.000		13.224	
33	4.000	-1.000	2.500		12.175	
33	4.000	-1.000	3.000		11.031	
33	4.000	-0.500	1.500		14.685	
33	4.000	-0.500	2.000		13.771	
33	4.000	-0.500	2.500		12.636	
33	4.000	-0.500	3.000		11.408	
33	4.000	0.000	1.500		14.904	
33	4.000	0.000	2.000		13.963	
33	4.000	0.000	2.500		12.798	
33	4.000	0.000	3.000		11.540	
33	4.000	0.500	1.500		14.685	
33	4.000	0.500	2.000		13.771	
33	4.000	0.500	2.500		12.636	
33	4.000	0.500	3.000		11.408	
33	4.000	1.000	1.500		14.065	
33	4.000	1.000	2.000		13.224	
33	4.000	1.000	2.500		12.175	
33	4.000	1.000	3.000		11.031	
33	4.000	1.500	1.500		13.141	
33	4.000	1.500	2.000		12.404	
33	4.000	1.500	2.500		11.476	
33	4.000	1.500	3.000		10.454	
33	4.000	2.000	1.500		12.034	
33	4.000	2.000	2.000		11.413	
33	4.000	2.000	2.500		10.623	
33	4.000	2.000	3.000		9.741	
33	4.000	2.500	1.500		10.858	
33	4.000	2.500	2.000		10.350	
33	4.000	2.500	2.500		9.696	
33	4.000	2.500	3.000		8.956	
33	4.000	3.000	1.500		9.700	
33	4.000	3.000	2.000		9.292	
33	4.000	3.000	2.500		8.761	
33	4.000	3.000	3.000		8.153	
33	4.000	3.500	1.500		8.613	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	4.000	3.500	2.000		8.291	
33	4.000	3.500	2.500		7.865	
33	4.000	3.500	3.000		7.372	
33	4.000	4.000	1.500		7.628	
33	4.000	4.000	2.000		7.374	
33	4.000	4.000	2.500		7.035	
33	4.000	4.000	3.000		6.638	
33	4.000	4.500	1.500		6.752	
33	4.000	4.500	2.000		6.552	
33	4.000	4.500	2.500		6.284	
33	4.000	4.500	3.000		5.965	
33	4.000	5.000	1.500		5.985	
33	4.000	5.000	2.000		5.827	
33	4.000	5.000	2.500		5.614	
33	4.000	5.000	3.000		5.357	
33	4.500	-5.000	1.500		5.432	
33	4.500	-5.000	2.000		5.302	
33	4.500	-5.000	2.500		5.125	
33	4.500	-5.000	3.000		4.910	
33	4.500	-4.500	1.500		6.057	
33	4.500	-4.500	2.000		5.896	
33	4.500	-4.500	2.500		5.677	
33	4.500	-4.500	3.000		5.415	
33	4.500	-4.000	1.500		6.752	
33	4.500	-4.000	2.000		6.552	
33	4.500	-4.000	2.500		6.284	
33	4.500	-4.000	3.000		5.965	
33	4.500	-3.500	1.500		7.513	
33	4.500	-3.500	2.000		7.267	
33	4.500	-3.500	2.500		6.938	
33	4.500	-3.500	3.000		6.551	
33	4.500	-3.000	1.500		8.327	
33	4.500	-3.000	2.000		8.025	
33	4.500	-3.000	2.500		7.626	
33	4.500	-3.000	3.000		7.160	
33	4.500	-2.500	1.500		9.166	
33	4.500	-2.500	2.000		8.801	
33	4.500	-2.500	2.500		8.324	
33	4.500	-2.500	3.000		7.773	
33	4.500	-2.000	1.500		9.990	
33	4.500	-2.000	2.000		9.559	
33	4.500	-2.000	2.500		8.998	
33	4.500	-2.000	3.000		8.357	
33	4.500	-1.500	1.500		10.741	
33	4.500	-1.500	2.000		10.244	
33	4.500	-1.500	2.500		9.603	
33	4.500	-1.500	3.000		8.876	
33	4.500	-1.000	1.500		11.351	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	4.500	-1.000	2.000		10.797	
33	4.500	-1.000	2.500		10.087	
33	4.500	-1.000	3.000		9.289	
33	4.500	-0.500	1.500		11.751	
33	4.500	-0.500	2.000		11.159	
33	4.500	-0.500	2.500		10.402	
33	4.500	-0.500	3.000		9.555	
33	4.500	0.000	1.500		11.891	
33	4.500	0.000	2.000		11.284	
33	4.500	0.000	2.500		10.511	
33	4.500	0.000	3.000		9.647	
33	4.500	0.500	1.500		11.751	
33	4.500	0.500	2.000		11.159	
33	4.500	0.500	2.500		10.402	
33	4.500	0.500	3.000		9.555	
33	4.500	1.000	1.500		11.351	
33	4.500	1.000	2.000		10.797	
33	4.500	1.000	2.500		10.087	
33	4.500	1.000	3.000		9.289	
33	4.500	1.500	1.500		10.741	
33	4.500	1.500	2.000		10.244	
33	4.500	1.500	2.500		9.603	
33	4.500	1.500	3.000		8.876	
33	4.500	2.000	1.500		9.990	
33	4.500	2.000	2.000		9.559	
33	4.500	2.000	2.500		8.998	
33	4.500	2.000	3.000		8.357	
33	4.500	2.500	1.500		9.166	
33	4.500	2.500	2.000		8.801	
33	4.500	2.500	2.500		8.324	
33	4.500	2.500	3.000		7.773	
33	4.500	3.000	1.500		8.327	
33	4.500	3.000	2.000		8.025	
33	4.500	3.000	2.500		7.626	
33	4.500	3.000	3.000		7.160	
33	4.500	3.500	1.500		7.513	
33	4.500	3.500	2.000		7.267	
33	4.500	3.500	2.500		6.938	
33	4.500	3.500	3.000		6.551	
33	4.500	4.000	1.500		6.752	
33	4.500	4.000	2.000		6.552	
33	4.500	4.000	2.500		6.284	
33	4.500	4.000	3.000		5.965	
33	4.500	4.500	1.500		6.057	
33	4.500	4.500	2.000		5.896	
33	4.500	4.500	2.500		5.677	
33	4.500	4.500	3.000		5.415	
33	4.500	5.000	1.500		5.432	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	4.500	5.000	2.000		5.302	
33	4.500	5.000	2.500		5.125	
33	4.500	5.000	3.000		4.910	
33	5.000	-5.000	2.000		4.817	
33	5.000	-5.000	2.500		4.670	
33	5.000	-5.000	3.000		4.491	
33	5.000	-4.500	2.000		5.302	
33	5.000	-4.500	2.500		5.125	
33	5.000	-4.500	3.000		4.910	
33	5.000	-4.000	2.000		5.827	
33	5.000	-4.000	2.500		5.614	
33	5.000	-4.000	3.000		5.357	
33	5.000	-3.500	2.000		6.385	
33	5.000	-3.500	2.500		6.130	
33	5.000	-3.500	3.000		5.826	
33	5.000	-3.000	2.000		6.963	
33	5.000	-3.000	2.500		6.661	
33	5.000	-3.000	3.000		6.303	
33	5.000	-2.500	2.000		7.540	
33	5.000	-2.500	2.500		7.187	
33	5.000	-2.500	3.000		6.772	
33	5.000	-2.000	2.000		8.089	
33	5.000	-2.000	2.500		7.684	
33	5.000	-2.000	3.000		7.212	
33	5.000	-1.500	2.000		8.575	
33	5.000	-1.500	2.500		8.121	
33	5.000	-1.500	3.000		7.595	
33	5.000	-1.000	2.000		8.959	
33	5.000	-1.000	2.500		8.465	
33	5.000	-1.000	3.000		7.895	
33	5.000	-0.500	2.000		9.207	
33	5.000	-0.500	2.500		8.685	
33	5.000	-0.500	3.000		8.087	
33	5.000	0.000	2.000		9.292	
33	5.000	0.000	2.500		8.761	
33	5.000	0.000	3.000		8.153	
33	5.000	0.500	2.000		9.207	
33	5.000	0.500	2.500		8.685	
33	5.000	0.500	3.000		8.087	
33	5.000	1.000	2.000		8.959	
33	5.000	1.000	2.500		8.465	
33	5.000	1.000	3.000		7.895	
33	5.000	1.500	2.000		8.575	
33	5.000	1.500	2.500		8.121	
33	5.000	1.500	3.000		7.595	
33	5.000	2.000	2.000		8.089	
33	5.000	2.000	2.500		7.684	
33	5.000	2.000	3.000		7.212	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	5.000	2.500	2.000		7.540	
33	5.000	2.500	2.500		7.187	
33	5.000	2.500	3.000		6.772	
33	5.000	3.000	2.000		6.963	
33	5.000	3.000	2.500		6.661	
33	5.000	3.000	3.000		6.303	
33	5.000	3.500	2.000		6.385	
33	5.000	3.500	2.500		6.130	
33	5.000	3.500	3.000		5.826	
33	5.000	4.000	2.000		5.827	
33	5.000	4.000	2.500		5.614	
33	5.000	4.000	3.000		5.357	
33	5.000	4.500	2.000		5.302	
33	5.000	4.500	2.500		5.125	
33	5.000	4.500	3.000		4.910	
33	5.000	5.000	2.000		4.817	
33	5.000	5.000	2.500		4.670	
33	5.000	5.000	3.000		4.491	
33	5.500	-5.000	2.000		4.374	
33	5.500	-5.000	2.500		4.253	
33	5.500	-5.000	3.000		4.104	
33	5.500	-4.500	2.000		4.771	
33	5.500	-4.500	2.500		4.627	
33	5.500	-4.500	3.000		4.451	
33	5.500	-4.000	2.000		5.192	
33	5.500	-4.000	2.500		5.022	
33	5.500	-4.000	3.000		4.816	
33	5.500	-3.500	2.000		5.630	
33	5.500	-3.500	2.500		5.431	
33	5.500	-3.500	3.000		5.191	
33	5.500	-3.000	2.000		6.075	
33	5.500	-3.000	2.500		5.843	
33	5.500	-3.000	3.000		5.566	
33	5.500	-2.500	2.000		6.510	
33	5.500	-2.500	2.500		6.245	
33	5.500	-2.500	3.000		5.929	
33	5.500	-2.000	2.000		6.915	
33	5.500	-2.000	2.500		6.616	
33	5.500	-2.000	3.000		6.263	
33	5.500	-1.500	2.000		7.267	
33	5.500	-1.500	2.500		6.938	
33	5.500	-1.500	3.000		6.551	
33	5.500	-1.000	2.000		7.540	
33	5.500	-1.000	2.500		7.187	
33	5.500	-1.000	3.000		6.772	
33	5.500	-0.500	2.000		7.715	
33	5.500	-0.500	2.500		7.346	
33	5.500	-0.500	3.000		6.913	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m²)
Group	x	y	z	Minimum	Maximum	Minimum
33	5.500	0.000	2.000		7.775	
33	5.500	0.000	2.500		7.400	
33	5.500	0.000	3.000		6.961	
33	5.500	0.500	2.000		7.715	
33	5.500	0.500	2.500		7.346	
33	5.500	0.500	3.000		6.913	
33	5.500	1.000	2.000		7.540	
33	5.500	1.000	2.500		7.187	
33	5.500	1.000	3.000		6.772	
33	5.500	1.500	2.000		7.267	
33	5.500	1.500	2.500		6.938	
33	5.500	1.500	3.000		6.551	
33	5.500	2.000	2.000		6.915	
33	5.500	2.000	2.500		6.616	
33	5.500	2.000	3.000		6.263	
33	5.500	2.500	2.000		6.510	
33	5.500	2.500	2.500		6.245	
33	5.500	2.500	3.000		5.929	
33	5.500	3.000	2.000		6.075	
33	5.500	3.000	2.500		5.843	
33	5.500	3.000	3.000		5.566	
33	5.500	3.500	2.000		5.630	
33	5.500	3.500	2.500		5.431	
33	5.500	3.500	3.000		5.191	
33	5.500	4.000	2.000		5.192	
33	5.500	4.000	2.500		5.022	
33	5.500	4.000	3.000		4.816	
33	5.500	4.500	2.000		4.771	
33	5.500	4.500	2.500		4.627	
33	5.500	4.500	3.000		4.451	
33	5.500	5.000	2.000		4.374	
33	5.500	5.000	2.500		4.253	
33	5.500	5.000	3.000		4.104	
33	6.000	-5.000	2.000		3.974	
33	6.000	-5.000	2.500		3.874	
33	6.000	-5.000	3.000		3.750	
33	6.000	-4.500	2.000		4.299	
33	6.000	-4.500	2.500		4.182	
33	6.000	-4.500	3.000		4.038	
33	6.000	-4.000	2.000		4.638	
33	6.000	-4.000	2.500		4.502	
33	6.000	-4.000	3.000		4.335	
33	6.000	-3.500	2.000		4.985	
33	6.000	-3.500	2.500		4.828	
33	6.000	-3.500	3.000		4.637	
33	6.000	-3.000	2.000		5.330	
33	6.000	-3.000	2.500		5.151	
33	6.000	-3.000	3.000		4.934	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	6.000	-2.500	2.000		5.662	
33	6.000	-2.500	2.500		5.460	
33	6.000	-2.500	3.000		5.218	
33	6.000	-2.000	2.000		5.966	
33	6.000	-2.000	2.500		5.743	
33	6.000	-2.000	3.000		5.475	
33	6.000	-1.500	2.000		6.226	
33	6.000	-1.500	2.500		5.983	
33	6.000	-1.500	3.000		5.693	
33	6.000	-1.000	2.000		6.426	
33	6.000	-1.000	2.500		6.168	
33	6.000	-1.000	3.000		5.860	
33	6.000	-0.500	2.000		6.552	
33	6.000	-0.500	2.500		6.284	
33	6.000	-0.500	3.000		5.965	
33	6.000	0.000	2.000		6.596	
33	6.000	0.000	2.500		6.324	
33	6.000	0.000	3.000		6.000	
33	6.000	0.500	2.000		6.552	
33	6.000	0.500	2.500		6.284	
33	6.000	0.500	3.000		5.965	
33	6.000	1.000	2.000		6.426	
33	6.000	1.000	2.500		6.168	
33	6.000	1.000	3.000		5.860	
33	6.000	1.500	2.000		6.226	
33	6.000	1.500	2.500		5.983	
33	6.000	1.500	3.000		5.693	
33	6.000	2.000	2.000		5.966	
33	6.000	2.000	2.500		5.743	
33	6.000	2.000	3.000		5.475	
33	6.000	2.500	2.000		5.662	
33	6.000	2.500	2.500		5.460	
33	6.000	2.500	3.000		5.218	
33	6.000	3.000	2.000		5.330	
33	6.000	3.000	2.500		5.151	
33	6.000	3.000	3.000		4.934	
33	6.000	3.500	2.000		4.985	
33	6.000	3.500	2.500		4.828	
33	6.000	3.500	3.000		4.637	
33	6.000	4.000	2.000		4.638	
33	6.000	4.000	2.500		4.502	
33	6.000	4.000	3.000		4.335	
33	6.000	4.500	2.000		4.299	
33	6.000	4.500	2.500		4.182	
33	6.000	4.500	3.000		4.038	
33	6.000	5.000	2.000		3.974	
33	6.000	5.000	2.500		3.874	
33	6.000	5.000	3.000		3.750	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	6.500	-5.000	2.000		3.615	
33	6.500	-5.000	2.500		3.532	
33	6.500	-5.000	3.000		3.429	
33	6.500	-4.500	2.000		3.882	
33	6.500	-4.500	2.500		3.786	
33	6.500	-4.500	3.000		3.668	
33	6.500	-4.000	2.000		4.156	
33	6.500	-4.000	2.500		4.046	
33	6.500	-4.000	3.000		3.911	
33	6.500	-3.500	2.000		4.432	
33	6.500	-3.500	2.500		4.308	
33	6.500	-3.500	3.000		4.155	
33	6.500	-3.000	2.000		4.703	
33	6.500	-3.000	2.500		4.563	
33	6.500	-3.000	3.000		4.393	
33	6.500	-2.500	2.000		4.960	
33	6.500	-2.500	2.500		4.805	
33	6.500	-2.500	3.000		4.616	
33	6.500	-2.000	2.000		5.192	
33	6.500	-2.000	2.500		5.022	
33	6.500	-2.000	3.000		4.816	
33	6.500	-1.500	2.000		5.387	
33	6.500	-1.500	2.500		5.205	
33	6.500	-1.500	3.000		4.984	
33	6.500	-1.000	2.000		5.537	
33	6.500	-1.000	2.500		5.344	
33	6.500	-1.000	3.000		5.111	
33	6.500	-0.500	2.000		5.630	
33	6.500	-0.500	2.500		5.431	
33	6.500	-0.500	3.000		5.191	
33	6.500	0.000	2.000		5.662	
33	6.500	0.000	2.500		5.460	
33	6.500	0.000	3.000		5.218	
33	6.500	0.500	2.000		5.630	
33	6.500	0.500	2.500		5.431	
33	6.500	0.500	3.000		5.191	
33	6.500	1.000	2.000		5.537	
33	6.500	1.000	2.500		5.344	
33	6.500	1.000	3.000		5.111	
33	6.500	1.500	2.000		5.387	
33	6.500	1.500	2.500		5.205	
33	6.500	1.500	3.000		4.984	
33	6.500	2.000	2.000		5.192	
33	6.500	2.000	2.500		5.022	
33	6.500	2.000	3.000		4.816	
33	6.500	2.500	2.000		4.960	
33	6.500	2.500	2.500		4.805	
33	6.500	2.500	3.000		4.616	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	6.500	3.000	2.000		4.703	
33	6.500	3.000	2.500		4.563	
33	6.500	3.000	3.000		4.393	
33	6.500	3.500	2.000		4.432	
33	6.500	3.500	2.500		4.308	
33	6.500	3.500	3.000		4.155	
33	6.500	4.000	2.000		4.156	
33	6.500	4.000	2.500		4.046	
33	6.500	4.000	3.000		3.911	
33	6.500	4.500	2.000		3.882	
33	6.500	4.500	2.500		3.786	
33	6.500	4.500	3.000		3.668	
33	6.500	5.000	2.000		3.615	
33	6.500	5.000	2.500		3.532	
33	6.500	5.000	3.000		3.429	
33	7.000	-5.000	2.000		3.294	
33	7.000	-5.000	2.500		3.224	
33	7.000	-5.000	3.000		3.138	
33	7.000	-4.500	2.000		3.513	
33	7.000	-4.500	2.500		3.435	
33	7.000	-4.500	3.000		3.337	
33	7.000	-4.000	2.000		3.737	
33	7.000	-4.000	2.500		3.648	
33	7.000	-4.000	3.000		3.538	
33	7.000	-3.500	2.000		3.959	
33	7.000	-3.500	2.500		3.859	
33	7.000	-3.500	3.000		3.736	
33	7.000	-3.000	2.000		4.173	
33	7.000	-3.000	2.500		4.063	
33	7.000	-3.000	3.000		3.927	
33	7.000	-2.500	2.000		4.374	
33	7.000	-2.500	2.500		4.253	
33	7.000	-2.500	3.000		4.104	
33	7.000	-2.000	2.000		4.553	
33	7.000	-2.000	2.500		4.422	
33	7.000	-2.000	3.000		4.262	
33	7.000	-1.500	2.000		4.703	
33	7.000	-1.500	2.500		4.563	
33	7.000	-1.500	3.000		4.393	
33	7.000	-1.000	2.000		4.817	
33	7.000	-1.000	2.500		4.670	
33	7.000	-1.000	3.000		4.491	
33	7.000	-0.500	2.000		4.887	
33	7.000	-0.500	2.500		4.736	
33	7.000	-0.500	3.000		4.553	
33	7.000	0.000	2.000		4.911	
33	7.000	0.000	2.500		4.759	
33	7.000	0.000	3.000		4.573	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	7.000	0.500	2.000		4.887	
33	7.000	0.500	2.500		4.736	
33	7.000	0.500	3.000		4.553	
33	7.000	1.000	2.000		4.817	
33	7.000	1.000	2.500		4.670	
33	7.000	1.000	3.000		4.491	
33	7.000	1.500	2.000		4.703	
33	7.000	1.500	2.500		4.563	
33	7.000	1.500	3.000		4.393	
33	7.000	2.000	2.000		4.553	
33	7.000	2.000	2.500		4.422	
33	7.000	2.000	3.000		4.262	
33	7.000	2.500	2.000		4.374	
33	7.000	2.500	2.500		4.253	
33	7.000	2.500	3.000		4.104	
33	7.000	3.000	2.000		4.173	
33	7.000	3.000	2.500		4.063	
33	7.000	3.000	3.000		3.927	
33	7.000	3.500	2.000		3.959	
33	7.000	3.500	2.500		3.859	
33	7.000	3.500	3.000		3.736	
33	7.000	4.000	2.000		3.737	
33	7.000	4.000	2.500		3.648	
33	7.000	4.000	3.000		3.538	
33	7.000	4.500	2.000		3.513	
33	7.000	4.500	2.500		3.435	
33	7.000	4.500	3.000		3.337	
33	7.000	5.000	2.000		3.294	
33	7.000	5.000	2.500		3.224	
33	7.000	5.000	3.000		3.138	
33	7.500	-5.000	2.000		3.006	
33	7.500	-5.000	2.500		2.949	
33	7.500	-5.000	3.000		2.876	
33	7.500	-4.500	2.000		3.189	
33	7.500	-4.500	2.500		3.124	
33	7.500	-4.500	3.000		3.043	
33	7.500	-4.000	2.000		3.371	
33	7.500	-4.000	2.500		3.299	
33	7.500	-4.000	3.000		3.209	
33	7.500	-3.500	2.000		3.551	
33	7.500	-3.500	2.500		3.471	
33	7.500	-3.500	3.000		3.371	
33	7.500	-3.000	2.000		3.723	
33	7.500	-3.000	2.500		3.635	
33	7.500	-3.000	3.000		3.525	
33	7.500	-2.500	2.000		3.882	
33	7.500	-2.500	2.500		3.786	
33	7.500	-2.500	3.000		3.668	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	7.500	-2.000	2.000		4.022	
33	7.500	-2.000	2.500		3.919	
33	7.500	-2.000	3.000		3.793	
33	7.500	-1.500	2.000		4.139	
33	7.500	-1.500	2.500		4.030	
33	7.500	-1.500	3.000		3.896	
33	7.500	-1.000	2.000		4.226	
33	7.500	-1.000	2.500		4.113	
33	7.500	-1.000	3.000		3.974	
33	7.500	-0.500	2.000		4.280	
33	7.500	-0.500	2.500		4.164	
33	7.500	-0.500	3.000		4.022	
33	7.500	0.000	2.000		4.299	
33	7.500	0.000	2.500		4.182	
33	7.500	0.000	3.000		4.038	
33	7.500	0.500	2.000		4.280	
33	7.500	0.500	2.500		4.164	
33	7.500	0.500	3.000		4.022	
33	7.500	1.000	2.000		4.226	
33	7.500	1.000	2.500		4.113	
33	7.500	1.000	3.000		3.974	
33	7.500	1.500	2.000		4.139	
33	7.500	1.500	2.500		4.030	
33	7.500	1.500	3.000		3.896	
33	7.500	2.000	2.000		4.022	
33	7.500	2.000	2.500		3.919	
33	7.500	2.000	3.000		3.793	
33	7.500	2.500	2.000		3.882	
33	7.500	2.500	2.500		3.786	
33	7.500	2.500	3.000		3.668	
33	7.500	3.000	2.000		3.723	
33	7.500	3.000	2.500		3.635	
33	7.500	3.000	3.000		3.525	
33	7.500	3.500	2.000		3.551	
33	7.500	3.500	2.500		3.471	
33	7.500	3.500	3.000		3.371	
33	7.500	4.000	2.000		3.371	
33	7.500	4.000	2.500		3.299	
33	7.500	4.000	3.000		3.209	
33	7.500	4.500	2.000		3.189	
33	7.500	4.500	2.500		3.124	
33	7.500	4.500	3.000		3.043	
33	7.500	5.000	2.000		3.006	
33	7.500	5.000	2.500		2.949	
33	7.500	5.000	3.000		2.876	
33	8.000	-5.000	2.500		2.702	
33	8.000	-5.000	3.000		2.641	
33	8.000	-4.500	2.500		2.848	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	8.000	-4.500	3.000		2.780	
33	8.000	-4.000	2.500		2.993	
33	8.000	-4.000	3.000		2.918	
33	8.000	-3.500	2.500		3.133	
33	8.000	-3.500	3.000		3.052	
33	8.000	-3.000	2.500		3.267	
33	8.000	-3.000	3.000		3.178	
33	8.000	-2.500	2.500		3.388	
33	8.000	-2.500	3.000		3.293	
33	8.000	-2.000	2.500		3.495	
33	8.000	-2.000	3.000		3.394	
33	8.000	-1.500	2.500		3.582	
33	8.000	-1.500	3.000		3.476	
33	8.000	-1.000	2.500		3.648	
33	8.000	-1.000	3.000		3.538	
33	8.000	-0.500	2.500		3.688	
33	8.000	-0.500	3.000		3.576	
33	8.000	0.000	2.500		3.702	
33	8.000	0.000	3.000		3.589	
33	8.000	0.500	2.500		3.688	
33	8.000	0.500	3.000		3.576	
33	8.000	1.000	2.500		3.648	
33	8.000	1.000	3.000		3.538	
33	8.000	1.500	2.500		3.582	
33	8.000	1.500	3.000		3.476	
33	8.000	2.000	2.500		3.495	
33	8.000	2.000	3.000		3.394	
33	8.000	2.500	2.500		3.388	
33	8.000	2.500	3.000		3.293	
33	8.000	3.000	2.500		3.267	
33	8.000	3.000	3.000		3.178	
33	8.000	3.500	2.500		3.133	
33	8.000	3.500	3.000		3.052	
33	8.000	4.000	2.500		2.993	
33	8.000	4.000	3.000		2.918	
33	8.000	4.500	2.500		2.848	
33	8.000	4.500	3.000		2.780	
33	8.000	5.000	2.500		2.702	
33	8.000	5.000	3.000		2.641	
33	8.500	-5.000	2.500		2.481	
33	8.500	-5.000	3.000		2.429	
33	8.500	-4.500	2.500		2.603	
33	8.500	-4.500	3.000		2.547	
33	8.500	-4.000	2.500		2.724	
33	8.500	-4.000	3.000		2.662	
33	8.500	-3.500	2.500		2.840	
33	8.500	-3.500	3.000		2.773	
33	8.500	-3.000	2.500		2.949	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	8.500	-3.000	3.000		2.876	
33	8.500	-2.500	2.500		3.048	
33	8.500	-2.500	3.000		2.970	
33	8.500	-2.000	2.500		3.133	
33	8.500	-2.000	3.000		3.052	
33	8.500	-1.500	2.500		3.204	
33	8.500	-1.500	3.000		3.119	
33	8.500	-1.000	2.500		3.256	
33	8.500	-1.000	3.000		3.168	
33	8.500	-0.500	2.500		3.288	
33	8.500	-0.500	3.000		3.198	
33	8.500	0.000	2.500		3.299	
33	8.500	0.000	3.000		3.209	
33	8.500	0.500	2.500		3.288	
33	8.500	0.500	3.000		3.198	
33	8.500	1.000	2.500		3.256	
33	8.500	1.000	3.000		3.168	
33	8.500	1.500	2.500		3.204	
33	8.500	1.500	3.000		3.119	
33	8.500	2.000	2.500		3.133	
33	8.500	2.000	3.000		3.052	
33	8.500	2.500	2.500		3.048	
33	8.500	2.500	3.000		2.970	
33	8.500	3.000	2.500		2.949	
33	8.500	3.000	3.000		2.876	
33	8.500	3.500	2.500		2.840	
33	8.500	3.500	3.000		2.773	
33	8.500	4.000	2.500		2.724	
33	8.500	4.000	3.000		2.662	
33	8.500	4.500	2.500		2.603	
33	8.500	4.500	3.000		2.547	
33	8.500	5.000	2.500		2.481	
33	8.500	5.000	3.000		2.429	
33	9.000	-5.000	2.500		2.282	
33	9.000	-5.000	3.000		2.239	
33	9.000	-4.500	2.500		2.386	
33	9.000	-4.500	3.000		2.338	
33	9.000	-4.000	2.500		2.487	
33	9.000	-4.000	3.000		2.435	
33	9.000	-3.500	2.500		2.583	
33	9.000	-3.500	3.000		2.527	
33	9.000	-3.000	2.500		2.673	
33	9.000	-3.000	3.000		2.613	
33	9.000	-2.500	2.500		2.754	
33	9.000	-2.500	3.000		2.691	
33	9.000	-2.000	2.500		2.824	
33	9.000	-2.000	3.000		2.757	
33	9.000	-1.500	2.500		2.881	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	9.000	-1.500	3.000		2.812	
33	9.000	-1.000	2.500		2.923	
33	9.000	-1.000	3.000		2.852	
33	9.000	-0.500	2.500		2.949	
33	9.000	-0.500	3.000		2.876	
33	9.000	0.000	2.500		2.957	
33	9.000	0.000	3.000		2.885	
33	9.000	0.500	2.500		2.949	
33	9.000	0.500	3.000		2.876	
33	9.000	1.000	2.500		2.923	
33	9.000	1.000	3.000		2.852	
33	9.000	1.500	2.500		2.881	
33	9.000	1.500	3.000		2.812	
33	9.000	2.000	2.500		2.824	
33	9.000	2.000	3.000		2.757	
33	9.000	2.500	2.500		2.754	
33	9.000	2.500	3.000		2.691	
33	9.000	3.000	2.500		2.673	
33	9.000	3.000	3.000		2.613	
33	9.000	3.500	2.500		2.583	
33	9.000	3.500	3.000		2.527	
33	9.000	4.000	2.500		2.487	
33	9.000	4.000	3.000		2.435	
33	9.000	4.500	2.500		2.386	
33	9.000	4.500	3.000		2.338	
33	9.000	5.000	2.500		2.282	
33	9.000	5.000	3.000		2.239	
33	9.500	-5.000	2.500		2.105	
33	9.500	-5.000	3.000		2.068	
33	9.500	-4.500	2.500		2.192	
33	9.500	-4.500	3.000		2.152	
33	9.500	-4.000	2.500		2.277	
33	9.500	-4.000	3.000		2.234	
33	9.500	-3.500	2.500		2.358	
33	9.500	-3.500	3.000		2.311	
33	9.500	-3.000	2.500		2.432	
33	9.500	-3.000	3.000		2.383	
33	9.500	-2.500	2.500		2.499	
33	9.500	-2.500	3.000		2.447	
33	9.500	-2.000	2.500		2.557	
33	9.500	-2.000	3.000		2.502	
33	9.500	-1.500	2.500		2.603	
33	9.500	-1.500	3.000		2.547	
33	9.500	-1.000	2.500		2.638	
33	9.500	-1.000	3.000		2.580	
33	9.500	-0.500	2.500		2.659	
33	9.500	-0.500	3.000		2.600	
33	9.500	0.000	2.500		2.666	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	9.500	0.000	3.000		2.606	
33	9.500	0.500	2.500		2.659	
33	9.500	0.500	3.000		2.600	
33	9.500	1.000	2.500		2.638	
33	9.500	1.000	3.000		2.580	
33	9.500	1.500	2.500		2.603	
33	9.500	1.500	3.000		2.547	
33	9.500	2.000	2.500		2.557	
33	9.500	2.000	3.000		2.502	
33	9.500	2.500	2.500		2.499	
33	9.500	2.500	3.000		2.447	
33	9.500	3.000	2.500		2.432	
33	9.500	3.000	3.000		2.383	
33	9.500	3.500	2.500		2.358	
33	9.500	3.500	3.000		2.311	
33	9.500	4.000	2.500		2.277	
33	9.500	4.000	3.000		2.234	
33	9.500	4.500	2.500		2.192	
33	9.500	4.500	3.000		2.152	
33	9.500	5.000	2.500		2.105	
33	9.500	5.000	3.000		2.068	
33	10.000	-5.000	2.500		1.945	
33	10.000	-5.000	3.000		1.913	
33	10.000	-4.500	2.500		2.020	
33	10.000	-4.500	3.000		1.985	
33	10.000	-4.000	2.500		2.091	
33	10.000	-4.000	3.000		2.055	
33	10.000	-3.500	2.500		2.159	
33	10.000	-3.500	3.000		2.120	
33	10.000	-3.000	2.500		2.222	
33	10.000	-3.000	3.000		2.180	
33	10.000	-2.500	2.500		2.277	
33	10.000	-2.500	3.000		2.234	
33	10.000	-2.000	2.500		2.325	
33	10.000	-2.000	3.000		2.280	
33	10.000	-1.500	2.500		2.363	
33	10.000	-1.500	3.000		2.317	
33	10.000	-1.000	2.500		2.392	
33	10.000	-1.000	3.000		2.344	
33	10.000	-0.500	2.500		2.409	
33	10.000	-0.500	3.000		2.360	
33	10.000	0.000	2.500		2.415	
33	10.000	0.000	3.000		2.366	
33	10.000	0.500	2.500		2.409	
33	10.000	0.500	3.000		2.360	
33	10.000	1.000	2.500		2.392	
33	10.000	1.000	3.000		2.344	
33	10.000	1.500	2.500		2.363	

Table II: (continued)

	Test location (m)			Illuminance (lux)		Luminance (cd/m^2)
Group	x	y	z	Minimum	Maximum	Minimum
33	10.000	1.500	3.000		2.317	
33	10.000	2.000	2.500		2.325	
33	10.000	2.000	3.000		2.280	
33	10.000	2.500	2.500		2.277	
33	10.000	2.500	3.000		2.234	
33	10.000	2.500	3.000		2.222	
33	10.000	3.000	3.000		2.180	
33	10.000	3.500	2.500		2.159	
33	10.000	3.500	3.000		2.120	
33	10.000	4.000	2.500		2.091	
33	10.000	4.000	3.000		2.055	
33	10.000	4.500	2.500		2.020	
33	10.000	4.500	3.000		1.985	
33	10.000	5.000	2.500		1.945	
33	10.000	5.000	3.000		1.913	

Test locations are referenced to the ground level at the forwardmost point of the vehicle, on the vehicle midline. Conventions for location variables are: x is distance ahead of the reference point, y is lateral distance with positive values toward the right from the driver's point of view, and z is height above the ground.

For each group of test points from 1 to 31, outcome is determined by dividing the photometric value at each point by the requirement for that point and averaging the resulting ratio over all points in the group. For minima, the result must be greater than 1. For maxima, the result must be less than 1. In order to be in overall agreement with the performance-oriented system, all group results must be as required. For Groups 32 and 33, each individual point must be below the maximum.

Table III Retroreflective efficiencies for vehicle-based headlighting

Observation angle (degrees)	Retroreflective efficiency (cd/m^2/lx)
0.10	342.86
0.15	324.34
0.20	300.00
0.25	271.54
0.30	239.66
0.35	207.09
0.40	174.51
0.45	144.00
0.50	116.57
0.55	92.23
0.60	72.34
0.65	56.57
0.70	44.91
0.75	36.69
0.80	31.20
0.85	28.11
0.90	26.40